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Shaping factors in the emergence of technological innovations: The case of tidal kite technology

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ABSTRACT

The technological innovation systems (TIS) literature offers a detailed and dynamic understanding of factors that enable successful innovation. However, few studies analyze what determines where in space value chain elements are developed as a new technology is diffused on a large scale. The purpose of this paper is to show how the TIS approach can be used to identify and analyze factors that shape spatial trajectories of emerging technologies. It proposes an adapted analytical framework that expands the conventional focus on one-dimensional supporting and blocking factors, to shaping factors that incorporate the spatiality of innovation. The approach is illustrated by examining innovation in tidal kite technology. The analysis finds that a supportive local context in western Sweden during the infancy of tidal kite technology, together with the availability of competent engineers and business development professionals, promoted the formation of locally embedded knowledge and competence. This in turn created a spatial path dependency that made developments gravitate towards Sweden, although the lack of domestic markets has also increasingly driven an expansion of activity to other regions, in particular the UK. Moreover, the analysis shows that shaping, and not only stimulating, the growth of emerging TIS is an important challenge for regional policymakers, and highlights the need for international policy coordination. The paper concludes that analyzing shaping factors in the emergence of new TISs can yield important insights, some of which may be overlooked with a narrow analytical focus on supporting and blocking factors.

1. Introduction

Global warming due to anthropogenic carbon emissions is destabilizing the climate system in ways that may be devastating for human societies and ecosystems around the world (IPCC, 2014). Avoiding the worst consequences requires a rapid transition to a low-carbon energy system within decades (IPCC, 2014, 2012; Rockström et al., 2017). Governments on different levels play an important role in sustaining and accelerating this development, by promoting new technologies that may reduce the cost and increase the availability of renewable energy (Mazzucato and Semieniuk, 2017; UNEP, 2017).

In the sustainability transitions literature, which encompasses several interrelated and overlapping concepts, models and frameworks (Coenen and Díaz López, 2010; Markard et al., 2012), the technological innovation systems (TIS) framework is often described as an appropriate approach for analyzing emerging technologies and informing policy interventions (Binz et al., 2014; Jacobsson and Bergek, 2011; Markard et al., 2015; Truffer, 2015). The TIS framework conceptualizes technology development and diffusion as the gradual development of sociotechnical system structures along the value chain for a new technology (Bergek et al., 2008a, 2008b; Hekkert et al., 2007; Hekkert and Negro, 2009). This process is understood by analyzing functions that describe how actors mobilize, develop and combine resources such as knowledge, financial capital, legitimacy and markets (Bergek et al., 2008a; Hekkert et al., 2007; Hekkert and Negro, 2009). The TIS literature focuses on analyzing strengths, weaknesses and dynamics in these functions, in order to identify factors that support and block structural development, and that can be used to guide policymakers. However, few TIS studies attempt to identify what determines where in space structural development occurs. This may be due to a neglect of the geography of innovation, which has been pointed out by a number of scholars (Binz et al., 2014; Coenen et al., 2012; Markard et al., 2012; Raven et al., 2012; Truffer and Coenen, 2012), but also connected to a general emphasis on factors that support and block rather than shape TIS growth.

The spatial distribution of structural development along the value chain is important because it determines where localized benefits are created as a renewable energy technology is diffused on a large scale.[1]

Abbreviations: TIS, technological innovation systems; R&D, research and development; RD&D, research, development and demonstration

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[1] The successful development and diffusion of new technologies also creates global benefits that impact the whole planet, such as mitigation of climate change.

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Regions where power is produced may enjoy strengthened energy security and reduced pollution, while enabling supply industries give rise to new jobs, increased tax revenues and knowledge spillovers to other sectors. In a globalized economy, however, it is far from certain that these benefits arise in the same region that originally enabled technological innovation, by making public investments and implementing supportive policies (Binz et al., 2017; Bunnell and Coe, 2001; De Backer et al., 2017; Ernst, 2002; Lovdal and Moen, 2013; Quitzow, 2015). The spatial configuration of value chains can develop in different and unexpected ways, which leads to uncertainties that may discourage policymakers from supporting new technologies and result in a slower global response to challenges such as climate change (Binz and Truffer, 2017). A better understanding of how spatial trajectories form as a result of innovation dynamics in early development stages can potentially reduce these uncertainties. In addition, it may enable the design of policies that not only stimulate the development of new technologies, but also ensure, or at least increase the likelihood, that key value chain elements are developed domestically.

The purpose of this paper is therefore to show how the TIS approach can be used to identify and analyze factors that shape spatial trajectories of emerging technologies. We propose an adapted analytical framework that distinguishes between regional sub-systems within a global TIS, and explains where structural development occurs by differences in resource formation processes at the sub-system level. Analyzing these processes allows for identifying shaping factors, which may reduce uncertainties and enable the design of more appropriate policies.

We illustrate the adapted analytical framework by analyzing the emergence of tidal kite technology, which is intended to produce electricity from low-velocity tidal streams and ocean currents (Minesto, 2016a). The technology was invented in 2004 and has since then been developed mainly by Swedish actors. Small-scale prototypes have been tested in tank, sea and ocean environments, and preparations for deploying the first full-scale demonstration are ongoing. A distinguishing feature of tidal kite technology is its dependence on suitable tidal streams or ocean currents that simply do not exist in Sweden. This rules out domestic deployment both for testing and commercial purposes (Andersson, 2013), which is why key actors from an early stage were forced to act on an international level to access funding, supportive policy schemes, and suitable locations for testing and demonstration (Andersson et al., 2017). It is accordingly an extreme case (Flyvbjerg, 2016), where international linkages and dynamics can be expected to be particularly extensive and decisive, which makes it appropriate for illustrating our adapted analytical framework as well as for learning more about factors that shape spatial trajectories.

After this brief introduction, we proceed in Section 2 by establishing a theoretical foundation and developing our analytical framework. Section 3 then describes the research design, while Section 4 analyzes the emergence of tidal kite technology. Thereafter, in Section 5, we discuss our findings, identify policy implications, highlight our contributions and suggest avenues for future research. Finally, our conclusions are presented in Section 6.

2. Theoretical foundation and analytical framework

As a result of criticism towards the traditional market failures approach to justifying and designing policy intervention in the economy (Jacobsson et al., 2017; Bleda and Del Rio, 2013; Jacobsson and Johnson, 2000; Lazonick and Mazzucato, 2013; Metcalfe, 1994; Smith, 2000), the sustainability transitions literature, which attempts to understand fundamental transformations of sociotechnical systems, has proposed a number of alternative and somewhat overlapping conceptual frameworks for analyzing technological innovation (Markard et al., 2012). The literature commonly views the economy as a dynamic system, characterized by increasing returns and positive feedback (Bergek et al., 2008b; Geels, 2005). Innovation is understood as a collective endeavor, involving a multitude of actors that engage in complex and cumulative learning processes (Bergek et al., 2008a; Markard and Truffer, 2008). The influence of institutions on the innovation process is emphasized and often put central to the analysis, and phenomena such as interdependence, path dependency and lock-in are widely acknowledged (Arthur, 2009; Carlsson et al., 2002; Geels, 2005; Unruh, 2000). In addition, policy intervention is seen as justified and desirable for successful innovation, and studies are often geared towards informing policymaking (Bergek et al., 2008a; Jacobsson and Johnson, 2000; Klein Woolthuis et al., 2005; Weber and Rohracher, 2012).

Within this field, the TIS approach is often promoted as appropriate for analyzing emerging technologies from a policy perspective (Binz et al., 2014; Jacobsson and Bergek, 2011; Markard et al., 2015; Truffer, 2015). The remaining part of this section describes the TIS approach in more detail, motivates the need to focus more on the process of shaping, particularly in the spatial dimension, rather than staying with the one-dimensional question of fast growth versus slow or blocked growth, and outlines an analytical framework that makes this possible.

2.1. The technological innovation systems (TIS) approach

The TIS approach is based on evolutionary economic theories (Markard and Truffer, 2008) and has strong linkages to other innovation systems approaches that focus on nations (Lundvall, 1992), regions (Cooke et al., 1997) or sectors (Malerba, 2002). Building on the notion of 'technological systems' proposed by Carlsson and Stankiewicz (1991), and later contributions by among others Jacobsson and Johnson (2000), Hekkert et al. (2007) and Bergek et al. (2008a, 2008b), a TIS can be defined as a sociotechnical system that enables the development, diffusion and utilization of a new technology. It exists in a context of other emerging technologies, established industry sectors and broader societal systems such as the political, financial and education systems (Bergek et al., 2015). Defining a TIS thus involves setting a system boundary in the sociotechnical dimension as well as specifying its spatial and temporal reach (Hillman and Sandén, 2008).

As a sociotechnical system, a TIS consists of social and technical components that can be categorized and described in somewhat different ways (Bergek et al., 2008a; Geels, 2002; Hughes, 1987; Sandén and Hillman, 2011). The conceptualizations available in the literature arguably attempt to capture the same underlying phenomenon; namely that the world seemingly consists of physical objects that are either inert (i.e. artifacts) or have some kind of individual or collective agency (i.e. actors). These physical objects interact systemically under the influence of rules that may be socially constructed (i.e. institutions), and exist as beliefs and values embedded in actors or as mechanisms and codes embedded in artifacts, or constitute fundamental characteristics of nature (such as the force of gravity). This paper therefore adopts the view that artifacts, actors and rules are the fundamental structural components of a TIS (see Sandén and Hillman (2011) for a similar view).

Artifacts include physical objects that constitute or enable the development of the technology in focus (i.e. machine components, testing infrastructure etc.) as well as ones in which codified knowledge is embedded (i.e. papers, hard drives etc.). Actors comprise firms, universities, research institutes, governments, public agencies and other organizations, but also individuals that may act as entrepreneurs, experts or parts of larger groups. Finally, rules consist of fundamental forces and characteristics of nature together with socially constructed regulative, normative and cognitive procedures. The latter are embedded in formal laws, regulations and standards as well as in informal norms, values and beliefs. In addition, it should be noted that networks are often highlighted as a structural component in the literature (Bergek et al., 2008a; Jacobsson and Johnson, 2000). Here, however, they are viewed as a system property, emerging from the interplay of artifacts, actors and rules, which is by no means intended to downplay their importance for the innovation process.

A central proposition in the TIS literature is that few structural components are in place when a new technology emerges (Bergek et al., 2008b). Analyses therefore tend to be geared towards understanding how TIS structure develops and grows over time through the entry, accumulation and alignment of artifacts, actors and rules (Bergek et al., 2008a, 2008b; Hekkert et al., 2007; Hekkert and Negro, 2009). Structural development thus refers to the expansion of TIS structure, which in turn corresponds to increased diffusion and use of the technology in question. To capture the complex and dynamic nature of structural development, it is common to analyze the performance and interdependence of key sub-processes, commonly referred to as functions (Bergek et al., 2008a; Hekkert et al., 2007). Although functions can be defined, grouped and interpreted somewhat differently (Markard and Truffer, 2008), they tend to revolve around processes that describe the creation, development and mobilization of essential innovation elements such as knowledge, financial capital and markets (Bergek et al., 2008a; Hekkert and Negro, 2009). Analyzing strengths, weaknesses and dynamics in functions makes it possible to identify factors that support or block the development of system structures. Actors with an interest in promoting a certain technology may then take measures to enhance supporting factors or counteract blocking factors, in order to enable or stimulate TIS growth.

TIS studies often focus on informing policymakers that aim to promote specific technologies. The underlying rationale is that certain technologies are considered desirable for social or environmental reasons, that their development and diffusion in society corresponds to TIS growth, and that policymakers can facilitate this growth by implementing policies that target supporting or blocking factors. However, in the following section, when looking more closely at what motivates public support to new renewable energy technologies, we will see that this logic is partially flawed and highlight the need to broaden the analytical focus in the TIS literature.

2.2. The spatiality of policy objectives when promoting new renewable energy technologies

Governments play an important role in sustaining and accelerating the transition to a low-carbon energy system by supporting the development and diffusion of new renewable energy technologies (Mazzucato and Semieniuk, 2017; UNEP, 2017). These efforts are at least partly motivated by a desire to contribute to mitigating climate change and other global environmental problems (EU, 2009; Joas et al., 2016). However, an additional driver, that arguably dominates in many cases, is the possibility of creating localized benefits in specific geographical contexts (GCEC, 2015; IPCC, 2012; IRENA, 2017, 2014). These may arise as a result of using the new technology[2] or stem from economic development in different parts of its value chain (i.e. development, production, installation and maintenance of technology). The former includes strengthened energy security and reduced local pollution, while the latter mainly consist of new jobs, increased tax revenue and knowledge spill-overs to other economic sectors.

The distribution of localized benefits between different regions depends on where power-producing installations and enabling supply industries are located as the new technology is diffused globally. However, in a globalized economy, where innovation, production and consumption are increasingly international phenomena, it is far from certain that value chain elements are developed in the same region that originally enabled technological innovation by making public investments and implementing supportive policies (Binz et al., 2017; Bunnell and Coe, 2001; De Backer et al., 2017; Ernst, 2002; Lovdal and Moen, 2013; Quitzow, 2015). This has been highlighted and discussed in relation to the German Energiewende, where extensive market deployment subsidies led to a rapid diffusion of photovoltaics (Buchan, 2012; Grau et al., 2011; Paris Innovation Review, 2012; Pegels and Lütkenhorst, 2014; Quitzow, 2015). Some argue that this unintentionally drove industrialization in China and that German policymakers might fail to achieve objectives related to domestic economic development (Buchan, 2012; Grau et al., 2011; Paris Innovation Review, 2012). Although other scholars dismiss this reasoning as oversimplified, emphasize more complex transnational dynamics and highlight that the Energiewende has led to domestic industrialization as well (Pegels and Lütkenhorst, 2014; Quitzow, 2015), the German case still illustrates how emerging TISs can follow unintended and unexpected spatial trajectories that are not in line with national policy objectives.

For policymakers that are solely interested in mitigating climate change, these spatial uncertainties are less relevant; TIS growth means that new renewable energy technology is developed, diffused and used, somewhere, which is what reduces global emissions. However, policymakers that also aim to create localized benefits are put in a more complex situation. They would certainly want to promote TIS growth, but also shape the emerging TIS in a way that leads to the development of key value chain elements in their local contexts. Moreover, from a global perspective, spatial uncertainties may discourage policymakers from supporting the development of new technologies (Binz and Truffer, 2017), which could result in a slower global response to climate change.

A better understanding of how spatial trajectories form, as a result of innovation dynamics in early development stages, would reduce uncertainties facing policymakers that engage in promoting innovation in new technology. In addition, it could potentially enable policymaking that ensures, or at least increases the likelihood, that key value chain elements are developed domestically as a new technology is diffused in society. Even though the TIS literature has largely failed to engage with this issue in the past, the TIS framework could potentially be developed to enable identifying not only factors that support and block the development of a new technology, but also factors that shape emerging value chains in the spatial dimension. Outlining such an adapted analytical framework is the focus of the next section.

2.3. Shaping factors as an alternative focus of TIS analysis

Shifting the focus of TIS analysis from identifying factors that simply block or support the development and diffusion of a particular technology, to factors that shape the spatial configuration of the value chains that enable its development, production and use, implies engaging with the geography of innovation. Even though TISs were originally conceptualized as systems that normally transcend territorial boundaries (Bergek et al., 2008a; Carlsson et al., 2002; Carlsson and Stankiewicz, 1991), scholars have argued that much of the TIS literature neglects that innovation processes are simultaneously embedded in local contexts and dependent on transnational interactions (Coenen et al., 2012; Hansen and Coenen, 2015; Markard et al., 2012). Moreover, they criticize the dominance of empirical studies that analyze nationally delineated TIS, while treating global developments as contextual and thereby possibly neglecting important dynamics (Coenen, 2015; Quitzow, 2015). A growing literature, commonly referred to as "geography of TIS", has recently emerged in response to this criticism (Hansen and Coenen, 2015; Truffer et al., 2015). It proposes different ways of making the geography of innovation more explicit in the analysis, and has begun exploring empirical approaches that focus on transnational linkages and dynamics (Binz et al., 2012; Binz and Truffer, 2017; Gosens et al., 2015; Quitzow, 2015; Vasseur et al., 2013).

In this paper, we propose an analytical framework that builds on these contributions by distinguishing between spatially delineated subsystems in a global TIS. Within these regional sub-systems, a broad range of resources that enable structural development are formed.[3] This

[2] Or more specifically, at least in some situations, as a result of replacing an old technology.

Table 1
The typology of resources used in this paper, drawing on Bergek et al. (2008a) but adjusted to the purpose of this paper.

Resource	Description
Knowledge	Scientific, technological, market and design knowledge that may be embedded in artifacts or explicitly coded in scripts (texts, pictures etc.).
Competence	Scientific, technological, market and design capabilities, embedded in individuals and their interaction.
Enabling technology	Generic infrastructure, products and services that are necessary for the development, diffusion and use of the technology.
Financial capital	Investments and other funds in the form of equity investments, R&D grants etc.
Legitimacy	The social acceptance and desirability of the technology as well as its compliance with relevant institutions.
Markets	New and existing markets for the technology.

occurs through creation processes that build on system internal structures (i.e. knowledge development through research and development (R&D)) as well as through mobilization processes that build on contextual structures (i.e. knowledge spillovers from other industry sectors) (Bergek et al., 2008b; Binz et al., 2015). Our analytical framework uses a typology of six different resources (Table 1), which is based on the list of functions proposed in the seminal contribution by Bergek et al. (2008a). However, since we focus on the result of processes (resources), rather than the processes themselves (functions), there is a need for certain adjustments (see Binz et al. (2015) for a similar view). Firstly, we view 'entrepreneurial experimentation', which describes variety-creation through testing and demonstration, as an integrated part of the formation of knowledge and competence, and its result is therefore captured by these resources. Secondly, the function 'resource mobilization' has been divided into three subcategories, corresponding to the resources competence, enabling technology and financial capital, in order to increase the level of detail necessary for analyzing shaping factors. Thirdly, 'influence on the direction of search' has been merged with 'legitimation'. Both these processes result in changes in beliefs and values that increase the perceived desirability of a technology and influence actors' investment and engagement decisions, which we capture through the resource legitimacy. Finally, 'development of external economies' has been omitted and is instead viewed as a result of the dynamic interplay between the remaining resource formation processes (see Hekkert and Negro (2009) for a similar view).

Resource formation processes on the sub-system level clearly exhibit regional dynamics (i.e. mobilization of financial capital may enable the development of new knowledge which in turn may strengthen legitimacy), but they are also entangled with processes in other sub-systems, which gives rise to interregional dynamics (i.e. financial capital mobilized in one region could be used to fund knowledge development in a second region which in the end may strengthen legitimacy in a third region). An important implication is that resource formation in one region can result in structural development elsewhere, which is what creates the spatial uncertainties discussed in the previous section.

Whereas some resources, such as knowledge published in scientific journals and financial capital, can be transferred quite easily between different regions, others are bound to specific places. The economic geography literature points out that competence and certain types of knowledge cannot easily be separated from their social context, which makes these resources spatially 'sticky'. (Asheim and Isaksen, 2002; Binz and Truffer, 2017; Boschma, 2004; Gertler, 2003). Although the concept of sticky resources is most often used in relation to knowledge and competence, it can be applied to other resources as well. For example, natural resource endowments, in particular renewable energy flows such as winds, waves and tides, can be highly localized. This means that markets and enabling technology, that sometimes depend on a proximity to these natural resources, may have a sticky character as well. Since sticky resources are difficult or impossible to transfer between regions, their formation can be expected to promote local structural development. This makes them particularly important for understanding what determines spatial trajectories of emerging TISs.

The spatiality of technological innovation processes described above is not captured by supporting or blocking factors. These are based on a one-dimensional conception of system growth that focuses on temporal dynamics and trajectories, which implies that the spatial dimension is made invisible. Therefore, we introduce shaping factors as an alternative analytical focus. The concept refers to properties that influence both temporal and spatial dynamics and trajectories in the complex processes involved when resource formation drives structural development. Shaping factors thus capture not only the 'why', 'what' and 'when', but also the 'where' of technological innovation processes, which make them more relevant for policy-oriented analysis. Illustrating how shaping factors can be identified, by distinguishing between regional sub-systems in a global TIS and analyzing resource formation processes on the sub-system level, is the focus of the next two sections.

3. Research design

To illustrate the merits of our analytical framework, we have chosen to analyze the development of tidal kite technology using a case study approach (Eisenhardt, 1989; Flyvbjerg, 2016; Yin, 2009). This section highlights the main characteristics of tidal kite TIS and motivates its relevance as a research case, delineates system boundaries and describes our methodology.

3.1. Research case: tidal kite technology

Tidal kite technology is one of many concepts developed to harness marine energy.[4] It consists of an underwater kite, moored to the seafloor or a floating structure, that produces electricity by moving in a figure-eight shape perpendicular to a current in the ocean (EMEC, 2016). The kite movement accelerates the water passing through the turbine up to ten times the actual current velocity (Minesto, 2016a). This makes it one of few technologies that might be able to exploit low-velocity tidal and ocean currents (Sandén et al., 2014). In addition, it enables a power plant that is smaller and lighter compared to most competing technologies, which can potentially lead to lower costs (Minesto, 2016a).

The technology concept was invented in 2004 and since then small-scale prototypes have been tested in tank, sea and ocean environments. A number of suppliers, universities, research institutes, investors and policymakers are involved in the development of the technology, although the Swedish firm Minesto is the key actor with patent rights covering the basic concept and several sub-systems. A distinguishing feature of tidal kite technology is its dependence on suitable tidal streams or ocean currents. This is a highly localized[5] natural resource

[3] It should be emphasized that our notion of resources that enable structural development goes beyond the function 'resource mobilization' suggested by Bergek et al. (2008a).

[4] Marine energy refers to power production from waves, tidal streams and ocean currents in the ocean, and several technology concepts are under development in Sweden. Tidal kite technology is, however, the only Swedish concept for tidal streams and ocean currents that has attracted significant resources and been demonstrated beyond simple small-scale prototypes (Andersson et al., 2017; Interview 10, 2016; Interview 9, 2016).

[5] The resource is localized in several respects. Firstly, deploying the technology requires access to a part of the ocean, which for countries usually implies having a coastline.

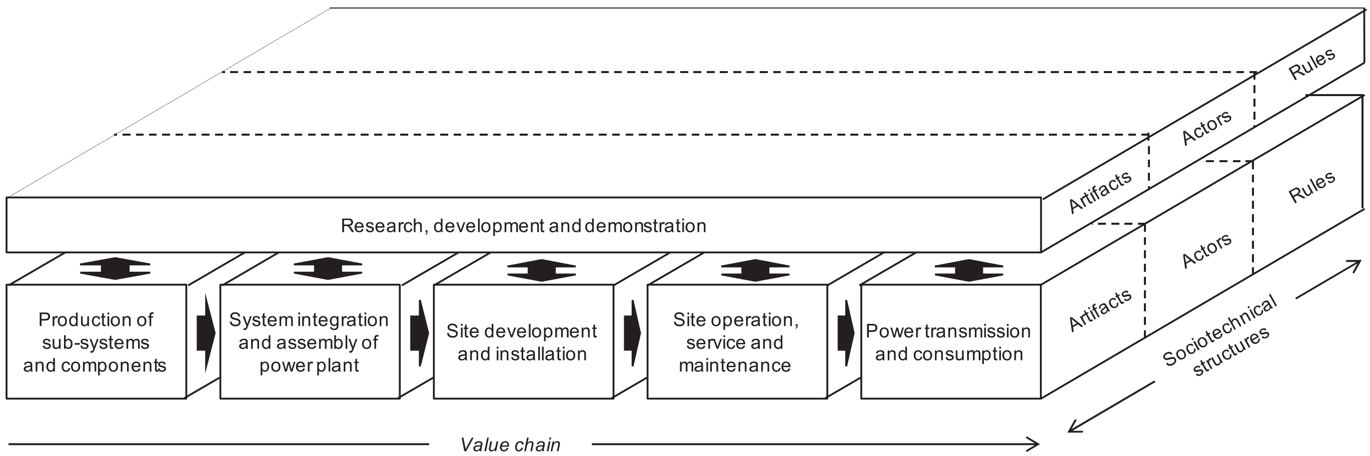

Fig. 1. The tidal kite TIS is defined as sociotechnical system structures along the value chain for electricity from a tidal kite power plant.

that is lacking in Sweden, which rules out domestic deployment both for testing and commercial purposes (Andersson, 2013; Interview 1, 2016; Interview 12, 2016; Interview 14, 2014).

The tidal kite TIS is accordingly a case where one regional sub-system – the Swedish one in which the technology originally emerged – is completely dependent on interactions with other regional sub-systems, to access certain resources that are spatially bound to deployment opportunities. Therefore, interregional interactions should be particularly extensive even in early development stages. This extreme nature of the case (Flyvbjerg, 2016) makes it appropriate for illustrating our analytical framework as well as for learning more about factors that shape spatial trajectories. Tidal kite technology is also a particularly interesting case from a Swedish policy perspective, since there is an overhanging risk that public investments in research, development and demonstration (RD&D) will yield limited localized benefits in Sweden. Moreover, the limited number of involved actors due to the early development stage facilitates an analysis that covers the global TIS, which is necessary to fully understand the connection between global structural development and regional resource formation.

3.2. System delineation

Case study research can be described as an approach that focuses on understanding the dynamics present within single settings (Eisenhardt, 1989; Flyvbjerg, 2016; Yin, 2009). When studying TISs, these settings are defined by a process of delineating system boundaries in the sociotechnical, spatial and temporal dimension (Hillman and Sandén, 2008). Sociotechnically, the tidal kite TIS is defined as artifacts, actors and rules along the industry-level value chain for electricity from a tidal kite power plant (Fig. 1). We include not only activities that relate to the production and use of tidal kite power plants, but also RD&D activities that are, in a way, responsible for creating and improving the other parts of the value chain. It should be pointed out, however, that the value chain is in an early development stage, which is manifested by the lack of continuous production and use of tidal kite power plants. This implies that structures relating to RD&D are the focus of our analysis, although a conceptualization of the full value chain is needed to conceive of and discuss potential future development paths for the tidal kite TIS. The boundary between the tidal kite TIS and its wider sociotechnical context is determined by the degree of specificity; artifacts, actors and rules that are to some extent specific to tidal kite technology are considered a part of the TIS, whereas more generic structures belong to its context.[6] To incorporate the spatial dimension, and enable analyzing interregional dynamics in resource formation processes, we distinguish between two regional sub-systems in the global tidal kite TIS: the 'Swedish TIS' and the 'foreign TIS', where the latter includes all regions except Sweden. This choice of system delineation is made for two reasons. Firstly, we want to highlight the Swedish policy perspective by delineating one sub-system along Sweden's national boundaries. Secondly, we want to limit the number of sub-systems to facilitate the analysis, and therefore let all TIS structures foreign to Sweden belong to a single sub-system. Admittedly, this limits the analytical resolution, but at the same time developments outside of Sweden are largely confined to the UK which makes this a minor problem. Finally, in the temporal dimension, the analysis is limited to cover the period from the invention of tidal kite technology in 2004 to the beginning of 2016.

3.3. Data collection and methodology

Our primary data sources are 15 personal interviews with key informants (Table 2). The interviews followed an open-ended interview guide that allowed for follow-up questions and reflections, and were also recorded and partially transcribed. In addition, we build on extensive desktop research, including media archives, industry reports, company materials, patent databases, information from public agencies and previous research.[7]

Data from interviews and desktop research were analyzed through a coding procedure, where categories from our analytical framework are used to organize empirical data, identify causal links, and build a narrative in relation to the research objective. The categories included the basic structural components of sociotechnical systems as well as the six resources highlighted in Table 1. In addition, we distinguished between structural development and resource formation in the Swedish and foreign sub-system, and strived to identify interactions and dynamics between these two regions. Throughout this process, we made an effort to continuously triangulate and cross-reference data, in order

(*footnote continued*)
Secondly, this part of the ocean must have suitable currents with velocities ranging from 1.0 to 2.5 m/s. And thirdly, the sites where these currents exist should be accessible, in the sense that it is physically, economically, socially and ecologically feasible to deploy tidal kite power plants. This localized nature of the resource is shared with other marine energy technologies, and to some extent with renewables in general. However, for solar, wind and bioenergy technologies, most regions have at least a limited resource that can be exploited. This is not the case for tidal kite technology, where many regions completely lack access to suitable waves, tidal streams and ocean currents.

[6] This approach admittedly implies a somewhat vague system boundary, since there is a continuous scale between the specific and the general. But for the purposes of this study, where the primary focus is on resource formation processes, the principle creates sufficient clarity.

[7] Media reporting and Minesto Annual Reports were accessed through the database Retriever Business (www.retriever-info.com). A patent search was performed in the European Patent Office (www.epo.org).

Table 2
Performed interviews with key informants.

No.	Interviewee(s)	Dur.	Type	Date
1	Entrepreneurs (two participants) at Swedish marine energy site developer	1.5 h	Face-to-face	Nov 2016
2	Inventor/PhD Candidate at Linköping University, Sweden	1 h	Telephone	Nov 2016
3	Professor at Chalmers University of Technology, Sweden	1 h	Face-to-face	Nov 2016
4	Civil Servant at The Swedish Energy Agency, Sweden	1 h	Telephone	Nov 2016
5	Senior Manager at Mitsui Science Studies Institute, Japan	1 h	Telephone	Jun 2016
6	Senior Manager at Midroc New Technology, Sweden	1 h	Telephone	May 2016
7	Project Manager at Minesto, Sweden	2.5 h	Face-to-face	May 2016
8	CEO of German industry supplier	1 h	Telephone	May 2016
9	Entrepreneur at Swedish technology developer, Sweden	1.5 h	Telephone	Mar 2016
10	Project Manager at RISE Research Institutes of Sweden	2 h	Face-to-face	Mar 2016
11	Board Member of Minesto, Sweden	1 h	Face-to-face	Mar 2016
12	CEO of Minesto, Sweden	2.5 h	Face-to-face	Jan 2016
13	Civil Servant at The Ministry of Enterprise and Innovation, Swedish Government	1 h	Face-to-face	Apr 2014
14	Senior Executive at Minesto, Sweden	1 h	Face-to-face	Apr 2014
15	Senior Project Managers (three participants) at Swedish industry supplier	1.5 h	Face-to-face	Apr 2014

to increase the reliability of our findings.

Following an event history approach (Negro et al., 2007; Poole et al., 2000; Reichardt et al., 2016), the analysis resulted in a timeline of events, for example the entry of a new actor, announcement of a public RD&D grant or successful demonstration of technology, that was divided into four episodes. For each episode, we describe structural development in the global TIS, and illustrate findings by mapping RD&D milestones and the network of involved actors. Moreover, we analyze the performance and dynamics of resource formation processes in the Swedish and foreign sub-systems. The relative importance for the global TIS of resource formation in each sub-system is also qualitatively assessed for each resource category, in order to highlight patterns and illustrate temporal and spatial differences. To ensure reasonable reliability of this assessment, we limited the scale to three levels of influence: 'no observation', 'minor' and 'major'. Finally, we identify factors that shape spatial trajectories, by analyzing the connection between regional structural development and resource formation.

4. The emergence of the tidal kite TIS

This section describes and analyzes the tidal kite innovation system from its inception in 2004 to the beginning of 2016. The narrative is divided into four episodes that are first examined separately, after which we analyze interregional dynamics and identify shaping factors.

4.1. Episode 1: the birth of a radical innovation (2004–2007)

The story of tidal kite technology starts when an engineer at SAAB, a Swedish multinational firm in the defense and aeronautics sector, realizes that the principles of a flying kite can be applied to harnessing energy from currents in the ocean (Interview 2, 2016). In 2004, the idea was presented to a venture creation department within SAAB, who decided to initiate an innovation project (Minesto, 2016b). This enabled further development of the concept, part of which took place in collaboration with Linköping University in Sweden (Interview 7, 2016), and resulted in the first patent application that was registered at the European Patent Office in 2006. Around this time, SAAB decided to dismantle innovation projects beyond their core business and offered Chalmers School of Entrepreneurship (CSE) – a venture creation platform within Chalmers University of Technology (Chalmers) in Gothenburg, Sweden – to take over the development of the tidal kite concept (Lundqvist, 2009). Through CSE, the innovation was connected to students that would act as surrogate entrepreneurs (Lundqvist, 2014), by building networks, developing business plans and carrying-out R&D activities. This included the development of a basic prototype, together with Linköping University, that was tested in sea conditions, which is considered an important milestone (Interview 6, 2016; Interview 7, 2016). Towards the end of the episode, the key stakeholders, including SAAB, Chalmers, the inventor and one of the surrogate entrepreneurs, formed the start-up company Minesto to commercialize the innovation.

During the episode, structural developments are confined to the Swedish sub-system and very limited (Fig. 2), which is not surprising given the very early development phase. There are few actors involved, although the networks among them are strong with extensive interaction. Knowledge is limited and artifacts are yet to materialize beyond the basic prototype, although a patent application has been registered. Formal institutions in terms of technology-specific laws, regulations and standards have not emerged, but there are high expectations and positive attitudes towards the technology among the involved actors (Dimming, 2006).[8]

The structural developments are almost exclusively enabled by knowledge, competence and legitimacy which are mobilized in the Swedish sub-system (Table 3). It was knowledge development, in the form of the conceptual invention in 2004, that initiated the TIS's development (Interview 2, 2016). This then led to mobilization of competence within SAAB as a project was formed within SAAB Ventures (Interview 6, 2016), which in turn enabled further knowledge development. Moreover, Chalmers and Linköping University were engaged through existing linkages with SAAB, bringing additional competence (Interview 2, 2016). As a result, knowledge development was accelerated and expanded to include early test activities, business development and network-building (Interview 2, 2016), which created legitimacy. Additional legitimacy was also brought by the involvement of renown Swedish actors such as SAAB, Chalmers and Linköping University as well as by generally positive attitudes to renewable energy technology (Holmberg, 2006) and positive developments in the global marine energy sector (OES, 2006). Finally, there is very limited mobilization of financial capital and enabling technology, and market formation is hardly relevant at this early stage.

4.2. Episode 2: incorporation and prototyping (2007–2011)

In the beginning of the second episode, Minesto is a newly established start-up company led by a graduate from CSE. Soon after its creation, Minesto is awarded 2nd prize in Venture Cup, a renowned Swedish innovation contest (Venture Cup, 2007). They also get the first patent published, which protects the basic technology concept and paves the way for Minesto's role as the key actor. Furthermore, Minesto is accepted as a participant in the UK Carbon Trust's Marine Energy

[8] Concurrent newspaper interviews with the involved actors reveal expectations that in hindsight can be considered naive, such as plans for prototype testing in ocean conditions in 2008 (Dimming, 2006).

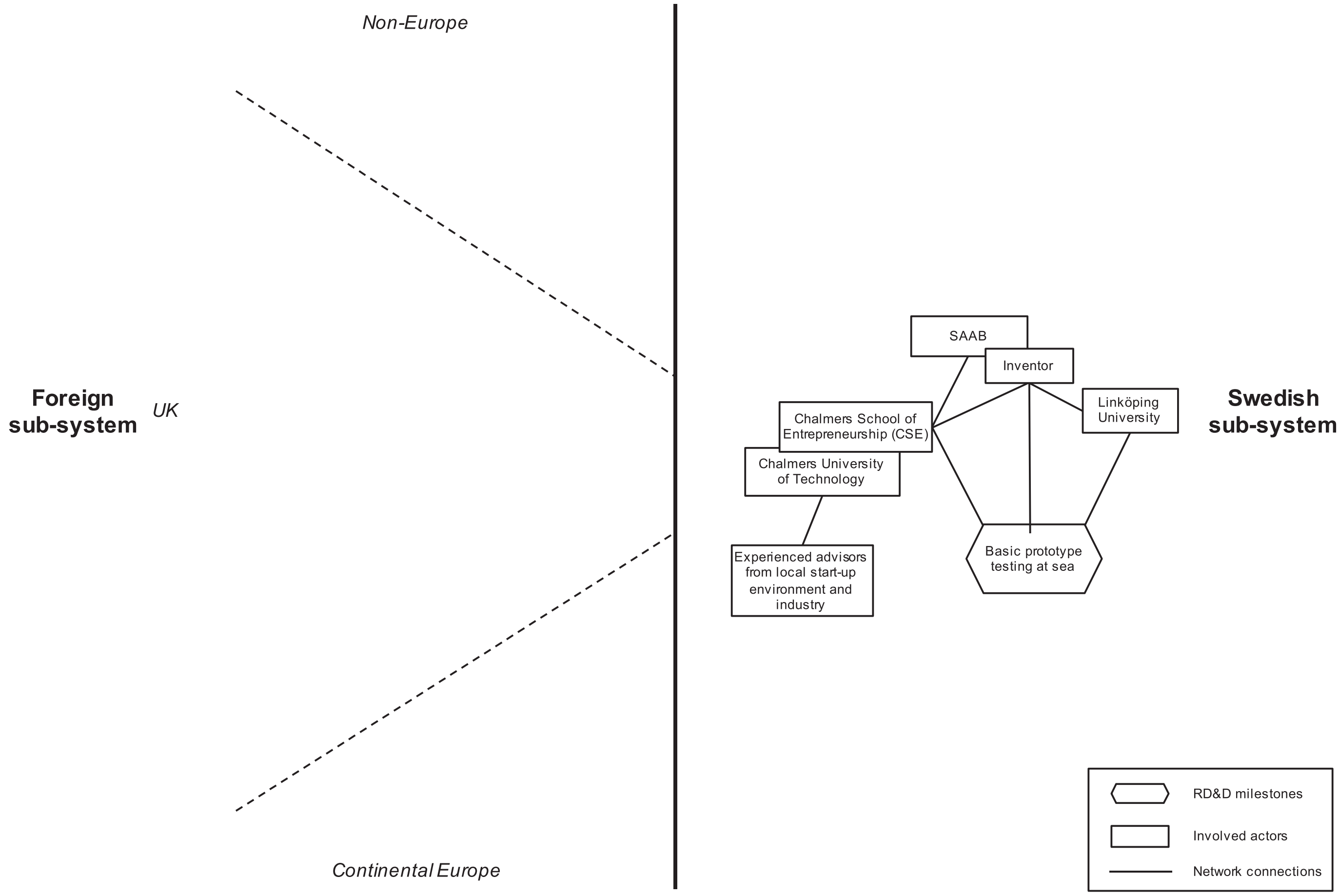

Fig. 2. Illustration of RD&D milestones, involved actors and network connections in the end of the period 2001–2007.

Table 3
Summary of resource formation in the Swedish and foreign sub-systems during the period 2001–2007, including a qualitative assessment of their relative importance for the build-up of TIS structures.

		Resource formation in the Swedish sub-system		Resource formation in the foreign sub-system
Knowledge	+ +	• Original invention and early concept development, which leads to patent application • Prototype tests at sea • Business development and network-building	0	
Competence	+ +	• Mobilization of key individuals from SAAB, Chalmers and Linköping University	0	
Enabling technology	+	• Mobilization of simple assets, enabling early sea tests	0	
Legitimacy	+ +	• Positive attitudes to renewable energy technology • Involvement of renown actors • Successful early sea tests	+	• Positive attitudes to renewable energy technology • Positive developments in the global marine energy sector
Financial capital	+	• Minor funding from involved actors	0	
Markets	0		0	

+ + major; + minor; 0 no observation.

Accelerator, a R&D program funded by the UK government. This gave access to experts and consultants that in particular highlighted that the technology concept may double the tidal power potential in the UK (Interview 2, 2016). Around the same time, Midroc New Technology, a venture capital firm based in Sweden, invests in Minesto and becomes its main owner (Interview 6, 2016; Karlberg, 2007). This made it possible to hire three more staff and commission a design study from a Swedish consultant that had been involved as an advisor in the early idea development (Interview 2, 2016). Based on the proposed design, Minesto started working on a scale 1:10 prototype in collaboration with a Swedish research institute, with some support from the Swedish Innovation Agency (VINNOVA) (Interview 7, 2016). The prototype was tested in a towing tank at SSPA, a Swedish hydrodynamics research institute, and at MARIN, a similar organization in the Netherlands with deeper tank facilities. A key milestone was reached in 2009 when electricity was produced during tank testing (NyTeknik, 2009). Encouraged by the successful test results, Minesto set-out to build an additional scale 1:10 prototype, intended for further tank testing and later ocean testing (Interview 7, 2016). However, mobilizing financial capital for this next step was challenging, even though the existing owners made additional investments. The financial crisis had just struck the world economy and investors were hesitant to engage in high-risk ventures with long time-horizons. However, eventually, BGA Invest, a family-owned venture capital firm in Sweden, invested in Minesto and became the second main owner, and was also joined by a number of smaller private investors (NyTeknik, 2010). This meant that the ocean

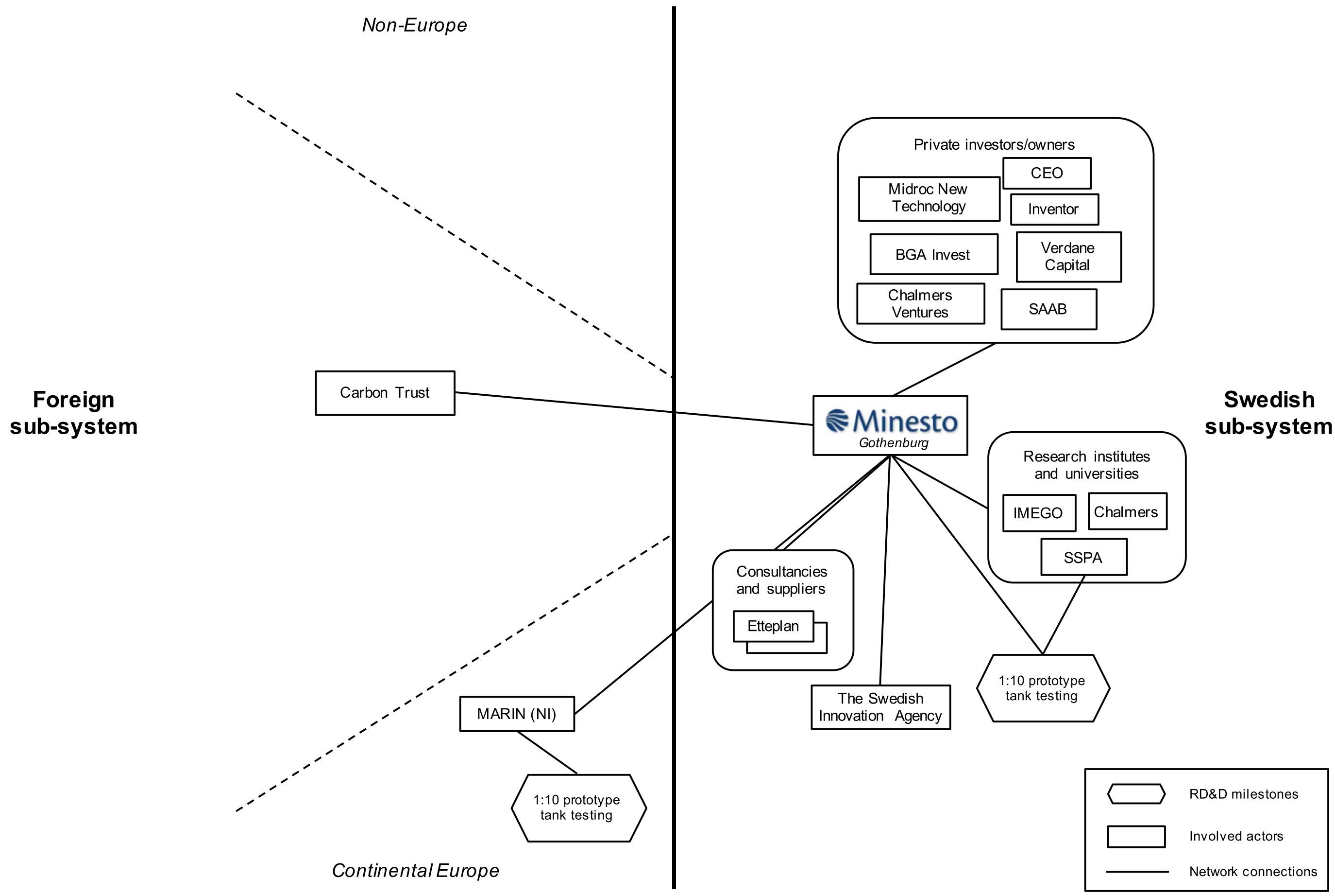

Fig. 3. Illustration of RD&D milestones, involved actors and network connections in the end of the period 2007–2011.

tests could get underway, and Portaferry, Northern Ireland, was chosen as the designated location. In the end of the episode, TIME Magazine ranked Minesto's technology as one of the top 50 best inventions in 2010, which gave wide-spread media coverage and paved the way for the future development (Harrell, 2011; Interview 6, 2016).

During the episode, the global TIS structure is gradually strengthened and begins to expand beyond the Swedish sub-system (Fig. 3). Knowledge development has led to a 1:10 scale prototype with a functional control system, and electricity has been produced for the first time. Minesto is the key actor, whose R&D activities in Gothenburg expands during the period. Its main owners, Midroc New Technology and BGA Invest, also take on prominent roles by providing financial resources and competence (Interview 6, 2016). In addition, Swedish consultants, research institutes and universities, for example Etteplan, IMEGO, SSPA and Chalmers, support knowledge development and provide important testing infrastructure. However, domestic public funding agencies have limited engagement and few suppliers are involved beyond the supply of standard components to prototypes. In the foreign sub-system, structural development can be identified mainly in the UK. Here, Minesto establishes a subsidiary and the Carbon Trust enters as a supportive government actor. Outside the UK, the research institute MARIN in the Netherlands engages by collaborating around test activities. Finally, technology-specific formal institutions have still not emerged, although policy schemes in the UK offer marine energy extended support. In addition, the high expectations and positive attitudes towards the technology persist (Dimming, 2009).

The structural development is mainly driven by resource formation in the Swedish sub-system, although other regions, mainly the UK, are beginning to have an influence (Table 4). At the core of developments lie knowledge, competence and legitimacy. Initially, the support from the Carbon Trust brought access to experts and consultants, who provided key knowledge and in-kind development resources. Moreover, it brought important legitimacy (Interview 12, 2016), since a key actor, on one of the major foreseen markets, explicitly acknowledged the potential of the technology concept. In addition, generally supportive marine energy policy schemes in the UK provided incentives for technology development. These developments were crucial for attracting Swedish venture capital from a strong owner that also supported the newly started Minesto with competence and a strong network. Thus, Minesto could mobilize competence and enabling technology, by hiring staff and initiate collaborations with consultants and research institutes, and carry-out R&D activities including prototype testing in both Sweden and the Netherlands. Successful test results together with Swedish and international awards further strengthened legitimacy, which paved the way for the mobilization of additional Swedish venture capital towards the end of the episode. In addition, the positive developments in the broader marine energy sector has started to materialize in Sweden as well, in the form of major public RD&D funding (The Swedish Energy Agency, 2010), which brings interest, high expectations and additional legitimacy.

4.3. Episode 3: into the ocean (2011–2014)

When the third episode starts, Minesto has started preparing for establishing an R&D center in Northern Ireland, in order to perform prototype tests in real ocean conditions. Collaborations are initiated with Queens University in Belfast, Strathclyde University in Glasgow, certification organizations, consultancies and suppliers. In addition, Minesto mobilizes competence from the Global Maritime Alliance, which brings together local companies and universities in Northern

Table 4
Summary of resource formation in the Swedish and foreign sub-systems during the period 2007–2011, including a qualitative assessment of their relative importance for the build-up of TIS structures.

		Resource formation in the Swedish sub-system		Resource formation in the foreign sub-system
Knowledge	+ +	• Minesto in-house R&D activities • Tank testing of scale 1:10 prototype	+	• Tank testing of scale 1:10 prototype
Competence	+ +	• Business expertise and network provided by strong owners • Collaborations with consultancies and research institutes • Local recruitment of Minesto staff	+	• Access to experts and consultants through the Carbon Trust
Enabling technology	+	• Tank testing facilities provided by SSPA	+	• Tank testing facilities provided by MARIN
Legitimacy	+	• Positive attitudes to renewable energy technology • Positive developments in the Swedish marine energy sector • Positive media coverage • Innovation awards • Successful test results	+ +	• Positive attitudes to renewable energy technology • Positive developments in the global marine energy sector • Supportive marine energy policy schemes in the UK • Innovation awards • Support from the Carbon Trust • Successful test results
Financial capital	+	• Mobilization of Swedish venture capital • Some public R&D funding	0	
Markets	0		0	

+ + major; + minor; 0 no observation.

Table 5
Average number of Minesto employees per year in Sweden and the UK from 2007 until 2014 (official figures based on Minesto annual reports). Note that until 2014, employees active in the UK had Swedish employments.

	Sweden	UK	Total
2007	1	–	1
2008	2	–	2
2009	6	–	6
2010	7	–	7
2011	9	–	9
2012	17	–	17
2013	24	–	24
2014	21	3	24
2015	25	5	30

Ireland to take advantage of opportunities in the emerging marine energy markets. Initially, the test activities are focused on the scale 1:10 prototype that had previously been tested in tank facilities (Interview 7, 2016). It is, however, soon replaced by a quarter scale prototype, which in 2013 produced electricity from ocean currents for the first time (Karlsson-Ottosson, 2013). Another result from the related R&D activities is additional patents that cover a number of critical sub-systems and also expands the protection to markets worldwide (Minesto, 2015a). The test activities in Northern Ireland and the development of the quarter scale prototype were made possible by financial resources from Minesto's Swedish owners and by public funding from the Swedish Energy Agency (The Swedish Energy Agency, 2014) and the Carbon Trust (NyTeknik, 2011). Moreover, the Crown Estate, which owns the seafloor around the UK, played a key role by granting the lease of the site in competition with other tidal energy technology developers (The Crown Estate, 2011). Although the developments in Northern Ireland mobilized some local and UK actors to the system, Minesto's rapidly growing R&D department remained in Sweden (Table 5), where there were also collaborations with suppliers of components and sub-systems to the prototype power plant (Interview 15, 2014; Marstrom Composite, 2015). Through the Swedish collaboration platform Ocean Energy Centre, Minesto also worked with actors such as Chalmers, the research institutes SP and SSPA, and other technology developers in the marine energy sector (Andersson et al., 2017). This involved knowledge sharing, collaborative R&D projects as well as political lobbying activities (Andersson et al., 2013). In addition, tidal kite technology gained a lot of attention and recognition, both through praise in Swedish business media and international awards (e.g. Minesto, 2013, 2011; Pentland, 2013; Sjödén, 2013).

The episode involves significant structural development in both the Swedish and foreign sub-systems (Fig. 4). The technology has advanced to a stage where both 1:10 and quarter scale prototypes have been successfully demonstrated in ocean conditions, where electricity has also been produced for the first time. A test platform has been established in Northern Ireland, complemented by simulators developed specifically for the technology. Minesto strengthens its role as the key actor by increasing their intellectual property rights. These are also demonstrated as strong when a court in the US dismisses a patent application from Honeywell concerning a similar technology concept. Thus, the key underlying knowledge is controlled by Minesto or embedded as competence in its R&D engineers (Interview 3, 2016; Interview 7, 2016), although some knowledge spillover to UK actors has probably occurred. A rapid increase of the number of involved actors can be seen, driven to a large extent by the test activities in Northern Ireland which attract local and UK actors. Moreover, the Carbon Trust expands its role to providing R&D funding and the Crown Estate enters as an important regulating body. In Sweden, the number of actors increase as well, but to a lesser extent than in the UK. The Swedish Energy Agency enters as an R&D funder and Minesto's network of suppliers is developed to include some closer relationships that go beyond the supply of standard components. Moreover, the networks among the actors in the Swedish marine energy sector are strengthened through the activities of the Ocean Energy Centre. Finally, technology specific institutions are still lacking, except for the high expectations that can be observed among the involved actors and in media, although the strong marine energy support schemes in the UK remain.

The structural development is increasingly driven by resource formation in the foreign sub-system, and knowledge, financial capital and enabling technology play a prominent role (Table 6). Initially, the mobilization of Swedish venture capital makes it possible to start establishing a test site and initiate further R&D activities, which also enabled additional mobilization of financial capital from the Carbon Trust and the Swedish Energy Agency. As a result, universities, consultants and suppliers from both Sweden and the UK entered the system, bringing knowledge, competence and capabilities. Minesto could also increase their staff significantly, recruiting mainly from Western Sweden. In addition, networks in the marine energy sector in Sweden were strengthened, which stimulated knowledge development and strengthened legitimacy through lobbying activities. Finally, there are indications of isolated knowledge development in the US, but this does not seem to drive any structural build-up (i.e. the patent application was dismissed).

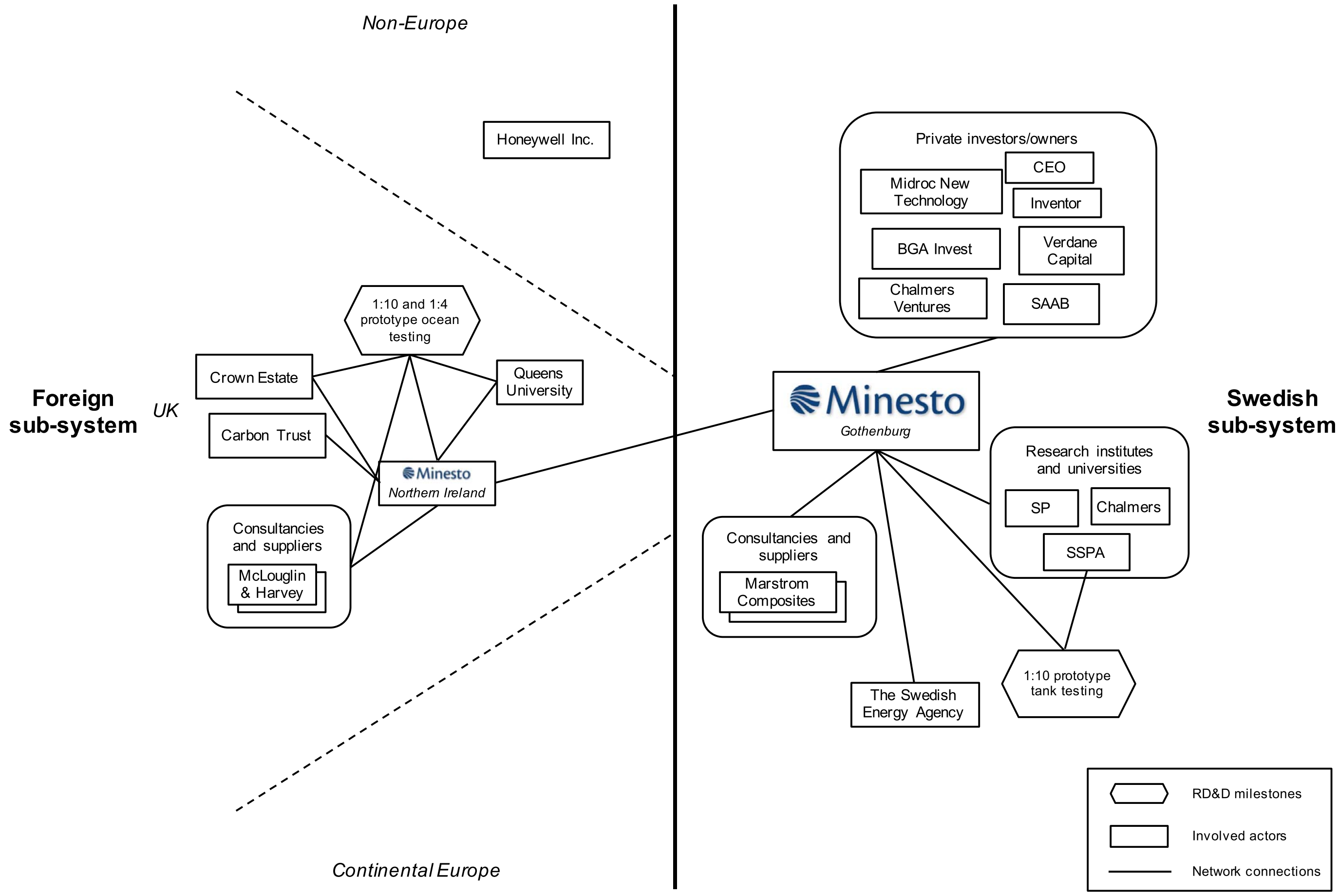

Fig. 4. Illustration of RD&D milestones, involved actors and network connections in the end of the period 2011–2014.

Table 6
Summary of resource formation in the Swedish and foreign sub-systems during the period 2011–2014, including a qualitative assessment of their relative importance for the build-up of TIS structures.

		Resource formation in the Swedish sub-system		Resource formation in the foreign sub-system
Knowledge	+ +	• Minesto in-house R&D activities leads to additional patents • Collaborative R&D projects	+ +	• Collaborative R&D projects • Ocean testing of 1:10 and quarter scale prototype leads to additional patents
Competence	+ +	• Business expertise and network provided by strong owners • Collaborations with universities, suppliers and consultancies • Local recruitment of Minesto staff	+	• Collaborations with universities, suppliers and consultancies
Enabling technology	+	• Some mobilization of standard components for prototypes	+ +	• Establishment of ocean testing facilities in Northern Ireland • Some mobilization of standard components for prototypes
Legitimacy	+	• Positive attitudes to renewable energy technology • Political networks developing in the Swedish marine energy sector • Positive media coverage	+ +	• Positive attitudes to renewable energy technology • Positive developments in the global marine energy sector • Supportive marine energy policy schemes in the UK • Industry awards • Successful results from ocean testing
Financial capital	+ +	• Mobilization of Swedish venture capital • R&D funding from the Swedish Energy Agency	+	• R&D funding from the Carbon Trust
Markets	0		0	

+ + major; + minor; 0 no observation.

4.4. *Episode 4: towards full-scale demonstration (2014–2016)*

The fourth episode constitutes an intense period of preparation activities for a planned demonstration project in Holyhead, Wales, although test activities in Northern Ireland are still ongoing (Interview 7, 2016). The Holyhead project involves developing, manufacturing and deploying a full-scale tidal kite power plant by 2017[9] as a first step, and thereafter gradually expand the installation to an array of 20 power plants and an installed capacity of 10 MW (Minesto, 2015a). However, developing the demonstration site and scaling-up the technology requires significantly more resources than previous development phases, which implies an order-of-magnitude increase in the mobilization of financial capital during the episode (Fig. 5). Investments enabling the first step of the Holyhead project, which was fully funded in the end of

[9] The project has been delayed and at the time of writing the ambition is to install the full-scale prototype in 2018.

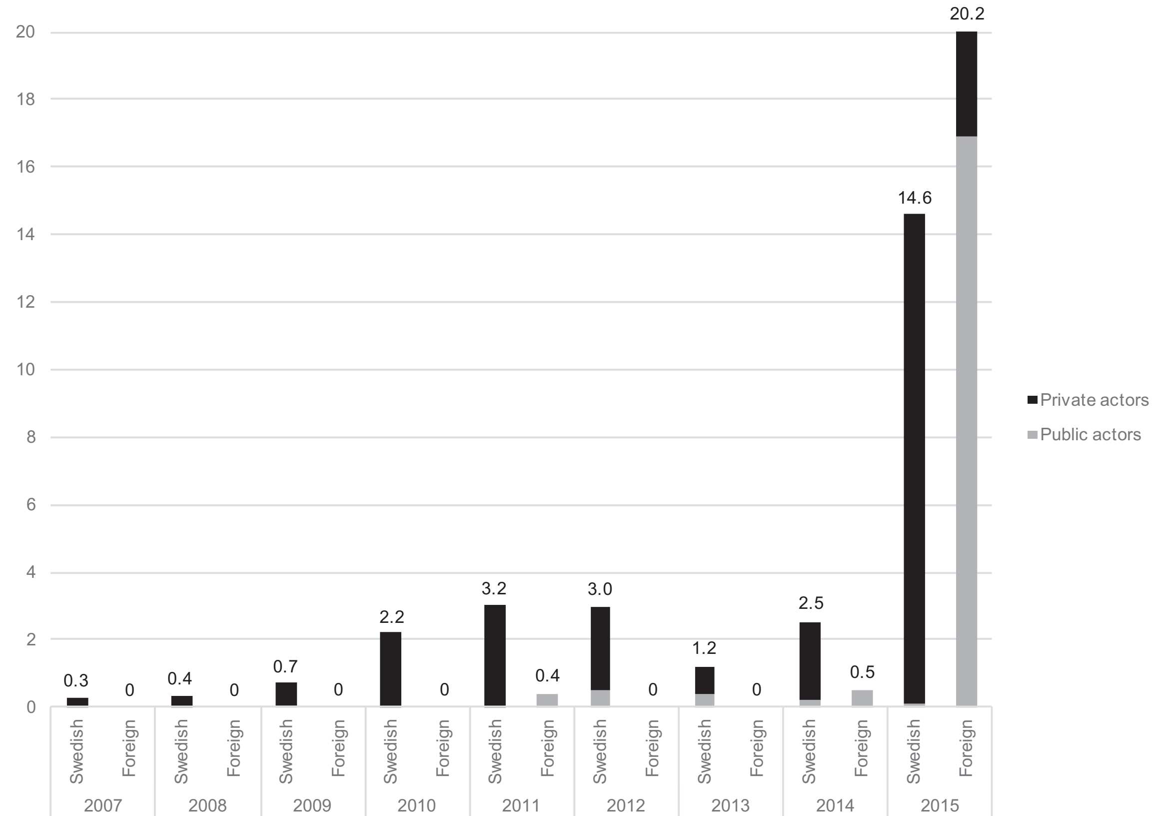

Fig. 5. Mobilization of financial capital in MEUR from 2007 until 2015, divided by source type (Swedish or foreign as well as public or private actors), and including Minesto equity investments and technology-specific RD&D projects (based on Minesto annual reports, media reporting and information from relevant public funding agencies).

2015, came from three main sources. Firstly, the Welsh government invested 13 MEUR of European regional development funds in the demonstration project (Minesto, 2015b), which essentially made them the first customer for tidal kite technology. Secondly, Minesto made an IPO at a Swedish stock exchange, raising around 16 MEUR from 2500 new shareholders (Minesto, 2015c). Thirdly, Minesto received a 3.5 MEUR investment from the public-private investment consortium KIC InnoEnergy (KIC InnoEnergy, 2015). These resources made it possible for Minesto to go ahead with the demonstration project and expand their network of collaborators. Bangor University in Wales was engaged as a partner in site development, together with other local consultants and suppliers (Interview 12, 2016). The UK firm McLaughlin & Harvey and the Royal Institute of Technology in Sweden were pointed out as key partners in delivering the project (KTH, 2016; McLaughlin & Harvey, 2015). And technology partnerships were formed with the German firm Schottel Hydro (power take-off system) (Interview 8, 2016) and the UK firm Subsea Riser Products (bottom joint) (Minesto, 2016c). However, the value chain for the project has only begun to emerge and more key actors are expected to enter the system before the power plant is deployed (Interview 11, 2016; Interview 12, 2016). Actors and resources were also increasingly mobilized through collaborative R&D projects. The most substantial one was the PowerKite project that received 5.1 MEUR in funding from the EU Horizon 2020 program, and gathered a broad consortium with actors from several European countries (Interview 3, 2016; Minesto, 2015d). In addition, knowledge was developed in collaborative R&D projects with a broader scope, involving other marine energy technology developers, suppliers and research institutes, both in Sweden and the UK, with funding from actors such as the Swedish Energy Agency, VINNOVA and the EU Eurostars program. Furthermore, and in parallel to the developments in Sweden and the UK, the system starts to expand to other regions through Minesto's market development activities. Discussions are initiated with actors on potential markets in the USA, Chile, South Korea, Japan and Taiwan (Interview 11, 2016; Interview 12, 2016; Interview 5, 2016), and a formal collaboration project aiming to explore the market for tidal kite technology is set up with Florida Atlantic University (Minesto, 2014).

The episode involves intense structural developments in the Swedish and foreign sub-system (Fig. 6). The technology has kept advancing and moved towards full-scale demonstration, although the results of this development are yet to materialize. Knowledge is still to a large extent embedded in Minesto's engineers or codified in a way that is controlled by the firm, although knowledge diffusion is likely to be stimulated by technology partnerships. The number of involved actors keep increasing, but this time driven by the full-scale demonstration project and mainly outside of Sweden. Bangor University in Wales and Royal Institute of Technology in Sweden engage in the developments, technology partnerships are formed with suppliers such as Subsea Riser Products and Schottel Hydro, and a wide range of consultants and suppliers support R&D activities and site development. The Welsh government enters the system as the first customer and public funding is provided by EU, UK and Swedish agencies. Private capital is mobilized from KIC InnoEnergy and a large number of new Minesto shareholders in Sweden, although the main owners are still Midroc New Technology and BGA Invest. Moreover, the Crown Estate continues to play an important role by granting the site lease in Wales (The Crown Estate, 2014). Finally, technology specific formal institutions are still lacking, while informal institutions can be identified in the form of high expectations among the involved actors and in media. The market support policies for marine energy in the UK can, however, be expected to have played a key role in the decision to locate the first full-scale demonstration project in Wales. Moreover, the Blue Energy Communication from the EU, highlighting the potential of marine energy, is likely to have raised expectations and strengthened legitimacy.

The developments are driven by resource formation in both the

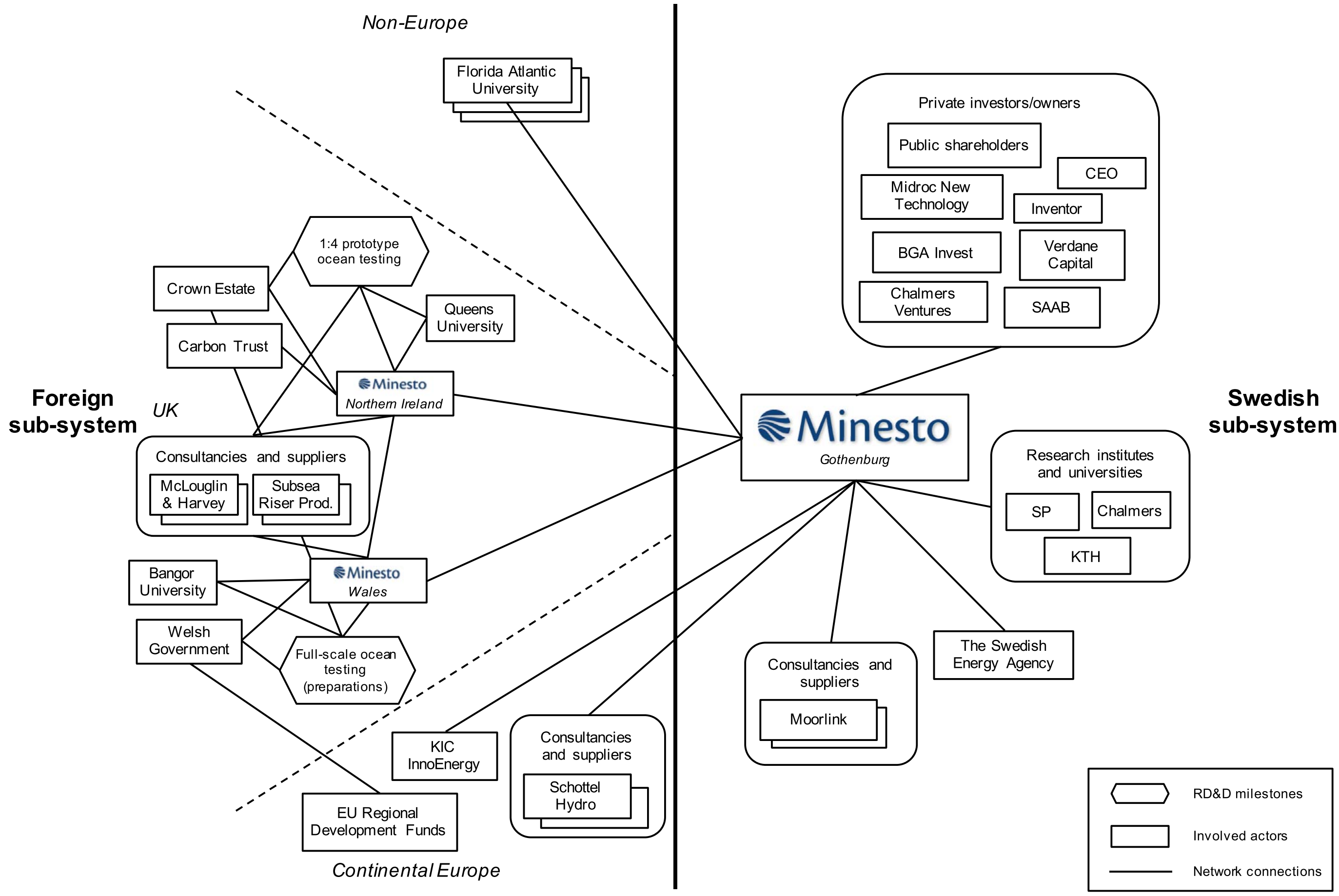

Fig. 6. Illustration of RD&D milestones, involved actors and network connections in the end of the period 2014–2016.

Table 7
Summary of resource formation in the Swedish and foreign sub-systems during the period 2014–2016, including a qualitative assessment of their relative importance for the build-up of TIS structures.

		Resource formation in the Swedish sub-system		Resource formation in the foreign sub-system
Knowledge	+ +	• Minesto in-house R&D activities • Major collaborative R&D projects • Collaborations with consultants, suppliers and universities	+ +	• Major collaborative R&D projects • Collaborations with UK universities, consultants and suppliers • Technology partners developing sub-systems • Continued ocean tests in Northern Ireland
Competence	+ +	• Business expertise and network provided by strong owners • Collaborations with universities, suppliers and consultancies • Local recruitment of Minesto staff	+ +	• Collaborations with universities, suppliers and consultancies • Formation of technology partnerships
Enabling technology	+	• Some mobilization of standard components	+ +	• Access to ocean testing facilities in Northern Ireland • Mobilization of standard components
Legitimacy	+	• Positive attitudes to renewable energy technology • Extensive positive media coverage • Compelling vision by Minesto, supported by technological advancements	+ +	• Positive attitudes to renewable energy technology • Supportive marine energy policy schemes in the UK (although uncertainties exist about their future) • Policy development in the EU (Blue Energy Communication) • Innovation awards • Support from key actors
Financial capital	+ +	• Mobilization of major private investments through Swedish IPO • R&D funding from the Swedish Energy Agency	+ +	• Mobilization of major investment in demonstration project from the Welsh government • R&D funding from the Carbon Trust, DECC and various EU offices • Mobilization of private investment from KIC InnoEnergy
Markets	0		+	• Welsh government enters as first customer

+ + major; + minor; 0 no observation.

Swedish and foreign sub-system, and financial capital and legitimacy are at the core of developments (Table 7). Initially, Minesto's plans create a compelling vision that is given legitimacy by previous technological advancements, and fueled by policy developments in the EU. The result is strengthened incentives, even though slow technological development in the global marine energy sector and uncertainties regarding the future policy support in the UK likely acted as barriers. In the end, the Welsh government entered the system as Minesto's first

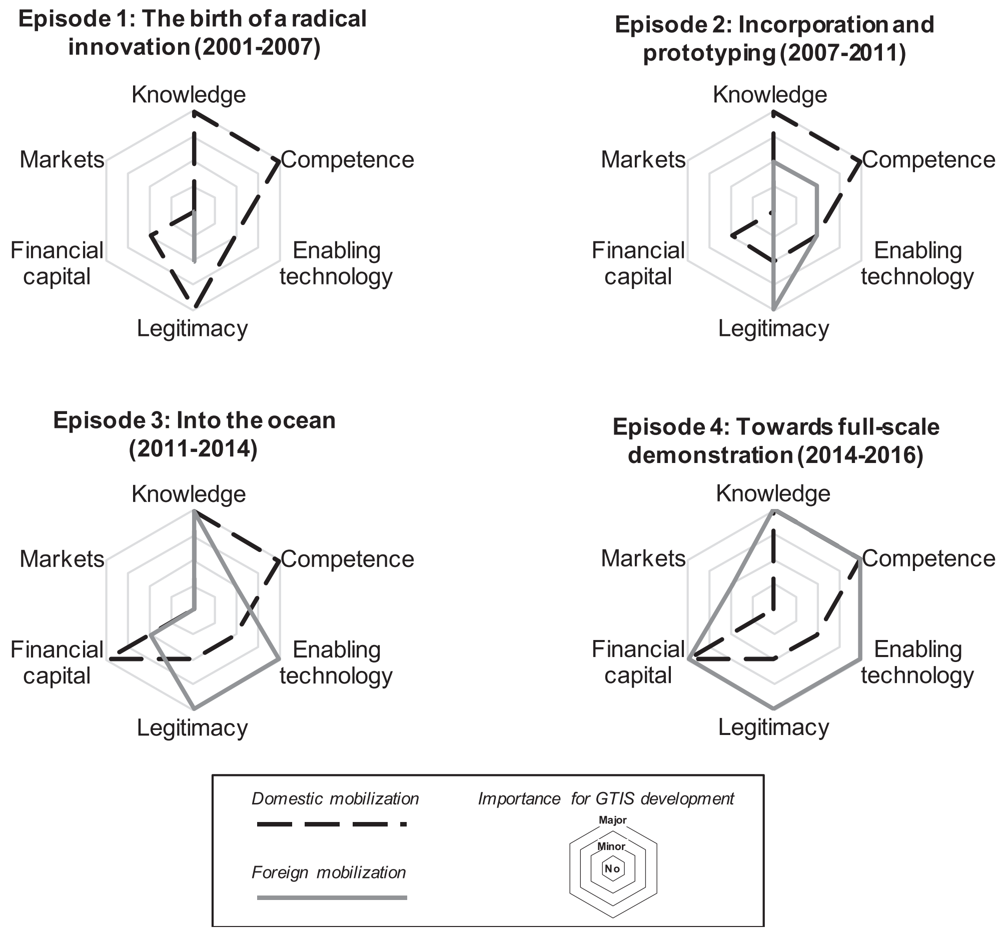

Fig. 7. Qualitative assessment of resource formation in the Swedish and foreign sub-systems (based on Tables 2, 3, 4 and 6).

customer, which is the first indication of market formation. This meant a vast increase in the mobilization of financial capital compared to previous episodes, but also implied certain demands regarding local sourcing of products and services for the demonstration project. The investment by the Welsh government in turn enabled mobilization of financial capital through an IPO in Sweden, since it strengthened the offering to potential investors. But in a similar vein the private capital raised was necessary for matching the funds provided by the Welsh government, which is required when dealing with European regional development funds. The extensive mobilization of financial capital in relation to prior phases (Fig. 7) in turn mobilized competence and enabling technology, and strengthened knowledge development through both in-house and collaborative R&D activities.

Finally, it should be emphasized that structural developments driven by the strong formation of financial capital in the Swedish and foreign sub-system during the episode have only just begun, and it is an open question what the final structure around the demonstration project in Wales and beyond will look like. However, it seems likely that Minesto will increase their local staff and engage more in collaborations with Welsh actors. This is of course necessary for certain activities, such as installation and maintenance, but may also expand to other parts of the value chain due to demands for local sourcing and potential benefits from co-locating testing, demonstration and R&D activities. A clear indication of this development was given in a keynote by Minesto's CEO in 2016 at the International Conference on Ocean Energy in Edinburgh: "We are a Swedish-Welsh company, that's how we see ourselves" (Edlund, 2016).

4.5. Interregional dynamics and shaping factors

The analysis shows that the tidal kite TIS started its development in Sweden and initially depended almost exclusively on resources mobilized in this regional sub-system, such as knowledge, competence and legitimacy (Fig. 7). But already in the second episode, the foreign sub-system started playing a role, mainly by providing legitimacy, although Sweden still dominated as the source of knowledge, competence and financial capital. In the third episode, foreign regions increased their importance by giving access to crucial enabling technology, in the form of ocean testing infrastructure, while knowledge, competence and financial capital were mainly mobilized in Sweden. Finally, in the fourth episode, the foreign sub-system started playing an equally important role as the Swedish sub-system, by providing financial capital, an early niche market as well as other key resources, although Sweden remained an important source of financial capital, knowledge and competence.

Looking more closely at the mobilization of financial capital, where available data enables a quantitative overview (Fig. 5), it is evident that the global TIS has depended almost completely on funds from Swedish private actors. However, the picture changes completely in 2015, when the volume surges by almost an order of magnitude, foreign actors contribute more than domestic actors, and public actors match private funding.

The Swedish and foreign sub-systems have clearly played different roles throughout the emergence of the global TIS. They have contributed with different resources to varying degrees, and also been subject to different amounts of structural development. When examining interregional dynamics, however, we see that resource formation in one region has led to structural development elsewhere.

Legitimacy derived from support by the UK Carbon Trust, as well as from earlier knowledge development and testing in the region around Linköping in central Sweden, mainly led to structural development in western Sweden. Moreover, although Northern Ireland provided access to enabling technology, knowledge and competence in connection to ocean testing activities, this resulted in limited local structural development, but rather supported the further formation of knowledge and competence in the Swedish sub-system.

It thus seems as if structural development has gravitated towards Sweden, even though essential resources have been formed abroad. The analysis indicates that this is due to early developments in Sweden, in particular the surrogate entrepreneurship offered by Chalmers School of Entrepreneurship which embedded the TIS in a supportive local context. This made it possible to mobilize key knowledge and competence, which in turn facilitated the mobilization of financial capital, strengthened legitimacy and enabled learning processes that resulted in the creation of additional knowledge and competence. These local self-reinforcing mechanisms resulted in a path dependency that shaped the global TIS along a spatial trajectory that favored structural development in Sweden. In addition, the availability of highly competent engineers and business development professionals in western Sweden was crucial for sustaining developments along this spatial trajectory. Without a context that could provide these resources throughout the emergence of the TIS, it is likely that structural development abroad, for instance in the UK, would have occurred to an even larger extent.

5. Discussion

The analysis of tidal kite technology has illustrated the merits of our adapted analytical framework and also yielded a number of empirical findings. In this section, we highlight these findings, extract implications for policymakers, and discuss theoretical contributions and future research avenues.

5.1. Empirical findings

Our analysis of tidal kite technology shows that the regional availability of resources, together with the extent to which they can be transferred in space, greatly influenced the spatial trajectory of the tidal kite TIS. Developments were initiated in Sweden but the TIS quickly branched out to other countries in order to access resources that could not be mobilized domestically. However, although important resources were only available in the foreign sub-system, structural development beyond Sweden has been limited. The analysis indicates that two factors have shaped the spatial trajectory in this way: the supportive context in western Sweden during the TISs infancy; and the local availability of competent engineers and business development professionals. Together, these shaping factors influenced the formation of locally embedded knowledge and competence, which resulted in a spatial path dependency that favored structural development in western Sweden.

The results thus confirm that certain types of knowledge and competence are spatially sticky resources that promote local structural development. However, our analysis broadens the conventional focus on social learning (Binz et al., 2015) and brings a number of insights about the transferability of other resources. Firstly, legitimacy can be non-sticky, since structural development in Sweden benefitted from the formation of this resource in the foreign sub-system. Secondly, not all types of knowledge are sticky, which is clear since the Swedish sub-system has certainly built on scientific knowledge which is globally available. Thirdly, the stickiness of competence can to some extent be overcome by international meetings during which social learning processes unfold, even though participants are normally located in different regions. This is evident when examining how the Swedish sub-system has benefitted from support by foreign experts. Fourthly, while some enabling technology, such as large-scale infrastructure, has a naturally sticky character, it does not necessarily promote local structural development. Testing activities in the Netherlands and Northern Ireland mainly led to structural development in Sweden, which may be because their limited extent enabled R&D staff from Sweden to oversee activities and engage in local learning processes (i.e. by travelling). Fifthly, financial capital can exhibit both a sticky and non-sticky character, depending on its source. The mobilization of public RD&D funding required international collaborations and accordingly influenced the spatial trajectory to some extent, while private investments were not conditioned in the same way. Finally, our analysis offers few direct insights about the influence of markets since their formation has been very limited. We will come back to this aspect when discussing expected future developments below.

It should be emphasized that tidal kite technology is in an early development stage where structural development is confined to RD&D. As a renewable energy technology advances towards commercialization and more parts of the value chain are developed, other factors will become more important for the spatial trajectory. The location of markets for further up-scaling and commercialization will naturally determine where structural development connected to site development and installation, site operation, service and maintenance, and power transmission and consumption occurs. For some technologies, such as tidal kite technology, these markets may be strongly bound to places that not necessarily coincide with the location of RD&D activities. This causes a shift in the spatial trajectory of the global TIS, which is indicated by the increasing structural development in the UK in episode four. Moreover, as the focus of innovation activity shifts from concept development to more incremental improvements in components and sub-systems, R&D activities tend to become more dependent on user-producer interactions, at least for innovation in complex products and systems (Huenteler et al., 2016). This makes spatial proximity between RD&D and other parts of the value chain more important, and thus creates additional incentives for structural development close to markets. For activities that are less bound to sites where technology is used, for example production of the different components and sub-systems that make up the technology, the classical argument is that regional differences in cost and availability of factor inputs will determine where actors choose to locate factories and facilities. This is in our framework explained by regional differences in the formation of resources such as competence, enabling technology and markets. However, since structural development in these parts of the value chain brings attractive localized benefits, such as increased tax income, new jobs and knowledge spillovers to other industries, regional policymakers will to some extent compete for developments to take place in their contexts by offering financial incentives and implementing other supportive policies. This challenges the conventional focus on cost and highlights the importance of industrial policy.

As a single case study, we do acknowledge that our analysis has a number of important limitations that have to be considered when building on its results. In particular, it concerns a narrowly defined technology that has emerged in a region that completely lacks a suitable natural resource endowment. This is an unusual situation, which calls for caution when making generalizations based on our findings. However, the narrow system boundary has at the same time enabled us to capture detailed dynamics in the innovation process. The extreme nature of the case also puts additional emphasis on the stickiness of knowledge and competence; the localization of these resources has, after all, kept the main part of the tidal kite TIS in Sweden, even though the technology cannot even be tested and demonstrated domestically. In addition, our analysis has suffered from a lack of quantitative data. This is due to the narrow definition and early development stage of the focal technology, which leaves adapted databases and statistics beyond reach.

5.2. Policy implications

Our findings have policy implications. For regions in which a promising new renewable energy technology has emerged, but where limited natural resources hinder the development of a domestic market, there will be an increased tendency for structural development abroad as the technology advances towards up-scaling and commercialization, both in parts of the value chain that are spatially bound to deployment sites and those that could potentially exist in other places. This implies a risk that public support only leads to growth of the global TIS while failing to stimulate continued structural development in the domestic sub-system, which is a challenge if policy interventions are partly motivated by creating localized benefits. For regions where there is a large potential market for a new technology, but where structural development in the early development stages has been limited, the situation is opposite. Here, the challenge is that support to pre-commercial technology deployment may not lead to structural development in parts of the value chain that are less bound to deployment sites, such as RD&D and production of components and sub-systems. This has recently been highlighted by evidence from Italy, where half the spending on deployment of renewable energy technologies between 2006 and 2014, largely driven by public support, was met by imported goods (Cai et al., 2017).

The key question from a regional perspective is therefore how policymakers can support global TIS growth while creating incentives for domestic structural development – basically how they can not only stimulate, but also shape the development. It is beyond the scope of this paper to analyze to what extent and how this is possible, but we still offer some reflections based on our findings. A first step is to distinguish between resource formation processes that drive global and regional structural development. In the global tidal kite TIS, for example, strengthened mobilization of financial capital in any regionally delineated sub-system would likely have stimulated structural development, but not necessarily in the same sub-system since at least some types of financial capital can easily be mobilized in one place and deployed elsewhere by multinational actors. On the other hand, the formation of certain sticky resources in a particular sub-system, such as knowledge and competence, is more likely to stimulate local structural development and bring the associated benefits. Policymakers that aim to promote structural development in specific regions should accordingly focus on identifying and strengthening the formation of sticky resources that influence spatial trajectories in a beneficial way. Of course, this raises an important question from a global perspective: if regional policymakers only focus on sticky resources that can shape developments towards their contexts, who supports the formation of other resources that may be as critical for the global TIS? This highlights the need for international policy coordination that can counteract potential negative effects of regional competition, which has been discussed in the context of wind power and photovoltaics (see Binz et al. (2017) and Quitzow (2015)). However, it also points to the possibility of making resources stickier through clever policies. For example, policy interventions aimed at strengthening the mobilization of financial capital in a regional sub-system (i.e. public investments in RD&D) could be designed in a way that promotes domestic structural development, by coupling support with mechanisms such as demands for local sourcing. This also occurred in the case of tidal kite technology, when financial capital enabling the demonstration project in Wales was mobilized from European regional development funds.

5.3. Theoretical contributions and future research

The main contribution of this paper is that it proposes and illustrates an analytical framework that focuses on shaping factors in the emergence of new TISs. It distinguishes between regional sub-systems within a global TIS, and explains the spatial distribution of structural development in the global TIS by differences in resource formation processes at the sub-system level. This approach is similar to Binz et al. (2015), but builds more strongly on the TIS framework and arguably captures more nuances by expanding the analysis to include a broader set of resources. Moreover, by enabling an analysis of the performance and dynamics of resource formation processes, both within and between sub-systems, our analytical framework allows for identifying factors that shape spatial trajectories. Compared to previous TIS studies that have been concerned with identifying factors that support or block one dimensional growth, this is an expansion of the analytical focus; where supporting and blocking factors merely influence temporal dynamics and trajectories, shaping factors incorporate the spatial dimension as well.

When applying this analytical framework to the case of tidal kite technology, we show that our approach can yield important insights, some of which may have been overlooked with a narrow analytical focus on supporting and blocking factors. The approach makes the spatial dimension of technological innovation explicit, highlights how emerging TISs branch out in space to access different resources, and reveals how the character of regional resource formation processes determine where structural development occurs. At the same time, more research is needed to improve the analytical framework and strengthen its empirical foundation.

One area that calls for further development is to relate the understanding of resource formation processes, and their way of influencing spatial trajectories, to the characteristics, maturity and value chain of the focal technology. Technology characteristics have been shown to influence resource formation dynamics, which may lead to different spatially shaping factors (Binz and Truffer, 2017; Huenteler et al., 2016). The tidal kite case shows that the formation of knowledge and competence promotes local structural development when technology is immature, but may become less influential as technologies advance towards commercialization. In addition, proximity to markets are obviously essential to develop structure in value chain segments that relate to the use of technology, while it may be less important for RD&D and production of components and sub-systems. An important task for future research is accordingly to integrate these dimensions to a larger extent in analytical approaches, in order to build a stronger empirical understanding of the shaping factors of emerging TISs.

Another challenge that is left for future publications is to increase the spatial resolution by analyzing more than two regional sub-systems simultaneously, which will be required when examining innovation in more mature and globalized TISs. It may also be appropriate to analyze sub-systems on multiple scales, since the spatial extent of resource formation processes can range from the local to the global. However, this quickly increases the complexity of analysis and creates methodological difficulties (Binz and Truffer, 2017).

On a final note, this paper highlights an important insight from a wider societal perspective, namely that the shape of sociotechnical systems matters. This is not only true for the spatial dimension, which is the focus of this particular paper, but also for other aspects of the system. For example, whether the future electricity system ends up having a centralized or decentralized structure could possibly influence its environmental impact as well as how benefits and costs are distributed between different social groups. Also, rapid technological advancements in automation and information technology could lead to massive unemployment or reduced working hours, depending on how the sociotechnical system that governs their development and use is structured. Therefore, we argue that technological innovation studies should focus more on how emerging sociotechnical systems can be shaped in a way that makes the most of their potential, and hopefully this paper has taken a small step in that direction.

6. Conclusions

The purpose of this paper is to show how the TIS approach can be used to identify and analyze factors that shape spatial trajectories of emerging technologies. We propose an adapted analytical framework that expands the conventional focus on one-dimensional supporting and blocking factors, to shaping factors that incorporate the spatiality of innovation. The approach is illustrated by examining innovation in tidal kite technology. The analysis finds that a supportive local context in western Sweden during the infancy of tidal kite technology, together with the availability of competent engineers and business development professionals, promoted the formation of locally embedded knowledge and competence. This in turn created a spatial path dependency that made developments gravitate towards Sweden, although the lack of domestic markets has also increasingly driven an expansion of activity to other regions, in particular the UK. Moreover, the analysis shows that shaping, and not only stimulating, the growth of emerging TIS is an important challenge for regional policymakers, and highlights the need for international policy coordination. Despite certain limitations in using a single case study, the paper shows that analyzing shaping factors in the emergence of new technologies, by examining the performance and dynamics in resource formation processes, can yield important insights, some of which may be overlooked with a narrow analytical focus on supporting and blocking factors. At the same time, more research is needed to improve the analytical approach and strengthen its empirical foundation by applying it to other cases.

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