Action points to advance commercialisation of the Dutch tidal energy sector

An analysis of the tidal energy Technological Innovation System in combination with lessons learned from the development of the wind energy industry

Master thesis

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Figure 1. Eastern Scheldt storm surge barrier. Source: http://dutchmarineenergy.com/

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Abstract

Water management has traditionally been focused on water safety, hygiene and agricultural problems, however, given the current need for sustainability in order to combat climate change, the possible production of sustainable energy is a desirable extension of integral water management. Tidal energy is a form of ocean energy which harnesses energy from the tides and has the potential to contribute significantly to sustainable energy solutions in certain coastal regions, thereby reducing carbon emissions and fighting climate change worldwide. Activities surrounding tidal energy have grown substantially over the last 10 years in Europe as well as in the Netherlands, however the technology is diffusing slowly. The aim of this thesis is finding action points that will advance commercialisation of the Dutch tidal energy sector. The method consists of a desk study on the evolution of wind energy in combination with a Technological Innovation System analysis of the Dutch tidal energy sector for which 12 professionals have been interviewed. This study showed that the following three aspects of the tidal energy TIS performance poorly and need attention: Market formation, the creation of legitimacy and knowledge development. Concrete, the Dutch tidal energy sector is currently hampered by a weak legitimacy that emerges from a gap of knowledge regarding environmental impacts. The conclusion of this study is that the initiation of knowledge consortia concerning environmental impacts is a possible way to address these problems simultaneously. Overarching, an increasing receptive attitude by the water sector in the Netherlands is necessary in order for the tidal energy developments to continue in the same rate as in Europe. In that way, professionals and companies in the Dutch water sector can export this new technology in the future as a sustainability aspect of integral water management.

Contents

Acronyms

DMEC	Dutch Marine Energy Centre
LCOE	Levelised Cost of Energy
PR China	People's Republic of China
R&D	Research & Development
OEE	Ocean Energy Europe
TIS	Technological Innovation System
TRL	Technology Readiness Level
WIPO	World Intellectual Property Organization

Units

kW	Kilowatt or 1×10^3 W
kWh	Kilowatt-hour or 3.6 MJ
MW	Megawatt or 1×10^6 W
GW	Gigawatt or 1×10^9 W

1 Introduction

1.1 Integral water management

Integral water management has historically been focused on water safety, hygiene and agricultural problems. The complex societal challenges that are present today, however, often overlap these traditional pillars and therefore benefit from a more interdisciplinary approach. Climate change is such a societal problem in need of an interdisciplinary approach, imposing a demand for sustainability in every aspect of society. In the last few decades, integral water management has been focused on solutions being climate proof, i.e. an adaptation approach to climate change. Instead of adaptation, mitigation is a possibility by, among others, decreasing fossil energy use. Fossil energy consumption is the main source of anthropogenic greenhouse gas emissions (Cook et al., 2016) and for climate change mitigation, a transition towards a renewable energy mix is needed. Water bodies and water movement offer various possibilities for renewable energy production and could, therefore, contribute to realising the renewable energy mix. The Global Water Partnership (2017) defines integral water management as "a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems". Given this demand for sustainability, including the renewable energy potential of water in integral water management will henceforth be vital when adequately addressing the interdisciplinary water, energy and climate challenges faced today.

Marine energy is a collective name for methods of sustainable and renewable energy production by harvesting the energy from seas, oceans and delta's. Marine energy consists of the following technologies, which are currently in development: tidal energy, wave energy, ocean thermal energy conversion and salinity gradient energy. Tidal energy is a collective name for the conversion of kinetic and potential energy of the tides into usable energy, mainly electricity (Ocean Energy Systems, 2017). In view of the four disciplines, tidal energy is the most mature technology with regard to the technology readiness level (Ocean Energy Forum, 2016). An advantage over wind- and solar energy is the predictability of tidal power, coinciding with the tidal cycles. The global technical potential of tidal energy is estimated 1100 TWh/yr (International Energy Agency, 2011), representing 4,5% of the global electricity production in 2015 (Enerdata, 2017). Even though the global potential is limited, the energy potential is concentrated in certain coastal areas. In that way, tidal energy has the potential to provide renewable energy solutions to offshore locations and remote communities. Tidal turbines can be installed in arrays placed offshore, but also as an addition to sea-defence infrastructure (e.g. the Eastern Scheldt storm surge barrier). The production of renewable energy can be perceived as a valuable and innovative asset for any water safety infrastructure.

The Netherlands has a legacy of water management and construction of water safety infrastructure, as such, it has a head start with regard to the potential integration of tidal energy devices into water safety infrastructure. The Dutch tidal energy sector is relatively young and many efforts are focussed on R&D and demonstration tests, as such the sector is yet for a large share dependent on subsidies. The development of tidal energy occurs globally, however, the Dutch tidal and wave energy sector is the third largest in the world with regard to the number of innovations and installed capacity (Scheijgrond & Raventos, 2015).The Dutch Marine Energy Centre is a not-for-profit network organisation initiated for supporting the marine energy sector, including tidal energy, in the Netherlands. The organisation is currently searching for actions to advance the developments in tidal energy in the Netherlands in order to enhance commercialisation.

1.2 Problem description

1.2.1 Society

In order to combat climate change, it is essential to transform our energy production into renewable energy production on a global scale. Several renewable energy technologies are in development or have already reached a commercial application. Fossil energy sources, however, still dominate the energy market because of their financial advantage: production prices of coal and gas combined cycle are 5 – 12ct /KWh and 4 – 7ct /KWh respectively (Lazard, 2016). Since fossil fuels have this advantage over renewable energy sources, the societal challenge is to find methods to advance renewable energy technologies despite the head start of fossil fuel technologies.

1.2.2 Academic

Tidal energy is positioned on the nexus between water management and renewable energy. Tackling academic challenges surrounding tidal energy, therefore, require an interdisciplinary approach including insights from both water science and energy science. However, tidal energy is currently in development and can be considered an innovation, therefore innovation science is taken into account. Every innovation is different and so are the actors surrounding a technology. Therefore, the determinants for commercial breakthrough vary per innovation. In recent decades, the most important insight in the field of innovation studies is the fact that innovation is not an individual but a collective activity, taking place within a so-called innovation system (Wieczorek et al., 2013). According to the idea of the innovation systems approach, new technologies diffuse and evolve slowly due to a competition with not only other innovations but also the incumbent prevailing system (Unruh, 2000). Both these systems (renewable energy sources as well as incumbent fossil fuel sources) employ forces that slow down the innovation of tidal energy. A competition from other renewable energy technologies can be expected since they are striving towards the same goal. Incumbent technologies do not want to give in any space and enjoy benefits over new technologies including:

"[a] design that has already benefited from all kinds of evolutionary improvements, costs and performance characteristics, a better understanding at the user side, adaptation of the socio economic environment in terms of accumulated knowledge, capital outlays, infrastructure, available skills, production routines, social norms, regulations and lifestyles." (Kemp, 1994, p. 5).

The inertia of the incumbent technology system could result in a so-called lock-in (Unruh, 2000), where the advantages described above are dominant to a point that it becomes very hard for new technologies to evolve. The academic challenge here is to firstly expose this imbalance and search for methods to break through this status-quo.

1.2.3 Business

In the Netherlands, several entrepreneurs are active developing tidal energy technology, taking a share in the global developments. Retaining a prominent position while the global tidal energy sector becomes commercial could result in an industrial success story for the Netherlands. Commercialisation of the tidal energy sector could firstly result in economic value creation for successful turbine developers. However, a successful tidal energy sector would also be of interest for engineering and consultancy companies concerning water management in and around delta's (e.g. Royal HaskoningDHV, Arcadis) as well as offshore construction companies. Dutch offshore contractors (e.g. Van Oord, Heerema, Huisman) are known worldwide for their expertise in offshore engineering and can potentially benefit by exploiting a share in this market potential. It is estimated that a global market is worth a potential €653 billion between 2010 and 2050 (Ocean Energy Forum, 2016).

Tidal energy turbines, in the Netherlands as well as worldwide, are in various stages of development, i.e. R&D, prototyping and demonstration (Ocean Energy Forum, 2016). Tidal energy technology diffuses slowly and understanding the reasons why is the main problem to be addressed. Currently, public and private finances are invested to facilitate the development process. The business challenge is to simplify and speed up the way towards commercialisation in order for a financially healthy sector to arise.

1.3 Aim

The main aim of this study is to find action points that will, when implemented, advance and facilitate the transition from an innovation in development towards a commercial industry. Finding the reasons that currently hamper the diffusion of the technology would create insights and thereby the possibility to create action points.

One way of finding action points is to investigate historic developments of an energy technology that is close to tidal energy. In consultation with Britta Schaffmeister and Pieter Bergmeijer, managing directors at respectively the Dutch Marine Energy Centre and Tidal Testing Centre, wind energy (on- and offshore) is chosen as the energy technology for investigation. The reasons for the selecting wind energy are the following:

- Offshore wind energy is a form of sustainable energy and therefore operates in the same market.
- Innovation of the technology is aimed at, among other targets, decreasing the levelised cost of energy (LCOE).
- A part of the industry operates offshore, which creates similar financial challenges, i.e. relative high capital expenditure (the generator, installation).
- The installation and maintenance of both technologies take place in harsh offshore environments.
- Both industries are dependent on the supply chain and manufacturing capability of the offshore industry.

Currently, the wind energy industry is entering the phase of commercialisation with the first wind parks being built without subsidy (Andresen, 2017). Since the start of the industry around ±1970, however, it has been a turbulent process of innovation including a lot of trial and error. Some domestic wind energy sectors have succeeded while others have failed, of which, in hindsight, lessons can be learned. Finding these 'lessons learned' from the development of the wind industry is therefore the first aim of this study.

Another way of finding action points is by analysing the innovation system surrounding tidal energy in the Netherlands. A method commonly used for the analysis of innovation systems surrounding a technology, is called Technological Innovation System (TIS). A TIS can be defined as a set of rules and actors that influence the speed and direction of innovation in a specific technological area (Markard & Truffer, 2008; Negro et al., 2007). The purpose of a TIS analysis is to assess the development in a certain technological field with regard to processes and/or structures that advance or oppose it (Wieczorek et al., 2013). The TIS concept has been developed for studying renewable energy technologies, examples include biomass gasification in the Netherlands (Negro et al., 2007) and offshore wind industry in Europe (Wieczorek et al., 2013). The second aim of this study, therefore, is to create a TIS analysis of tidal energy in the Netherlands.

The development of tidal energy, however, is not limited to the Netherlands. Since 1990, the world has seen a rapid globalisation (KOF Swiss Economic Institute, 2017), therefore, international collaborations increase as well as border-crossing technology and information exchange. Innovation in the Netherlands should be considered as being part of a world rapidly globalising, especially because the Netherlands ranks 1 in the globalisation index (KOF Swiss Economic Institute, 2017). An example of globalisation in the tidal energy sector are the current EU wide subsidy programmes for testing of tidal technology. In order to assess the Dutch tidal energy TIS, therefore, it is necessary to reflect internationally. In 2016, about 52% of companies in the world developing tidal energy were based in the EU (JRC, 2016). Therefore, the third aim of this study is an analysis of the European tidal energy sector.

1.4 Research question

What are action points that will advance the commercialisation of the Dutch tidal energy sector, based on the evolution of on- and offshore wind energy and an analysis of the tidal energy Technological Innovation System?

1.5 Sub-questions

1: What have been successful actions in the evolution of on- and offshore wind energy?

2: How does the European tidal energy sector perform in terms of Technology Innovation System functions?

3: How does the Dutch tidal energy sector perform in terms of Technology Innovation System functions?

4: How does the Dutch tidal energy Technology Innovation System relate with the European tidal energy Technology Innovation System and the wind energy Technology Innovation System?

2 Theory

2.1 Tidal energy

2.1.1 Tidal forces

Tidal energy is the energy dissipated by tidal movements as a result of the gravitational and centrifugal forces of the earth, moon and sun (Rourke, Boyle, & Reynolds, 2010). Due to gravitational pull, a bulge of water is present on the side of the earth that is closest to the moon. On the other side of the earth another water bulge is present as a result of the centrifugal force. These water bulges circle the Earth once every 24 hours, 50 minutes and 28 seconds, resulting in 2 high tides and two low tides for every landmass on earth (Rourke et al., 2010). The highest tidal differences in the world include the Baie du Mont-Saint-Michel in France (13,5m), the Severn Estuary in the UK (15m) and the Bay of Fundy in Canada (16m)(Desplanque & Mossman, 2001). Tidal currents differ from ocean currents, which are currents flowing around the world as a result of wind, solar heating of surface waters or density and salinity variations and are usually seasonal, slow-moving (±1 m/s) and unidirectional (Ocean Energy Systems, 2017). Due to the geospatial distribution of tidal energy resources (Figure 2) in combination with local obstructions elevating the tidal potential, the tidal energy resource is found on specific locations: i.e. narrow straits between land masses or at coastlines that include headlands or sea mouths. This displacement of water results in local currents with speeds up to 5 m/s (NOAA, 2017) of which the energy can be harnessed via two methods: tidal range and tidal stream technology. Tidal range technology consists of a barrage that traps a volume of water in a bay during high tide which is released during a low tide or vice versa (Bernshtein, 1996). Tidal stream technology harnesses the kinetic energy in a flow of water, in a similar fashion as wind energy is harnessed (Garrett & Cummins, 2005). The global potential resource for tidal stream is larger than for tidal range (IRENA, 2014). Also, entrepreneurial activities in the Netherlands are mainly focussed on tidal stream technology and therefore, the introduction aside, tidal stream technology is meant during this thesis when tidal energy is mentioned.

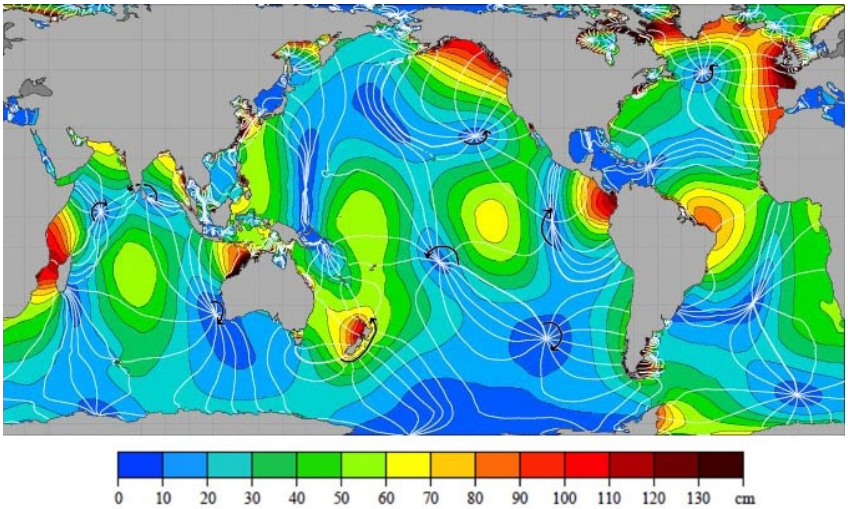


Figure 2. Global height of semi-diurnal tidal difference. The color indicates the tidal difference. The white lines indicate Greenwich phase lag every 30º. Source: Richard Ray (Goddard Space Flight Center) as published in *(Pugh & Woodworth, 2014).*

2.1.2 Global potential and scenario estimations

It is difficult to identify reliable estimates for global tidal energy resources due to the relatively immature state of technology (International Energy Agency, 2011; World Energy Council, 2016). As a result, scientific estimates of the global technical potential vary by an order of magnitude. In order to cope with this disagreement, both high and low estimates are presented in this chapter. Charlier & Justus (1993) firstly calculated a global theoretical potential of 3 TW of which 1 TW is located in relatively shallow waters. However, due to technical, geographical and environmental constraints, only a limited amount of this potential is practically feasible: the technological potential. A slow moving tide can produce substantial tidal power, however water speeds of at least 2 m/s (Jacobson, 2009) – 2,5 m/s (Rourke et al., 2010) are necessary in order for tidal stream turbine to be economical. In addition, shipping routes, fishing grounds and protected areas are a limiting factor for the technological potential (The Carbon Trust, 2011).

Current testing projects show a capacity factor of 0,07 in Marsdiep, 0,17 in Den Oever and 0,60 at the SeaGen project (JRC, 2016) with a global average of 0,20 - 0,35 (Jacobson, 2009). Projections on the future global average, however, range from 0,25 - 0,40 (IRENA, 2014) to 0,37 – 0,45 (UK Energy Research Center & Energy Technologies Institute, 2014). Estimates of the technical potential range from 0,02 TW (Jacobson, 2009) to 1 TW installed capacity (IRENA, 2014). One of the first estimates for potential electricity generation is Baker (1991) with 1000 TWh/yr. Recent estimates by established institutes coincide more or less with this number: 1100 TWh/yr (International Energy Agency, 2011) and 1200 TWh/yr (Ocean Energy Systems, 2017). A comparison with global electricity production and the potential of wind energy and solar PV is presented in Table 1.

Energy source	Theoretical potential in TWh/year	Technical potential in TWh/year	Technical potential as percentage of world electricity production in 2015 (24.089 TWh[3])	Technical potential as percentage of world energy production in 2015 (160.377 TWh[4])
Tidal	7000[1]-7800[2]	180[1]-1200[2]	075[1]-4,95%[2]	0,11[1]-0,75%[2]
Wind[1]	630000	410000	1702%	256%
Solar PV[1]	14900000	3000000	12454%	1871%

Table 1. Estimated installed capacity and exploitable energy in comparison with wind energy, solar PV and world energy production figures. Source: (1) (Jacobson, 2009); (2) (Ocean Energy Systems, 2017); *(3) (International Energy Agency, 2017); (4) (Enerdata, 2017).*

Ocean energy technologies have not been considered in a major global energy scenario modelling up to 2008, however, hereafter early projections on the potential contribution of tidal energy to the future energy system have been made (Edenhofer & Pichs-Madruga, 2011), as visible in Table 2.

Scenario	Energy production in TWh/yr		Scenario description
	2030	2050	
Energy (R)evolution Reference	11	25	No policy changes
Energy (R)evolution Advanced	420	1943	Assumes 80% carbon reduction
IEA World Energy Outlook 2009	13	N/A	
ETP Blue map hi NUC 2050	N/A	99	Nuclear share is increased to 2000 GW
ETP BlUE Map hi REN 2050	N/A	552	Renewable share is increaesed to 75%

Table 2. Selection of models from major published studies that include ocean energy, according to (Edenhofer & Pichs-Madruga, 2011) .

This wide range of results can be attributed to uncertainty with regard to the cost reduction in combination with uncertainty with regard to the degree to which climate change mitigation will drive a transformation of the energy sector (Edenhofer & Pichs-Madruga, 2011).

2.1.3 Unique characteristics of tidal energy

As shown here above, solar PV and wind energy are abundant and relatively well distributed on a global scale, while tidal energy resources are limited and concentrated in certain coastal areas. This results on relative meagre capacity estimates on a global scale (Table 1), however for specific coastal countries substantial estimates are present. 12 GW is the calculated potential for the UK, representing 10% of the UK electricity demand in 2009 (Burrows et al., 2009). In France, a total of only 5 locations in Bretagne and Normandy have an estimated 2-5 GW potential (INNOSEA, 2016). Therefore, the contribution of tidal energy in the global sustainable energy mix might be limited, but in certain regions tidal energy can be a substantial power source. More specifically: islands and remote areas that are not connected to the energy grid can benefit from tidal energy installations. On remote locations where the weather and climate vary widely throughout the year, wind- and solar energy might not provide an adequate solution given the inherent unpredictability of the wind or insufficient sunlight during winter. Tidal energy can provide a predictable power supply 4 times daily, regardless of the weather conditions. Additionally, the construction costs of a tidal power plant do not have to be assigned to energy production (IRENA, 2014), e.g.: the tidal barrage at La Rance (France) also serves as a highway reducing the travel distance around the bay by 30km for 60.000 vehicles daily (de Laleu, 2009).

2.1.4 Cost competitiveness

Cost estimates indicate that tidal energy is currently not competitive, but it has the potential for cost reduction (UK Energy Research Center & Energy Technologies Institute, 2014). The common parameter for comparing the costs of electricity production is LCOE. The LCOE, often displayed in [€/kWh], takes into account all the costs of a production unit over a lifetime and relates that to the total amount of energy produced. The calculation is as follows (Astariz, Vazquez, & Iglesias, 2015):

$$LCOE = \frac{Present\ value\ of\ costs\ over\ a\ lifetime}{Energy\ ouput\ over\ a\ lifetime} = \frac{\sum_{t=0}^{n} \frac{C_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{E_t}{(1+r)^t}}$$

C_t	=	costs in year t	n	=	expected lifetime of power unit
E_t	=	electrical output in year t	t	=	year
r	=	discount rate			

Current demonstration projects of tidal energy depict an LCOE of 0,25 - 0,47 €/kWh (IRENA, 2014), while conventional energy sources and other renewable energy sources currently comprise a lower LCOE, as visible in Figure 4. Cost reduction, however, is possible as has been experienced by other renewable energy technologies. In Figure 3, the development of LCOE values for wind energy and solar PV are visualised; illustrating a decrease of 67% and 86% in LCOE over the years 2009-2017 for wind energy and solar PV respectively (Lazard, 2017). Studies show that the implementation of the first 200 MW could decrease the LCOE of tidal energy by two thirds (SI Ocean, 2013).

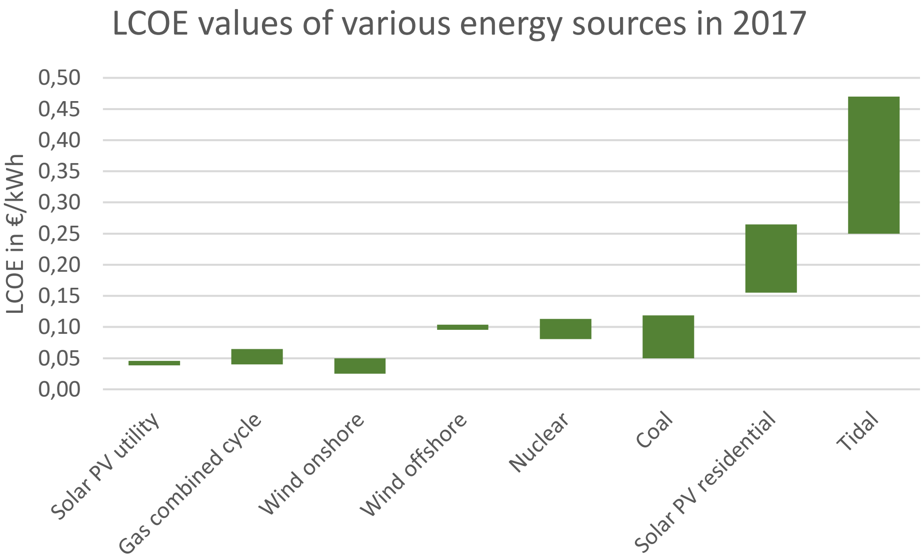


Figure 4. LCOE value of various energy technologies. Source: this work, based on data from Lazard (2017) and IRENA (2014).

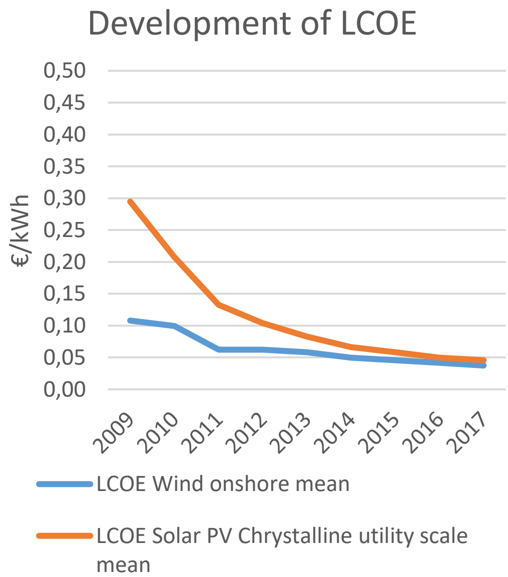


Figure 3. Development of LCOE values over the years 2009-2017 for wind onshore and solar PV. Source: Lazard (2017).

When an incumbent (energy) technology is embedded in society, alternative technologies can be locked out for long periods of time, even if they provide improvements with regard to the established system (Unruh, 2000). The results of the current carbon lock-in are persistent market and policy failures that result in a failure of new carbon-saving technologies, despite the environmental and possibly economic benefits. Some technologies have proven to be successful in breaking through this lock-in, whereas others strand in the process. In order to find elements to enhance tidal energy developments, therefore, tidal energy will be studied as an innovation.

2.2 Framework for analysis

2.2.1 Innovation systems approach

A new idea or invention put to use, becomes an innovation (Chappin, 2008). Rogers (2003, p. 11) defines innovation as "an idea, a practice or an object that is perceived as new by an individual or other unit of adoption". Tidal energy devices can be considered as such. For a long time, it has been thought that an innovation process is an autonomous technological process where the efforts of the entrepreneur would be fully responsible for the outcome (Smits & Kuhlmann, 2004). However, Kuhn (1962) and Rip (1978) have shown that an innovation process is inevitably embedded in a socio-economic environment of which it is totally dependent. Thus, it is the result of socio-economic factors, on top of the technological development in the narrow sense that will create and enhance an innovation. Innovation, therefore, should not be considered an individual act, but a process that interacts with the system surrounding the technological invention (Edquist, 2001). This idea is known by the name of the innovation systems approach (Nelson, 2002).

2.2.2 Technological Innovation System

Starting with Freeman and Lundvall in the 1980s, innovation was viewed as bordered by nation states with a National Innovation System (Freeman, 1987) being a set of elements and relationships which are active in the production, diffusion and usage of new knowledge, bordered or rooted within a certain nation state (Lundvall, 1992). Later on, a distinction is made between National (NSI), Sectoral (SSI) and Technological Innovation Systems (TIS). However, it remains questionable which entities in these systems could be considered essential for the innovation. Nelson (2002) describes these entities as *functions* of an innovation system. Scientific opinions vary, however, on what functions are determinant in the process.

2.2.3 Functions of innovation systems

Galli & Teubal (1997) are one of the first to propose a disconnection between actors and functions, since an actor can have multiple roles and subsequently functions. Functions are from now on distinctive from actors and should be seen as overlying the actors or organisations within the system. Extrapolating on that, Liu & White (2001) proposed the following set of functions:

- Research (development, engineering)
- Implementation (manufacturing)
- End-use (customers of the product)
- Linkage (bringing together knowledge)
- Education

Following up, several studies have come up with different functions. Hekkert, Suurs, Negro, Kuhlmann & Smits (2007) assessed and combined all these publications to produce a set of functions that has been widely acclaimed: *"Functions of innovation systems: A new approach for analysing technological change".* The proposed set of functions is the following:

Function 1 (F1): Entrepreneurial activities

Entrepreneurs are an essential core of the innovation system. The role of the entrepreneur is turning newly developed knowledge and technologies into an actual product or service in order to take advantage of the business opportunity (Hekkert et al., 2007). Entrepreneurs can be new entrants who see a market potential or incumbent firms who are exploring business development opportunities. An important part of the role of the entrepreneur is creating an influence on the rest of the innovation system, since his functioning depends on it (Van de Ven, 1993).

Function 2 (F2): Knowledge development

Research and development of technical knowledge are essential for a new innovation. Knowledge development is a result of entrepreneurial activities, but can also be performed by scientists (Otto, 2009). This function relates to the variety of technological options that are developed and includes 'learning by searching' and 'learning by doing' (Otto, 2009).

Function 3 (F3): Knowledge diffusion

The exchange of information and thus the networking activity is the third function crucial to the innovation system. McKelvey (1997) has particularly stressed this function based on an analysis of an innovation system compared with evolutionary economics theory. Important actors are organisations that function as intermediary in the system.

Function 4 (F4): Guidance of the search

As with knowledge diffusion, this function is also based on a comparison with evolutionary economics. The principles of evolutionary economics are variety, selection and retention (Hekkert et al., 2007). The function 'guidance of the search' can be expressed as the natural and artificial process of selection between all technologies. Since resources are limited, a selection of entrepreneurs and technology designs is necessary for the advancement of the best competitors. An example of guidance is the content of innovation policy of the government. By implementing certain targets and subsidies, the government is applying an artificial way of selection (Hekkert et al., 2007)

Function 5 (F5): Market formation

The presence of a market, i.e. the possibility to sell a product, is essential for a successful innovation. This function encompasses all activities that are focussed towards a market creation from the very start. Previously the effect of the embedded market system has been described as counteracting since it has various benefits over new technologies (Unruh, 2000). It is therefore useful for developing innovation systems to have or create temporary niche markets where specific applications of the innovation can flourish (Hekkert et al., 2007; Schot, Hoogma, & Elzen, 1994).

Function 6 (F6): Resources mobilisation

Either financial and human resources are essential for a healthy innovation system and are necessary as input for all other functions (Hekkert et al., 2007). Resources are necessary for knowledge development and are a very important prerequisite for the function of knowledge development (Hekkert et al., 2007). Venture capital, entrepreneurial investments and government subsidies are the most important financial resources (Otto, 2009).

Function 7 (F7): Creation of legitimacy

The companies and individuals in an incumbent system often have financial interests in the status-quo. Additionally, humans have a natural aversion towards change. In order to progress, a new technology often has become part of the incumbent regime or even overthrow it, a process often cited as 'creative destruction' (Hekkert et al., 2007; Unruh, 2000). Advocacy for the new technology can benefit the creative destruction, for example by putting a new technology on the agenda, lobbying for resources and favourable tax regimes (Hekkert et al., 2007).

2.2.4 Phase of development

An emerging technology on a path towards commercialisation goes through several phases of development. There are several (academic) methods for the identification and division of the development phase. Hekkert et al. (2007) propose the following categorisation: Pre-development, development, take-off, acceleration and stabilisation. Key indicator in the identification is the degree of diffusion of the technology (Figure 5).

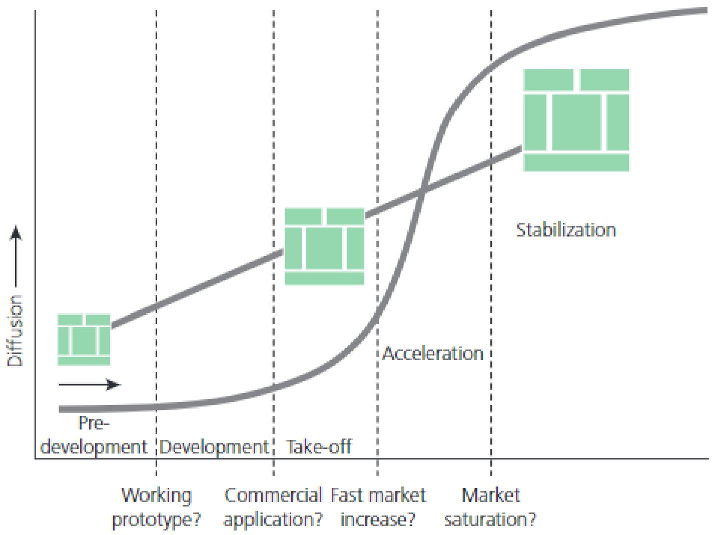


Figure 5. Development phase and diffusion of technology. Source: (Hekkert et al., 2011a)

Depending on the phase of development, an emerging technology needs different entities in order to progress. It has been found that certain system functions are more important than others, depending on the development phase (Hekkert, Heimeriks, Harmsen, Negro, 2011a). In Figure 6, supportive functions are filled green and the most important functions are in bold (Hekkert et al., 2011a). If the important or supportive functions are missing in a certain development phase, they can block the performance of the entire innovation system (Hekkert et al., 2011a). The black arrows simulate the relations that happen in that phase, while the grey arrows are the relations from a previous phase, still occurring.

2.2.4.1 Pre-development

This phase starts with the first developments of the technology, in theory and thereafter in a laboratory setting. A benchmark in this phase is a proof-of-principle, showing the technological possibilities (Hekkert, Boer, & Eveleens, 2011b). Due to the early stage of the development, various different prototypes are emerging without a dominant design. The target function in this phase is knowledge development and supportive functions include knowledge diffusion, guidance of the search and resources mobilisation (Hekkert et al., 2011b).

2.2.4.2 Development

The benchmark for this phase is a working prototype (Hekkert et al., 2011b), which needs to be transformed into a commercial product. This is done by entrepreneurs and therefore, entrepreneurial activity and experimentation is the most important function. The first experiments and pilot plants will be put in in place, showing the technology in practice. During this phase, knowledge development happens by learning-by-doing instead of theoretical knowledge developments as seen in the pre-development phase (Hekkert et al., 2011b). Therefore, knowledge diffusion is the second most important function during this phase. Also, the variety of designs will decrease resulting in the eventual rise of a dominant design.

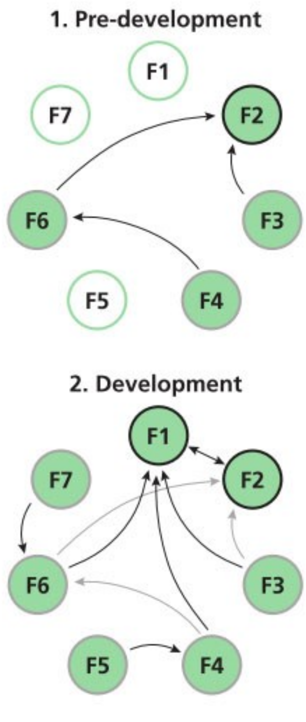


Figure 6. Function relations in pre-development and development phase. Source: (Hekkert et al., 2011a)

2.2.4.3 Take-off

A commercial application defines the start of this phase, resulting in a growth of production. Entrepreneurial experimentation and production is critical (Hekkert et al., 2011b) and increasingly the creation of legitimacy (function 7).

2.2.4.4 Acceleration and stabilisation

During the acceleration phase, a high technology diffusion is a key indicator. Market formation is the most important function during this phase, creating the opportunity for diffusion. Supportive functions are entrepreneurial activity, resources mobilisation and guidance of the search (Hekkert et al., 2011a). At last, stabilisation is reached, the saturation of the market is the indicator for this phase and the degree of diffusion stabilises (Hekkert et al., 2011a).

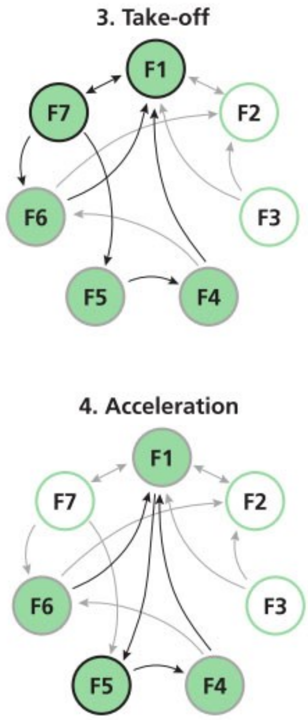


Figure 7. Function relations in take-off and acceleration phase. Source: (Hekkert et al., 2011a)

3 Method

The TIS method is used in order to find answers to the sub-questions and the main research question and is chosen for the following reasons (Hekkert et al., 2007):

- TIS is purposely made for the analysis of sustainable energy technologies like tidal energy
- A comparison between various innovation systems is possible
- The possibility to systematically map the determinants of innovation
- Creating the opportunity to create policy targets and instruments to reach them
- In between national, sectoral and technological innovation system studies, TIS is most suitable given the tidal energy technology focus of this study

The overall method can be found in Figure 8. Firstly, an analysis of the evolution of wind energy is made in order to find 'lessons learned' that can be of value for the tidal energy sector. Secondly, an analysis of the European tidal energy developments is performed in order to create a context for comparison of the Dutch tidal energy sector. Lastly, a TIS analysis of the Dutch tidal energy sector will be performed. An explanation of these steps can be found in the next chapters.

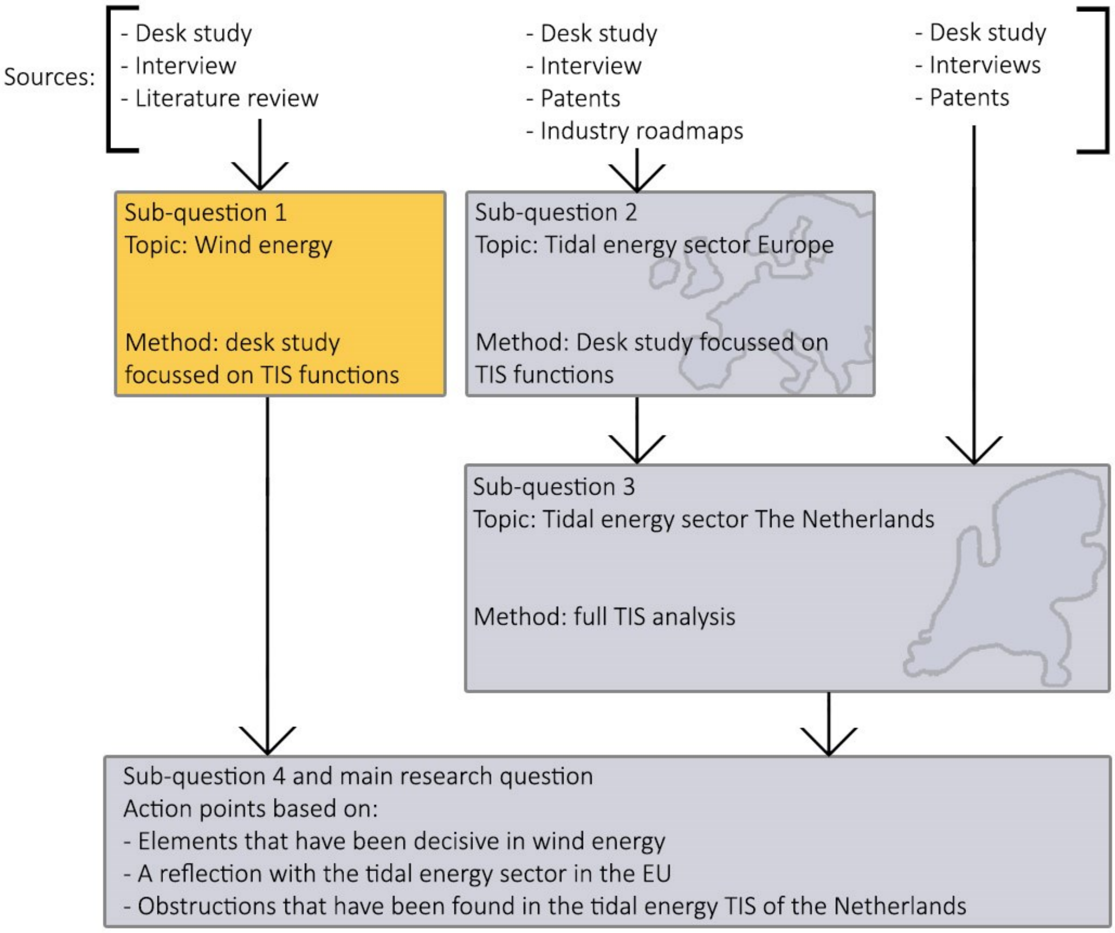


Figure 8. Method for this thesis. Source: this work.

3.1 Method wind energy

3.1.1 Research design

In order to find action points in the evolution of wind energy, a desk research is performed. Scientific literature is reviewed and where necessary, supplemented with data from industry reports. To verify these findings, an expert is interviewed. The use of industry reports, scientific literature and an expert interview results in triangulation, increasing the accuracy of the research. In this chapter, the People's Republic of China (PR China), Denmark, Germany, the Netherlands, Sweden, the United Kingdom and the United States are investigated since these countries have been key players in the development of wind energy and are consequently the subject of scientific literature. Of these countries, however, the main focus will be on Denmark, Germany and the Netherlands, since most entrepreneurs were active in these countries during the 1980s and 1990s.

3.1.2 Data collection

In order to find lessons learned that can be connected to tidal energy, TIS is used as the framework for analysis. Consequently, TIS literature concerning wind energy has been searched for, yielding the following documents:

- The emergence of growth industry: a comparative analysis of the German, Dutch and Swedish wind turbine industries (Johnson & Jacobsson, 2003).
- Learning in wind turbine development (Kamp, 2002).
- Transforming the Energy Sector: the Evolution of Technological Systems in Renewable Energy Technology (Jacobsson & Bergek, 2004).

In addition, the following non-TIS literature is used:

- Fostering a renewable energy technology industry: An international comparison of wind industry policy support mechanisms (Lewis & Wiser, 2007).
- The wind energy (r)evolution: A short review of a long history (Kaldellis & Zafirakis, 2011).
- 30 Years of wind policy (IRENA & GWEC, 2012)
- Progress and recent trends in wind energy technology (Islam, Mekhilef, & Saidur, 2013).
- Catching up: the rise of the Chinese wind turbine industry (Lefevre-Marton, 2013)
- Wind energy: trends and enabling technologies (Kumar et al., 2016).

The tidal energy industry is currently in the development phase (see 4.3.2), where working prototypes are demonstrated and first (niche) markets are sought. Similar innovation characteristics have been visible for wind energy in the period 1973 - 2007. Because of the similarities with regard to innovation characteristics, the main temporal scope of this chapter is 1973 - 2007. It must be noted that in academic tradition recent studies are preferred when performing a literature research, however due to the temporal scope of this research (1973 – 2007) older sources are also appropriate.

3.1.3 Data analysis

The before mentioned literature and industry reports are studied and presented in a chronologic order with a scope on the TIS functions. The presence of a TIS function will be a shown as follows: an entity benefiting or counteracting system function 1 is visualised as (F1+) or (F1-) respectively. As a conclusion of this chapter, the 'lessons learned' are distilled from the text and presented per TIS function.

In the period 1973-2007, different development phases and characteristics were present and therefore a sub-division is made in the analysis. For this, different models can be used, but usually a subdivision in two clear phases is possible (Utterback, 1994). The first phase is characterised by design experimentation combined with entries and exits of entrepreneurs and a small market. The second phase typically includes market growth (Utterback, 1994), less new entrants (Utterback & Suárez, 1993) and a natural selection of firms (Johnson & Jacobsson, 2003). As the TIS method is intentionally created for the analysis of sustainable energy technologies classification (Hekkert et al., 2011b; Hekkert et al., 2007), it is well suited as a categorisation in this chapter. The temporal categorisation which is used, therefore, is in accordance with previous studies concerning wind energy developments (Johnson & Jacobsson, 2003; Utterback & Suárez, 1993). Therefore, the following temporal categorisation is used in this thesis:

Pre- development (up to 1972)

Development phase 1 (1973 – 1989)

Justification: The start of the development phase is characterised by a working prototype (Hekkert et al., 2011b). Even though wind turbines have been produced before the 1970s (mainly for agricultural purposes), the 1973 oil crisis sparked a global interest in wind turbines for electricity production, resulting in the development of several prototypes.

Development phase 2 (1990 – 2007)

Justification: Because notable changes occur within the development phase, a distinction is made between development phase 1 and development phase 2 in accordance with the decision of previous publishers (Johnson & Jacobsson, 2003). The start of this phase is the appearance of the dominant design (Hekkert et al., 2011b).

Take-off and acceleration (2007 – present day)

Justification: Around this time, the wind energy market was growing, as is visible with the gradual rise of cumulative installed capacity (see Figure 9). According to the TIS literature, in general, a take-off phase is characterised by a commercial application of the technology (no subsidy involved) and a rising market (Hekkert et al., 2011b). When looking for data identifying the start of this phase, the following events stand out around 2007/2008: In 2007, European member states announced a commitment for a 20% renewable share in primary energy consumption by 2020 (TPWind Advisory Council, 2006). In addition, a 50 GW installed offshore wind target for 2020 was initiated, sparking the growth of the offshore wind market (Breton & Moe, 2009). Shortly after, several countries initiated offshore wind targets: 6 GW (by 2020) for France (Wind Power Monthly, 2016) 18 GW (by 2020) for the United Kingdom (Department of Energy and Climate Change, 2013) and 4,45 GW (by 2023) for The Netherlands (Sociaal-Economische Raad, 2013), sparking the offshore wind industry in North-west Europe. Also, globally, the installed capacity was increasing with a higher rate since ± 2007 (Figure 9).

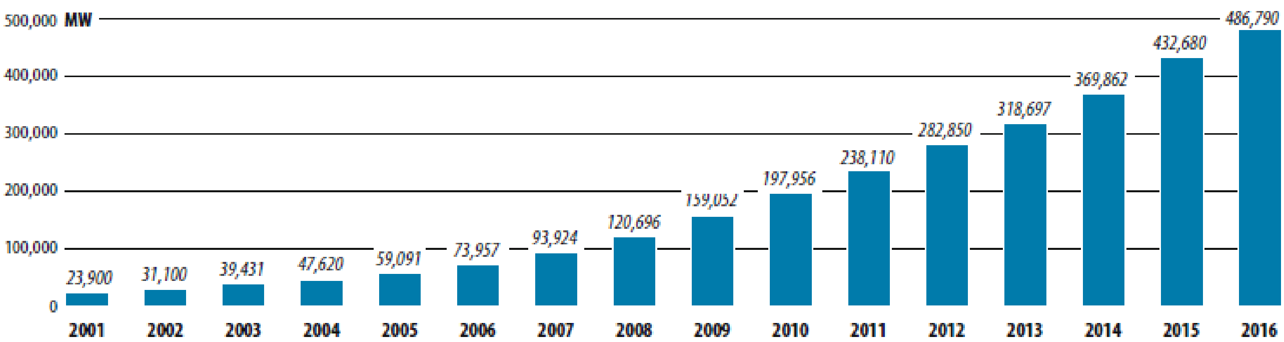


Figure 9. Global cumulative installed wind power (on- and offshore), Dec 2016. Source: Global Wind Energy Council (2016).

As a result, global installed capacity passed 200.000 MW in early 2011. Given these events in combination with the supporting data Figure 9, 2007 is identified as the start of the take-off phase in this study. According to TIS literature, in general, the take-off is followed by an acceleration phase which is visible by a rapid market growth (Hekkert, Boer, et al., 2011). For wind energy, this occurs shortly after the take-off, as a rapid market growth is visible from 2007 onwards (see Figure 9).

Stabilisation

The acceleration phase is followed by a stabilisation phase which is identified by a market saturation. Market saturation can be identified by a stable number of installed capacity, i.e. newly installed turbines equal decommissioned wind turbines. Considering the continuous growth in installed capacity in recent years (Figure 9), it can be concluded that the stabilisation phase is not yet reached 2017.

3.2 Method tidal energy Europe

As a first scope with regard to tidal energy, the European developments are investigated by means of a desk research. The aim of this research is, firstly, to identify which barriers are currently faced in the European sector in order to be able to reflect these later on with the barriers in the Dutch tidal energy sector. The data used for this research are the following sources:

- Industry reports, among others:
    - 2016 JRC Ocean Energy Status Report (JRC, 2016)
    - Ocean Energy Strategic Roadmap (Ocean Energy Forum, 2016)
    - Dutch Wave & Tidal energy sector. TKI Wind Op Zee (Scheijgrond & Raventos, 2015)
    - Marine energy technology roadmap 2014 (UK Energy Research Center & Energy Technologies Institute, 2014)
    - International vision for ocean energy (Ocean Energy Systems, 2017)
- Patent analysis using the WIPO database
- Interview with professional on European level

3.3 Method tidal energy the Netherlands

3.3.1 Research design and data collection

The TIS analysis of the Dutch tidal energy sector is performed using the following sources:

- 11 interviews of professionals within the Dutch tidal energy sector
- Patent analysis using the World Intellectual Property Organization (WIPO) database

Since the Dutch tidal energy sector is the subject of this part, Dutch professionals working in the sector will be interviewed. The interviews are taken into account, because it is impossible to evaluate an innovation system purely by quantitative criteria. The reason for this is that technologies and regions are different per innovation system and therefore, no optimal configuration can be applied (Hekkert et al., 2011a). This triangulated method (quantitative and qualitative sources) is used in order to increase the validity of this study. A total of eleven experts from prominent organisations within the Dutch tidal energy sector are interviewed and presented in this study as participants B- J. The questions of the interview are focussed on the TIS functions within the Dutch tidal energy sector, to be found in Appendix A.

3.3.2 Data analysis

Structural analysis

In accordance with the TIS method, the entities within the Dutch tidal energy sector are identified and mapped. The entities are: actors, networks, institutions and infrastructure. Actors will be subdivided into the following categories: governmental bodies, knowledge institutes, educational organisations, industry, supportive organisations (Luo et al., 2012).

Determining the phase of development

As presented in the theoretical framework, the system functions that are most important for an innovation is dependent on the phase of development. Therefore, determining the phase of development is done in this chapter.

System function analysis

On the basis of the interviews with experts, the system functions of the Dutch tidal energy sector are valued using a 5-step scale: Absent, weak, moderate, strong and excellent, as is used in previous studies (Hekkert, Heimeriks, et al., 2011; Luo et al., 2012). These values should not be considered a final product, but are means in order to find obstacles that hamper the innovation system. Every interview has been used to create an assessment of the participant's valuation of the performance of the seven functions. When the expertise of the participant on a specific function was adequate, the valuation was taken into account. When a participant suggested he or she had limited expertise on a specific function or knowledge about a specific system function was questionable, this data was is not taken into account. For every function, an average value is calculated on the basis of a participant's opinions on the system function. This results in an average of 8.7 valuations per function. A final assessment of a system function is made on the basis of an overall interpretation of all information: the function average, patents, and industry reports, as done in previous studies (Hekkert, Heimeriks, et al., 2011; Negro et al., 2007; Otto, 2009; Wieczorek et al., 2013).

4 Results

4.1 Wind energy

4.1.1 Pre – development (–1972)

The earliest devices for harnessing wind energy are found thousands of years ago in the Persian Empire (200 BC) and later in the Netherlands and the Mediterranean (1300-1875 AD) (Fleming & Probert, 1984). An often recognised pioneer of the wind turbine for electricity production is Danish scientist Poul la Cour with his Askov windmill in 1891. The rapid development of airplane propellers during the First World War resulted in knowledge development regarding the blades, followed by the first wind turbines during the period 1930 – 1970 in the United States, Denmark, France, Germany and the United Kingdom (Kaldellis & Zafirakis, 2011). Danish pioneer Johannes Juul, a former student of Poul la Cour, introduced the Gedser (200 kW) in 1960, a successfully operating wind turbine and a precursor of today's dominant design.

4.1.2 Development phase 1 (1973 – 1989)

Before the oil crisis of 1973, most states were highly dependent on fossil fuels. In 1973, the oil crisis shook up the global energy market with rising (fossil) energy prices. This created economic issues and also, countries started questioning their energy security. Denmark, for example, had an exceptionally high dependency with 90% of its energy supply based on oil imports (IRENA & GWEC, 2012), creating a high incentive to look for alternative energy sources. In contrast, the Netherlands had substantial gas resources, creating a smaller incentive with regard to energy security (van Kuik, personal communication, July 5, 2017).

The development of wind turbines rose gradually in Northern European countries with the primary reasons being the rise of the energy prices and substantial wind resources (Kaldellis & Zafirakis, 2011). The developments started around 1980, with a rising number of entrepreneurs, experimental designs and a small market (Johnson & Jacobsson, 2003; Nelson, 1994)(F1+)(F2+). During this era, around 15 – 20 companies were involved in the wind energy industry in the Netherlands (Gert Verbong, as cited in Johnson & Jacobsson (2003), 19 in Germany and 26 in Denmark (Johnson & Jacobsson, 2003)(F1+).

In these countries, several socio-economic trends influenced the innovation system surrounding wind energy. In the Netherlands, the green movement was small and subsequently little incentive was present for the utilities to open their scope for renewable energy technologies (F7-). In Germany, a larger green movement influenced the utilities to look into renewables like wind energy (Johnson & Jacobsson, 2003)(F7+). In Denmark, a decision in parliament led to a rejection of nuclear power (1985), resulting in a large focus on renewable energies including a target of 100 MW wind energy before 1990 (IRENA & GWEC, 2012). Additionally, in Denmark, the wind turbines were managed by local cooperations, creating a high social support for wind energy (van Kuik, personal communication, July 5, 2017)(F7+).

4.1.2.1 Technology

During this period the energy production of wind turbines increased 5% annually, mainly due to upscaling in combination with progress in terms of aerodynamics, structural dynamics and improvements in the generator (Hameed, Hong, Cho, Ahn, & Song, 2009)(F2+). In this experimental phase, various sorts of turbine designs appeared, including, among others, the vertical-axis turbine and horizontal-axis turbine with either one-, two- or three-bladed rotor heads (F2+). Mastering the dynamics of the one-bladed machine turned out to be much harder than the two- and three-bladed turbines (van Kuik, personal communication, July 5, 2017). The two-bladed design is 6% more efficient than a single bladed design and the three bladed design adds 3% on top of the two-bladed concept (Islam et al., 2013). These significant increases, however, are compromised by a lower capital expenditure in one- and two-bladed designs. The decisive factors, however, for the one- and two-bladed designs to be eliminated, has been the relative high noise level and the visual impact, since three-bladed wind turbines are visually calmer (Islam et al., 2013; Kaldellis & Zafirakis, 2011; van Kuik, personal communication, July 5, 2017). This occasion shows that with a technology highly dependent on social acceptance, the design process is not only driven by efficiency but also by impact on society.

4.1.2.2 Policy and market development

During this period (1980-1990), the following countries were mainly active: Denmark, the Netherlands, Germany, the United States, the United Kingdom and Sweden (Johnson & Jacobsson, 2003; Lewis & Wiser, 2007). In all five countries the financial support for R&D was present and often substantial (F6+). The Netherlands, Germany and the UK performed a technology-push (van Kuik, personal communication, July 5, 2017): Forcefully creating wind turbine R&D in order to start an industry (F2+). In the Netherlands, consortia were formed between the research institutes, universities and businesses (F3+). Because of this continuous technology-push since the 1980s, the Netherlands is, in terms of wind turbine R&D, currently still one of the leading countries (van Kuik, personal communication, July 5, 2017). Despite the prosperous R&D, however, the market formation in the Netherlands was particularly bad in relation to other countries (van Kuik, personal communication, July 5, 2017)(F5-). Policy measures included free prototype testing at ECN (Janssen & Westra, 2000; as cited in Johnson & Jacobsson, 2003a)(F2+)(F4+) and a subsidy (F6+). The amount of subsidy was connected to the size of the turbine, causing turbines to grow disproportionally big and not cost-competitive outside the Netherlands (F4-)(F5-). At the end of the 1980s, there was one company producing <100kW turbines and 4 companies producing 200-500 kW turbines (de Bruijne, 1995; Johnson & Jacobsson, 2003). This incentive also stimulated some Dutch entrepreneurs to choose the 2-bladed turbine as their design.

In Denmark and Germany the market formation started off better (van Kuik, personal communication, July 5, 2017)(F5+). In Denmark, as early as around 1976, a tax on electricity was imposed, which was used for financial support for R&D in renewable energy (F6+). One of the measures included a capital grant of up to 30% of installation costs (IRENA & GWEC, 2012). Another financial tax incentive for families who invested in community wind power, resulting in a rise of wind energy cooperatives (F5+). Apart from addressing financial resource mobilisation, this incentive indirectly creates social support (F7+). In the state of California (United States) an investment tax combined with a utility act (PURPA) promoting sustainable energies (F5+) initiated the earlier described wind parks sometimes referred to as the ‘California boom’ from 1980-1985. Around 16.000 wind turbines were installed with a capacity ranging from 20 up to 350 kW. A large share of these wind turbines were supplied by Danish companies (IRENA & GWEC, 2012). Thus, financial resources were available in all aforementioned countries and, according to van Kuik (personal communication, July 5, 2017), the availability of relatively more financial resources did not directly lead to success of some countries over others.

In Germany, The Netherlands and Denmark, the incentives resulted in the appearance of entrepreneurs, whom mainly focused on smaller turbines (< 1 MW). In Sweden, however, instead of small entrepreneurs, large incumbent companies (e.g. SAAB) stepped in the industry (F1+) and created MW-size turbines (F2+). A substantial subsidy program was active in Sweden and, up to 1979 subsidies in Sweden were higher than Germany and the Netherlands (F5+). However, after a decade of development most of the companies had halted their pursuits due to an economic non-feasibility at that time (F1-)(Johnson & Jacobsson, 2003).

Forcefully creating large wind turbines (F4-) and thereby ignoring the potential benefits that come with gradual upscaling, could have attributed to the non-viability of the turbines and the eventual downfall of the Swedish industry. Other countries also had large incumbent companies creating wind turbines, for example Boeing in the United States and Stork featuring Fokker in the Netherlands (van Kuik, personal communication, July 5, 2017). They all chose to create a MW-size turbine from scratch and thereby neglecting a potential learning curve. All these companies have failed, however, and the currently leading companies in existence today have all started as small entrepreneurs (van Kuik, personal communication, July 5, 2017).

4.1.3 Development phase 2 (1990 – 2006)

Characteristic for the 1990s is upscaling of the individual wind turbine size as well as the wind turbine market. Upscaling the wind turbine has been a general trend with the aim of increasing the LCOE. Several reasons for this are:

- At increased heights, wind speeds are higher and the wind profile is more uniform
- A larger energy yield for a given surface area
- Upscaling results in relative lower capital expenditure

These benefits have resulted in a gradual increase of the height and rotor diameter from 15m (1980), 112m (2000) (Garrad et al., 2009) up to 164m as of 2017 (MHI Vestas V164, 8 MW), corresponding with an increase in rated capacity. The growth of the wind energy market resulted in a rapid increase in installed capacity. The global installed capacity had grown from approximately 500 MW in 1990 to 4800 MW in 1995, 17,400 MW in 2000 and 74,223 MW at the end of 2006 (Global Wind Energy Council, 2006). The amount of entrepreneurs in the 1980s had lowered (F1-) due to cases of bankruptcy, mergers and acquisitions (Johnson & Jacobsson, 2003, van Kuik, personal communication, July 5, 2017)(F4+). Some entrepreneurs continued independently, others were taken up into incumbent firms like Siemens and General Electric (van Kuik, personal communication, July 5, 2017).

In the beginning of the 1990s, the search for the dominant design had halted with the majority of the industry working on three-bladed horizontal-axis wind turbines (van Kuik, personal communication, July 5, 2017)(F4+). Together with market expansion, the emergence of the dominant design heralded the transition from the experimental phase to the market formation phase. Even though the dominant design was clarified, the technological innovation inside the turbine continued long after 1990 with mechanical varieties inside the turbine (Johnson & Jacobsson, 2003).

4.1.3.1 Technology

During this period, research is focused on understanding wind dynamics on sea and innovation inside the turbine, e.g. material properties and controllers (van Kuik, personal communication, July 5, 2017)(F2+). An aspect of guidance of the search (F4+) in wind turbine technology is the battle between stall and pitch regulation. Wind turbine rotors need regulation in order to avoid excessive wind speeds creating dangerous rotor speeds. Before the 1990s, wind turbines were mostly stall-regulated, meaning that the blades are bolted on the rotor hub with a fixed angle. The blades were designed in order to create an aerodynamic feature called stall, resulting in purposely wasting potential wind energy and hereby slowing down the rotor. Pitch-regulated wind turbines, on the other hand, can change the pitch of the blades and therefore regulate the amount of stall. These benefits combined have resulted in pitch regulating technology to become dominant since the mid-1990s. Currently, all wind turbine manufacturers and developers use pitch-regulation (van Kuik, personal communication, July 5, 2017).

4.1.3.2 Policy and market formation

It is during this phase that in some countries the domestic wind energies industry failed, while others flourished. During this period several national governments implemented policies with varying results. In the Netherlands and Germany, "the consortia for knowledge development were functioning properly" (F2+)(van Kuik, personal communication, July 5, 2017). In Denmark, wind energy companies were large enough to detect what is needed and take action themselves (F1+), where in the Netherlands this was due to the cooperation (F3+)(van Kuik, personal communication, July 5, 2017). The installed capacity in Germany and the Netherlands was 20 MW and 33 MW respectively in 1989. Around this time, these countries introduced a similar programme for the stimulation of the home market: The German 100 MW programme (aiming at 100 MW total installed capacity) and the Dutch Windplan program aimed at installing 50 MW annually for a period of 5 years (Johnson & Jacobsson, 2003). Moreover, the Dutch government had created a target of 1000 MW for the year 2000. Both programmes were ambitious, considering the installed capacity at the time.

The German 100 MW programme turned out to be successful and initiated further virtuous cycles of market growth (Jacobsson, S., Bergek, 2004)(F5+). A ceiling of 40 turbines for each category was used, therefore benefiting the smaller entrepreneurs (mostly German). This, and other selection measures favoured German entrepreneurs (Hoppe-Kilper, 2000, Molly, 1999, as cited in Johnson & Jacobsson, 2003) resulted in the German manufacturers to yield 57% of the projects (F4+), the Danish 35% and the Dutch 7%. Around the same time (1991-1992), Germany and Denmark introduced an electrical feed-in tariff set at 90% and 85% respectively in relation to the average consumer electricity price (IRENA & GWEC, 2012)(F5+). These market stimulation measures resulted in the German market expansion from 20 MW (1989) to over 500 MW in 1994 (Klaassen, Miketa, Larsen, & Sundqvist, 2005).

In the Netherlands, despite the success in the experimentation phase, several issues hampered the progress in the 1990s. Firstly, the overall market exploitation was small due to a limited formation of the domestic market (Johnson & Jacobsson, 2003)(F5-). The ambitious Windplan project stranded in 1993, partly due to a siting problem: Finding locations and getting building permits was difficult and slow (F7-) due to the high population density in the Netherlands (Gipe, 1995). In order to eradicate this problem, the Dutch national government signed an agreement with the provinces for the distribution of 1000 MW, however the local governments were not taken into account in this decree. Therefore, they had little reason to support wind energy and because the national government did not intervene effectively, the building permit problem was not addressed (Jacobsson, S., Bergek, 2004). The underlying problems are that wind power was not an important political issue on the national agenda in combination with a lack of social support (F7-). Also, the municipalities created their own development plans and wind turbines were not included (Kamp, 2002). The government tried to intervene by introducing the Environment Premium Regulation: a premium for wind turbine owners in windy regions, provided that the turbine produced little noise (Kamp, 2002). The problem remained, however, in spite of this measure. Because this problem was not addressed adequately, only 40 MW of the targeted 100 MW was installed by 1990 in the Netherlands (Kamp, 2002).

The second problem in the Dutch casus is the failure to exploit foreign markets. Due to the subsidy programmes in the Netherlands, turbines had evolved towards relatively large two-bladed designs. These turbines were economically optimised for the Dutch subsidy programmes, however therefore not cost-competitive in foreign markets. As a result, the Dutch entrepreneurs failed to exploit the booming German market in the 1990s (F5-).

A third problem in wind turbine development in the Netherlands is a partly failure of interacting between actors in the innovation system (Kamp, 2002). As a result of the technology-push, The Netherlands was very successful in 'learning by searching', visible in the substantial R&D in the Netherlands. 'Learning by interacting', however, describes the degree of interaction between actors in the innovation system: manufacturers, research institutes, government and wind turbine owners (Kamp, 2002). This communication is very important for the development of the technology, since it creates a feedback for the manufacturers. It has been shown that especially interaction between manufacturers and utilities (turbine owners) as well as manufacturers and research institutes was very difficult (Kamp, 2002)(F3-). Also, interaction in between manufacturers was almost completely lacking due to distrust. In contrast, all these interactions have been very effective in Denmark (F3+), working in favour of overall wind turbine developments (Kamp, 2002).

4.1.3.3 Exploiting the domestic potential

The goal of creating a domestic wind turbine manufacturing industry is two-fold: creating a method for domestic renewable energy production as well as setting up an exporting industry for economic reasons. This is clearly visible in Denmark with Vestas, for example: The Danish domestic market accounts for 5 GW (Vestas, 2017), but Vestas has a total installed capacity of 83 GW worldwide (June 2017).

It is questionable to what extent the exploitation of the home market is a prerequisite for the creation of an export industry. However, as will be shown in this chapter, it is in the domestic market in which these companies got the opportunity to grow and consequently develop their technologies.

The currently leading global wind energy companies have emerged from countries with a domestic wind potential and additionally, the exploitation of that potential is shown to be an important factor for the development of the wind energy company (Table 3) (Johnson & Jacobsson, 2003; Lewis & Wiser, 2007).

Country	Cumulative capacity in 2004 (in MW)	Leading domestic companies	Percent of capacity installed by domestic company
Germany	16.649	Enercon, Repower, Nordex	54%
Spain	8.263	Gamesa, Ecotecnia	73%
United States	6.750	GE Wind	49%
Denmark	3.083	Vestas, Bonus/Siemens	99%
India	3.000	Suzlon	51%
Italy	1.261	none	0%
The Netherlands	1.081	none	0%
Japan	991	Mitsubishi	32%
United Kingdom	889	DeWind	0%
China	769	Goldwind	21%
Canada	444	none	0%
Australia	421	none	0%
Brazil	30	none	0%

Table 3. Installed capacity per country and corresponding leading domestic companies. Source: (Lewis & Wiser, 2007).

In 2004 the top 5 countries with regard to installed wind capacity (Germany, Spain, United States, Denmark and India) are also home to nine of the top ten global leading wind turbine manufacturing companies. Vice versa, a large wind potential and installed capacity does not implicate a large domestic wind manufacturer. A country might have purchased the wind turbines abroad or the previously present manufacturer has ceased to exist. In terms of installed wind energy capacity (2004), Italy and the Netherlands rank 6 and 7 respectively, however do not have any leading wind companies.

In Figure 10, the relation between 'the percent of the homeland capacity installed by a domestic company' and 'the global capacity installed by domestic wind company' is visualised for up to 2004. This shows that the possibility for a domestic company to grow on the home market is not linked to the size of this market, but the percentage exploited. Denmark has a relative small domestic potential, however this modest space has been fully exploited almost exclusively by Danish companies in the early years of development (99% in 2004).

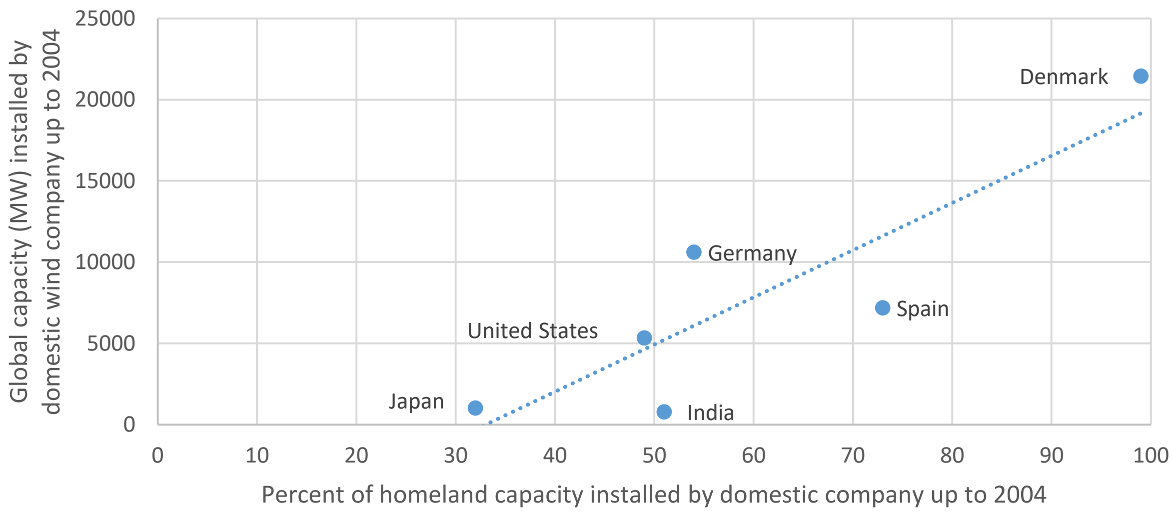


Figure 10. Scatter plot of "Percent of homeland installed capacity installed by domestic company up to 2004" vs. Global capacity installed by domestic wind company up to 2004. Source: this work, based on data from Lewis & Wiser (2007).

4.1.4 Take-off and acceleration (2007 – present day)

Several events demonstrated the take-off of the wind energy sector in 2007, including a gradual growth in cumulative installed capacity and the first offshore wind parks (see 3.1.3 for justification). Also, the effects of ongoing mergers and acquisition were exposed: at the end of 2013 the top 10 wind turbine manufacturers had an 69,5% global market share (Kumar et al., 2016).

"The start of offshore wind had become clear" (van Kuik, personal communication, July 5, 2017). In Denmark, in the run-up for this period, the first offshore wind parks appeared, starting with Middelgrunden, 40 MW, (2000), Horns Rev 1, 160 MW (2002) and Rødsand 1, 166 MW (2003). Following the lead of Danish offshore wind parks, several other countries in Europe initiated offshore wind targets, starting the rapid exploitation of the North Sea. Compared to onshore wind, offshore wind has various benefits as well as disadvantages. The benefits include:

- Good wind resources available on oceans: offshore wind sites contain higher wind speeds as well as a more uniform profile (Kumar et al., 2016)
- Offshore wind parks and turbines tend to be bigger due to less spatial restrictions (Kumar et al., 2016).
- Less social resistance simply because it is less visible (van Kuik, personal communication, July 5, 2017).

A disadvantage of offshore wind is the higher cost of installation, power transmission and maintenance due to the offshore environment (Kumar et al., 2016).

4.1.4.1 Technology

The technology of on- and offshore wind turbines is very similar, apart from the structural foundation (Kumar et al., 2016). Various structures for fixating the wind turbine to the sea bed exist, however due to depth-restrictions research is currently focusing on creating floating structures. A main aspect of technological innovation in this period continued inside the turbine: the battle between direct-drive and gearbox technology (F2). Up to ± 2010, a gearbox was used in almost all wind turbine models. Much research has been put into direct-drive technology: a generator with a permanent magnet that operates directly on the rotor speed, therefore no gearbox is needed. The benefits of using direct-drive is two-fold (Morris, 2011): First of all, the gearbox is a high-maintenance part and therefore effects the reliability and the capacity factor of the turbine. Secondly, without the gearbox the turbine head would be lighter, resulting in installation cost reduction. Up to ± 2010, direct-drive technology was not financially competitive with gearbox technology. However, since the costs of the permanent magnets have declined and advancements have been made in the generator, direct-drive technology is growing in market share and may take the lead. According to van Kuik (personal communication, July 5, 2017), however, it is possible that, in this case, both technologies will be used in the future.

4.1.4.2 Policy and market formation

Market formation in this phase is largely dependent on a country's stimulation policy. In the beginning of this phase, the United Kingdom created some tenders for wind offshore, afterwards Germany was leading and now the Netherlands is leading with regard to offshore wind installation (van Kuik, personal communication, July 5, 2017)(F5+). The Dutch research consortia of research institutes, universities and companies have been growing gradually since the 1980s. While the first consortium started with a budget of 3 million Dutch guilder (or €1,36 million), the budget for the latest consortium consists of €60 million (van Kuik, personal communication, July 5, 2017)(F2+)(F3+).

4.1.4.3 People's Republic of China

Up to 2009 the PR China has been in the background, however, from 2009 up to 2016 the country has been leading in terms of annual installed capacity and consequently in terms of total installed capacity (Figure 11). At the end of 2016, PR China had an installed capacity of 168.732 MW, representing 34,7% of the global installed capacity (Global Wind Energy Council, 2017).

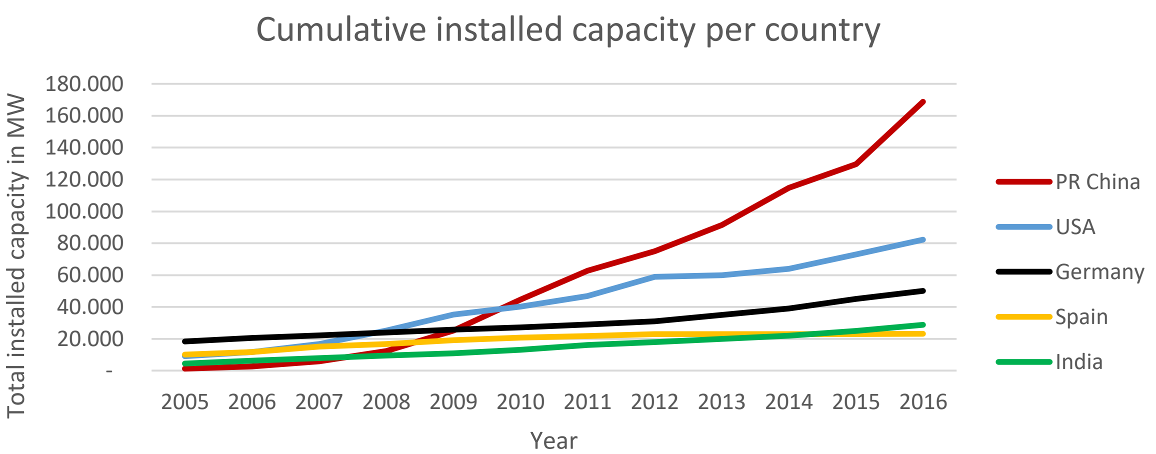


Figure 11. Cumulative capacity of top 5 countries with regard to installed capacity. Source: this work, based on data from (IEA, 2017) for the years 2005-2015 and GWEC (2016) for 2016 (visualises data of December 2016).

A Princeton University study has shown the following reasons for the Chinese wind industry to catch up (Lefevre-Marton, 2013):

- Chinese firms have progressively introduced turbine technology (F2+) and have increased their capabilities promptly (F1+), comparable to global leading companies. Technology transfer has taken place in the form of licensing, joint developments, acquisitions and technical assistance contracts with either a European or a United States based company (F2+)(F3+). For example, Goldwind, currently global market leader, has purchased direct-drive technology from a German company in 2008.
- The Chinese government has introduced policies (F6+)(F7+) stimulating rapid growth of the Chinese market (F5+) along with measures to ensure Chinese firms dominated this domestic market. Consequently, the resulting competition (F4+) between the domestic Chinese companies was the main driver for technology developments (F2+). Currently, the first 11 largest manufacturers in the Chinese market are domestic companies. The first non-domestic manufacturer in PR China is Vestas with a 2,2% market share (Global Wind Energy Council, 2017).
- A relatively limited governmental support for the wind energy industry in both Europe and the United States before the 2000s have caused a relative slow growth of the industry (F4-)(F7-), creating the possibility for the Chinese firms to catch-up.

4.1.5 Lessons learned from the evolution of wind energy

The following lessons learned (1-9) are taken from the development phase 1 (4.1.2) and development phase 2 (4.2.3) and form the answer to the sub-question: “What have been successful actions in the evolution of on- and offshore wind industry?”

Entrepreneurial activities

No specific lesson for this function has been found. A universal TIS lesson that is confirmed by the wind energy casus, however, is the following: entrepreneurial activities form the core an innovation system and are hampered when the other functions are not performing well.

Knowledge development

(1) In the Netherlands, consortia were formed between the research institutes, universities and businesses, sparking knowledge development. Because of this technology-push initiated by the government, the Netherlands is currently one of the leading countries with regard to R&D in wind energy.

Knowledge diffusion

(2) Competition is natural in a free market, creating a stimulus for technology developers not to show all business activity. It has been shown, however, that a lack of communication between wind turbine developers has inhibited the overall development in the Netherlands with respect to the development in Denmark and Germany.

Guidance of the search

(3) When upscaling a wind turbine gradually instead of in one go, the chance of eventually succeeding has shown to be higher. All current globally leading wind turbine manufacturers have started as small entrepreneurs, making small steps during upscaling. MW-size turbines that have been built from scratch did not make it.

Market formation

(4) All current globally leading wind turbine manufacturers have emerged from countries with an exploited domestic wind capacity. Vice versa, countries who have exploited their domestic wind

resources have produced most of the world's leading manufacturers. It has been shown that the exploitation of a home market, even though relatively small (Denmark), has been essential in the succeeding of all currently thriving wind energy industries.

(5) The aloof attitude of the Dutch government resulted in permit and bureaucratic issues from local authorities and therefore a siting problem. This siting problem turned out an important restraint on the testing and demonstration of wind turbines in the Netherlands. In Germany, demonstration and testing was facilitated properly and, additionally, included selection measures favouring German entrepreneurs.

(6) The Dutch subsidy program stimulated the development of relatively large wind turbines, which turned out to be unfit for the first German markets. During the same time, Danish turbine manufacturers exported to Germany and Sweden.

Resources mobilisation

(8) Financial resources are a necessity, however, it has been found that the availability of relatively more financial resources did not directly result in the success of some countries over others.

Creation of legitimacy

(9) Public opinion and social impact has an influence on the (dominant) design. In wind turbines, two-bladed turbines were abandoned due to the noise level and the fact that three-bladed turbines were visually calmer.

4.2 Tidal energy Europe

In this chapter, the status-quo of tidal energy developments in Europe is given and elaborated per TIS function.

4.2.1 Function 1: Entrepreneurial activities

There are many actors that have invested in the technology over the past 10 years (Participant A, personal communication, 6 Oct 2017). In Table 4 and Table 5, a summary of the status of demonstration and commercial projects in Europe is visualised.

Country	Number of projects	Cumulative capacity in MW (installed + planned)
United Kingdom	12	21,7
France	4	21,6
The Netherlands	3	1,7

Table 4. Overview of European projects and total capacity in 2017. Source: this work based on JRC (2016).

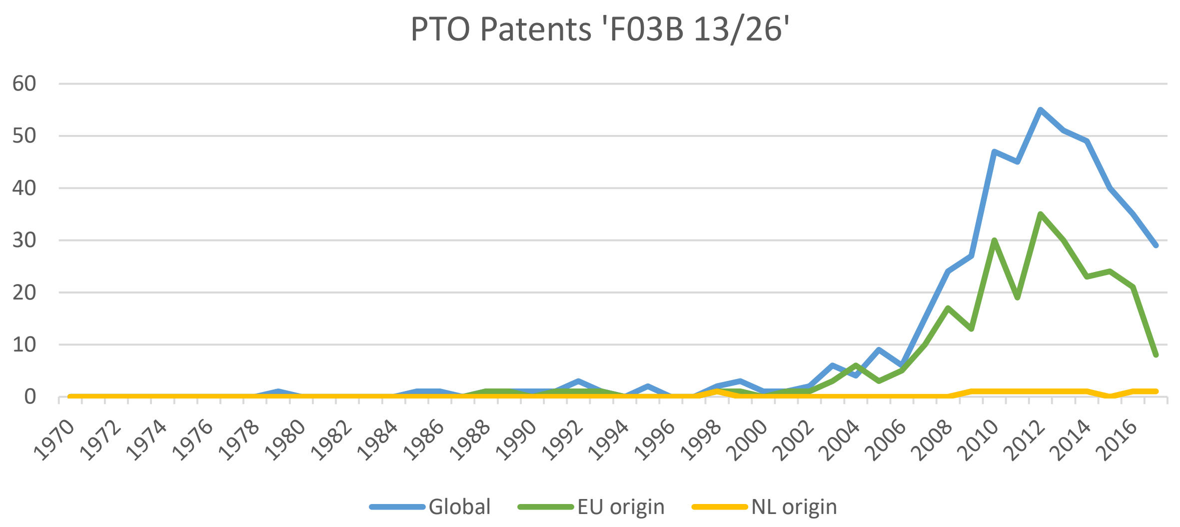
Five largest projects by capacity	Country	Capacity in MW	Status in 2017
Normandie Hydro	France	14	Planning for full commissioning in 2018
Sound of Islay	United Kingdom	10	Planning for full commissioning in 2018/2019
Holyhead Deep	United Kingdom	10	0,5 MW to be installed in 2018
Meygen phase 1B	United Kingdom	8	Construction and full commissioning in 2018
Meygen phase 1A	United Kingdom	6	In operation since 2016

Table 5. Overview of European projects and status in 2017. Source: this work based on JRC (2016).

From a total of 21 demonstration and commercial projects worldwide, 19 of these projects are within the Europe, the remaining two are in Canada and China (JRC, 2016). This indicates the prominent role of Europe within the global tidal energy developments (JRC, 2016). Up to 2010, the industry consisted of small entrepreneurs, however after this period, large engineering companies have started developing tidal turbines (ABB, Alstom, Andritz Hydro, DCNS, Hyundai Heavy Industries, Kawasaki Heavy Industries, Siemens, and Voith Hydro)(IRENA, 2014).

4.2.2 Function 2: Knowledge development

As an indicator for knowledge development, a PCT patent analysis has been performed (Figure 12). PCT patents are a special kind of patent that can be applied for within any PCT signatory nation and are a useful indicator for global trends (McDowall, Ekins, Radošević, & Zhang, 2013). F03B 13/26 is the patent classification for 'mechanical engineering […], machines or engines for liquids […], power stations or aggregates […], characterised by using tide energy'. Clearly visible is the rise in patents since ±2002 in Europe as well as worldwide. Up to 2016, 55% of all patents originate from an author within the EU. This shows that the major share of knowledge development has taken place in the Europe in the last 10 years. Noteworthy is the pinnacle in 2012 and global decline afterwards. This trend is for a large share accountable to the European decline and is potentially explained by a varying level of EU support. The graph shows substantial technical knowledge development, however knowledge development regarding environmental impacts is a different topic. In 2009, Inger et al., determined that the knowledge base regarding the effects on the environment of marine energy devices is limited, followed by an urgent call for research. Frid et al. (2012) state there is a growing body of knowledge regarding environmental impacts of offshore wind farms, but also that a knowledge base for marine energy devices is lacking. Recently, however, a long term study consisting of 18.000 hours observation



concluded there is no correlation between species density and location of the offshore tidal energy test site Fall of Warness in the UK (Long, 2017).

Figure 12. PCT Patents concerning F03B 13/26. Source: this work on the basis of the WIPO database.

4.2.3 Function 3: Knowledge diffusion

On European level, there are several networks active: FORESEA and MARINET2 being the main testing projects. In FORESEA, finance from the EU is provided to test facilities and with these finances the turbines of the entrepreneurs can be tested. According to Participant A (Personal communication, 6 Oct 2017) knowledge diffusion is considered sufficient in the tidal energy innovation system.

4.2.4 Function 4: Guidance of the search

In 2014, 76% of R&D efforts in the sector were focussed towards the development of a horizontal axis turbine, showing a convergence in dominant design (JRC, 2016). Because many tidal energy devices are in a prototype and demonstration phase, learning currently occurs by testing in actual conditions. The guidance of the search is currently done by the market and the finance (Participant A, personal communication, 6 Oct 2017). Given this market, the number of current projects is enough to have a healthy competition where different concepts are still progressing (Participant A, personal communication, 6 Oct 2017).

4.2.5 Function 5: Market formation

The development of a market in Europe is currently obstructed by two things: access to finance and 'red tape' (Participant A, personal communication, 6 Oct 2017), the latter being excessive and redundant bureaucracy and formalities that hinder action and decision-making. With regard to finance, an investment fund and an insurance and guarantee fund is necessary (Ocean Energy Forum, 2016). The value of a guarantee fund is illustrated by the financial construction of the Tidal Bridge consortium: A guarantee by the Indonesian government was provided, resulting in an interest rate of only 1% for a commercial loan of €200 million (Participant A, personal communication, 6 Oct 2017). This guarantee makes it easier to get finance and similar constructions are necessary (Participant A, personal communication, 6 Oct 2017).

4.2.6 Function 6: Resources availability

There is sufficient human expertise for the developments. The current tidal energy developments can benefit from the oil and gas sector, the wind energy sector and the overall offshore sector (Participant A, personal communication, 6 Oct 2017). In time, human resources might become a problem, but currently it is not a bottleneck (Participant A, personal communication, 6 Oct 2017). Access to finance is one of the two major barriers hampering developments (Participant A, personal communication, 6 Oct 2017). Investments in tidal energy is venture capital and, therefore, a high premium is included with commercial loans, driving up the already relatively high costs.

4.2.7 Function 7: Creation of legitimacy

Throughout Europe, there is a lack of understanding by the authorities because the technology is new (Participant A, personal communication, 6 Oct 2017), a problem also visible with other renewables. This creates a high and redundant administrative burden with regard to permits and finances. The gravity of this problem differs per country: In Scotland there is a government body called Marine Scotland managing every permit, whereas in France for every permit there is a different institution (Participant A, personal communication, 6 Oct 2017).

4.2.8 Barriers hampering developments in European tidal energy sector

The main two barriers hampering the development in the European tidal energy sector are access to finance and red tape (excessive and redundant bureaucracy)(Participant A, personal communication, 6 Oct 2017).

4.3 Tidal energy the Netherlands

4.3.1 Structural analysis

In every innovation system, there are four types of components: actors, networks, institutions and infrastructure (Luo et al., 2012). A full overview of the structural analysis can be found in Appendix B. In this chapter, prominent features of the structural analysis are elaborated.

4.3.1.1 Actors

In Table 6, an overview of the industry concerning tidal energy in the Netherlands is presented. The core is formed by 8 major technology developers.

Industry	Type	
Tocardo International B.V.	Technology developer	Two-bladed horizontal axis tidal stream turbine. Inshore application as well as floating offshore. Developing the Universal Floating System (UFS).Part of Tidal Bridge consortium and BlueTEC consortium.
Ronamic B.V.	Technology developer	Tidal range turbine
FishFlow Innovations B.V.	Technology developer	Horizontal axis tidal stream turbine. Part of the Tidal Bridge consortium.
Pentair Fairbanks Nijhuis	Technology developer	Tidal range turbine + three-bladed horizontal axis tidal stream turbine.
Tidalys	Technology developer	Bankruptcy. Horizontal axis tidal stream turbine. Developing platforms, Electrimar1800 en Electrimar4200.
Deepwater Energy B.V. / Oryon Watermill	Technology developer	Vertical axis turbine.
Water2Energy	Technology developer	Vertical axis tidal stream turbine.
SeaQurrent	Technology developer	Tidal kite. Part of ForeSea project. Testing at Marin.
IHC	Technology developer	Not active. Wave roter, vertical axis turbine.
Landustrie	Technology developer	Low-head tidal turbine
Strukton	Offshore contractor	Part of Tidal Bridge consortium
Bluewater (Energy Services)	Offshore contractor	Part of BLUEtec consortium
Huisman Equipment	Offshore contractor	Partly funded the Oosterschelde project. Constructed the structural array for Oosterschelde project.
Damen Shipyards	Ship construction	Part of BlueTEC constortium. Construction of BlueTEC platform.
Antea	Consultancy and guidance for project developers and technology developers	Project developer Testing at Kornwerderzand in close collaboration with Tocardo. Projectleader FORESE. Part of TTC-GD, Tidal Bridge, Dynamic Tidal Power (DTP) in POWER consortium
BT Projects	Project developer	Tidal Technology Center Grevelingendam (TTC-GD). Hydro electric powerplant Doesburg. Brouwersdam.
Dutch Expansion Capital	Investor	Part of 'Tidal bridge' consortium. Investor in Tidalys.
MET-Support		Creates technical standardization for tidal energy in co-operation with NEN: MET-CERTIFIED.
Nextco	Consultancy	
PwC	Consultancy	Part of Energiedijken consortium.

Table 6. Structural analysis of the actors within the Dutch tidal energy sector. Source: elaboration on DMEC and Hoefnagels (2015).

4.3.1.2 Institutions

In a structural analysis in the functions approach, soft institutions include habits, routines and shared concepts used in repetitive situations (Luo et al., 2012),. Hard institutions include rules, norms and strategies. A well-functioning innovation system includes supportive institutions that have the ability to function well (Luo et al., 2012).

Name	Type	Note
Energieakkoord	Agreement	14% share renewable energy production by 2020, 16% in 2023.
SDE+ Water	Regulation	Feed-in tariff Energie uit Water: 0,13 €/kWh
Besluit Rijkswaterstaat Vismortaliteit	Regulation	Fish mortality from new projects concerning 'energy from water' should have a 'nihil' impact (0,1% mortality of all passages)

Table 7. Institutions in the Dutch tidal energy sector. Source: this work.

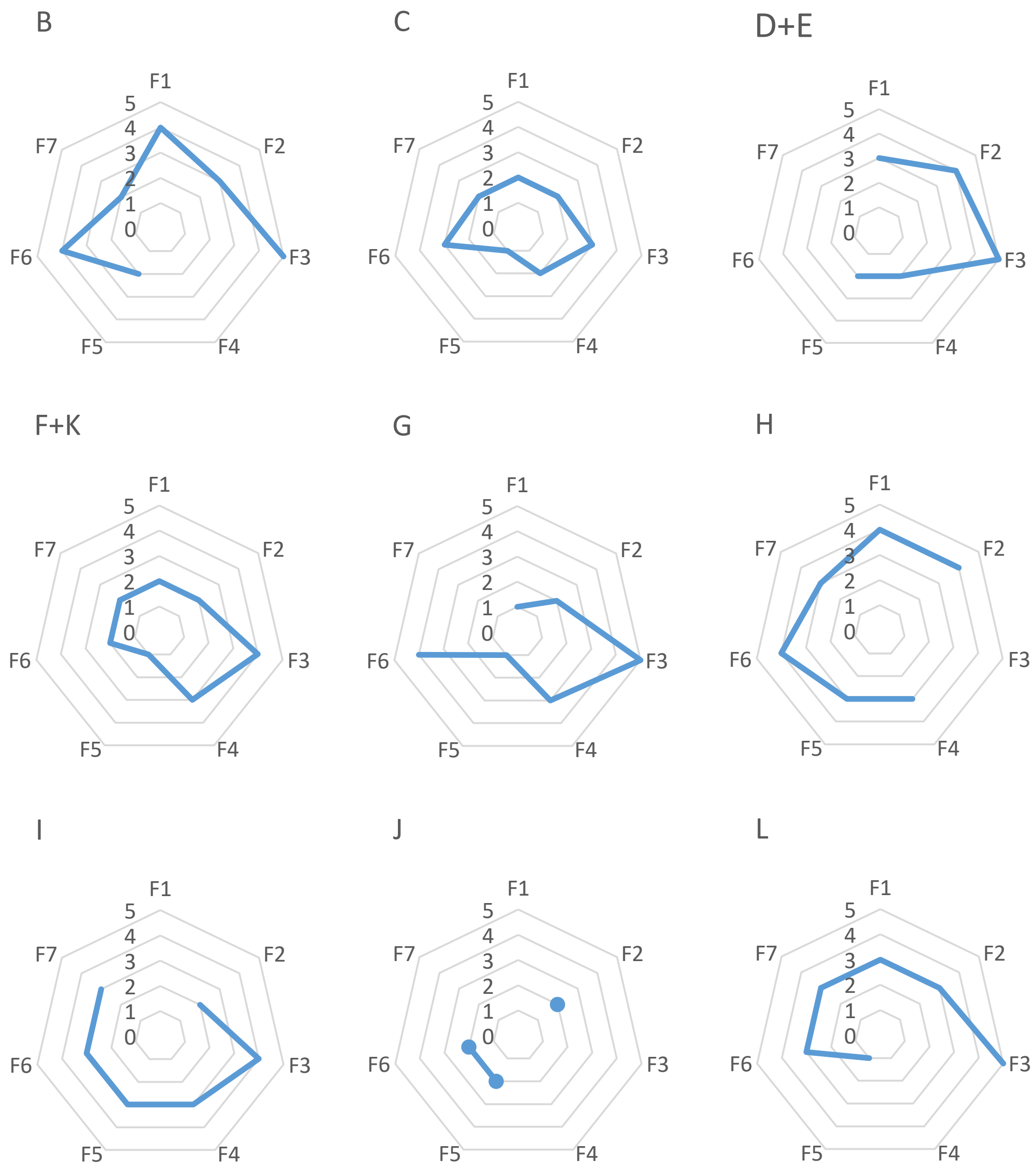
The Stimuleringsregeling Duurzame Energie+ (SDE+) is a regulation for the distribution of available finances provided by the Dutch government for the implementation of sustainable energy technologies. The grant of the SDE+ is based on a first come, first serve principle or cost-effective ranking. This means a grant application can be submitted on a specific amount (e.g. 10 ct/kWh), however, companies that have submitted an application for 9 ct/kWh or lower will be served first. In the current SDE+ regulation, there is no distinction made between energy technologies, meaning tidal energy has to compete with other sustainable energies like solar PV or offshore wind.

4.3.2 The phase of development

For tidal stream, there are several working prototypes worldwide, however with no commercial application (i.e. in operation without subsidy). According to the indicators proposed by (Hekkert et al., 2011b), this qualifies as the phase 'development': efforts are focussed towards a commercial application and market formation. Also, experimentation with regard to the design is still visible: a dominant design is not yet present. These TIS characteristics correspond with the characteristics of the characteristics found in wind energy development phase 1, during 1973-1989. Therefore, it is estimated that the development of tidal energy is ± three decades behind of wind energy.

4.3.3 System functions analysis and structural causes

The individual spider graphs, as a result of the interviews, are presented in Figure 13. An incomplete figure means an interviewee expertise on the specific function was questionable and therefore not taken into account.

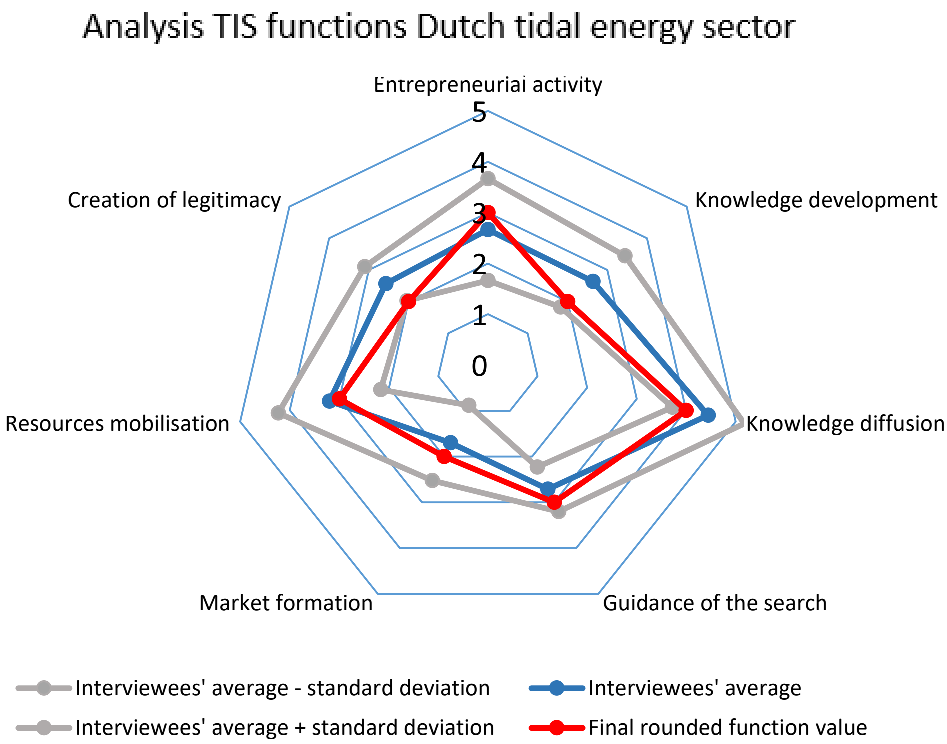


Grade	Function performance
1	Absent
2	Weak
3	Moderate
4	Strong
5	Excellent

F1: Entrepreneurial activities
F2: Knowledge development
F3: Knowledge diffusion
F4: Guidance of the search
F5: Market development
F6: Resources mobilisation
F7: Creation of legitimacy

Figure 13. The TIS graphs of institutes and organisations interviewed for this study. Participant A is a non- Dutch professional on European level and therefore not taken into account in this chapter.

In Figure 14, the combined TIS graph is visualised. In blue, the interviewee's average is visible and in grey, the dispersion of the standard deviation. The final rounded function values are visible in red and are elaborated further in this chapter.



Grade	Function performance
1	Absent
2	Weak
3	Moderate
4	Strong
5	Excellent

Figure 14. Analysis TIS functions of the Dutch tidal energy sector. Source: this work on the basis of interview evaluations.

4.3.3.1 Function 1: Entrepreneurial activities

In the Dutch tidal energy sector, 8 technology developers are currently active (see Table 6) working on various concepts, i.e. horizontal-axis, vertical-axis and low-head tidal range. Adjacent to this core of entrepreneurs are knowledge institutes, network organisations and an engineering-consultancy company. The participants rate the entrepreneurial activities on average 2.7, with a large dispersion. Participants valuating the entrepreneurial activities high, advocate there are sufficient entrepreneurs and the right type. Participants depicting a lower grade advocate the following: there are sufficient technology developers, i.e. turbine inventors and manufacturers, however the following actor is missing: an incumbent project developer or (offshore) contractor on an industrial level, which has the experience and financial capability to commence project developments. As Participant G stated:

> *"Currently there is no project developer that will initiate tidal energy as a power plant. When there are plans for a coal power plant, several project developers will rise. In wind energy this trend is coming, but for tidal energy this will not happen. It also makes sense, because the natural resource is limited"* - (personal communication, 23 Aug 2017).

Strukton, Huisman and Bluewater are large companies that have shown interest in tidal energy, however the latter two have currently halted their efforts in tidal energy and Strukton is mainly active in the Tidal Bridge consortium. As Participant F clarified:

> *"In these large construction and offshore companies, the subject of tidal energy is very small."* - (personal communication, 5 okt 2017).

Given the amount, the variety and performance of the entrepreneurs, 'entrepreneurial activity' is valued 3 out of 5.

4.3.3.2 Function 2: Knowledge development

Knowledge development in the Dutch tidal energy sector occurs mainly at the technology developer level with additionally limited research at knowledge institutes and universities. Participants averagely rate knowledge development 2.6, with three messages coming forth the interviews:

- Research on tidal energy is limited at research institutes and universities (Participant B, personal communication, 14 Aug 2017). Two PhD researchers concerning tidal energy are currently active in the Netherlands.
- There is a gap between the knowledge development at research institutes and knowledge demand at the technology developers. For example, Deltares is active in the hydrodynamic modelling of near- and far-field effects of tidal turbines in estuaries, however turbine developers encounter a practical technology problem in their turbine (Participant K, personal communication, 5 Oct 2017).
- Research concerning the environmental impacts are insufficient (Participant B, personal communication, 14 Aug 2017).

One idea to increase knowledge development is proposed by Participant J:

> "*In other parts of the offshore industry, knowledge consortia are formed between several organisations, businesses, knowledge institutes, government, and a shared research topic is investigated by which all parties benefit.*" - (personal communication, 22 Aug 2017)

Currently, there are no such knowledge consortia for knowledge development in tidal energy, however this construction could be valuable to address the gap of knowledge with regard to impact on the environment.

In Figure 12 (p 31.), the PCT patents of the world, the EU and the Netherlands are visualised. Five PCT patents originate from the Netherlands, which constitutes 4% of European PCT patents and 2% of global PCT patents. This is a relatively small amount despite the Netherlands being a small country. These insights combined, knowledge development is rated 2 out of 5.

4.3.3.3 Function 3: Knowledge diffusion

As visible in the structural analysis (Appendix B), there are various networks in the Dutch tidal energy sector, facilitating knowledge diffusion. Consequently, all participants value knowledge diffusion neutral to very strong, with a mean of 4.4. Critique however, is given on the quality of the network:

> *"The number of networks is not limiting, however it is questionable whether the network learns from the mistakes that are made. I doubt whether the network uses the full potential to progress, for example to involve Rijkswaterstaat. The fact that Rijkswaterstaat is not in the network might be a problem." – (*Participant F*, personal communication, 5 Okt 2017)*

Given these insights, knowledge diffusion is rated 4 out of 5.

4.3.3.4 Function 4: Guidance of the search

In the Dutch tidal energy sector, various concepts of tidal turbine are in development – an indicator of experimentation, *i.e.*: 2 horizontal axis tidal stream concepts, 2 vertical axis tidal range concepts, 3 Archimedes screw concepts (2 stream and 1 range), a vertical axis tidal stream concept and a tidal kite. Even though these concepts vary greatly in TRL level, a clear divergence of experimentation is not yet visible, an evident difference with regard to the European sector. It should be noted, however, that the physical landscape of possible tidal energy locations varies up to such a level that the emergence of a dominant design in tidal energy is not eminent.

> *"Different physical properties, i.e. free stream, low-head water pressure, high-head water pressure vary so that it might not be considered one discipline and therefore multiple solutions are possible. This is a great difference with regard to the development of wind energy and might be the reason for the fact that knowledge institutes are not clearly adhering to one concept."*- (Participant K, personal communication, 5 Oct 2017).

There are coaching projects for small entrepreneurs, however, larger companies do not perceive an active guidance from anywhere but their own company (Participant H, personal communication, 28 Aug 2017). With regard to guidance from the government, an important role is considered for the RVO, but is deemed insufficient:

> *Not enough encouraging projects are supported by the government with adequate resources. A part of the reason is the current mechanism of competitive tenders, by which emerging technologies have to compete for financial support."*- (Participant L, personal communication, 4 Oct 2017).

Participants value guidance of the search neutral or bad with an arithmetic mean of 2.7. Due to the insufficient guidance from the Dutch government and the non-perceived guidance at larger companies, guidance of the search is valued 3 out of 5.

4.3.3.5 Function 5: Market formation

The possibility of implementing a tidal energy power plant is depending on the physical resource. These conditions can be found on, in general, 2 locations: Firstly, tidal energy turbines can be applied inshore at estuaries and sea mouths, either obstructed or not (*e.g*. Oosterschelde, the Netherlands). Secondly, offshore application is possible at sites with tidal and ocean currents (e.g. Bay of Fundy, Canada, and Pentland Firth, Scotland, respectively). The market formation is, therefore, limited to these categories worldwide.

The Netherlands

In the Netherlands, the potential locations for tidal energy are limited to water safety infrastructure like storm surge barriers and dikes and one offshore location at Marsdiep. These exploitation of these locations is deemed necessary for demonstration and testing of tidal turbines, showing feasibility of the technology and a potential decrease in LCOE (Participant F, personal communication, 5 Oct 2017, Participant H, personal communication, 28 Aug 2017). A project called Energising Delta's (2013 – 2015) was aimed at creating knowledge on the combination of water safety infrastructure, water management and sustainable energy generation. The companies Tocardo, REDstack and Strukton have collaborated with Deltares, ECN and Erasmus University Rotterdam in order to create knowledge concerning the tidal energy implementation in existing dikes. Currently, the Afsluitdijk and Oosterscheldekering are currently used as demonstration and testing of tidal turbines. Also, a demonstration facility for tidal turbines at the Grevelingendam is planned for construction in 2018. Apart from demonstration, the aim of these facilities is to create knowledge development concerning the energy production while minimising environmental impact. At the Oosterscheldekering, for example, a PhD research is taking place, investigating the hydrodynamic impacts of the turbines on the transport of sediment in the Oosterschelde.

The realisation of Dutch projects is generally considered difficult among participants, due to 2 main obstacles: permit procedures and financial complications. Firstly, permits are often refused due to a gap of knowledge with regard to the fish mortality of the turbines (elaborated in 4.2.3.7: Creation of legitimacy). Secondly, it is complicated to develop a favourable business case, which is currently always depending on a subsidy and the feed-in tariff set by the SDE+ (Participant K, personal communication, 5 Oct 2017). Subsidy generally comes from the provincial governments or a European regional development fund (INTERREG). The feed-in tariff for tidal energy is currently set at 13ct per kWh, an incentive deemed insufficient by some participants (Participant H, personal communication, 28 Oct 2017, Participant L, personal communication, 4 Oct 2017), given the early status of development of tidal energy.

Export potential

While in the Netherlands the exploitable resource is limited, the potential abroad is significantly higher as shown in chapter 2.1.2. A second limiting factor for the Netherlands is that the country lies a delta at the end of some of Europe's main rivers and, therefore, tidal energy locations are inherently obstructing passages of migratory fish. Internationally, the possible locations for implementation are more diverse and especially offshore applications do not imply a direct obstruction of migratory species. Any current international projects are either initiated by the Dutch technology developer or organised via a European funded demonstration project. It should be noted that only the larger technology developers have potential activities or connections with the international markets. A notable project is the Dutch Tidal Bridge consortium, which strives towards building a floating bridge spanning the Larantuka Strait, Indonesia, with tidal turbines installed underneath. While improving the connection between the islands in the developing region of Eastern Indonesia, the bridge will have 18 to 23 MW installed capacity. A feasibility study is currently executed and the project achieved the status of National Strategic Project in Indonesia. This project is an example of how sustainable development and water management of delta's can be combined in order to create a solution.

Overall, the function of market formation is valued on average 1.7 out of 5 by the participants. Given the hampered demonstration projects and the insufficient connectivity with the international markets, market formation is valued 2 in this study.

4.3.3.6 Function 6: Resources availability

Resources availability constitutes of 2 entities (financial resources and human resources) and is valued on average 3.2 by the participants. Due to a difference between the two topics, they are elaborated individually.

Financial resources are valued 2.7 out of 5 by the participants. A division is visible between the technology developers who rate the financial resources neutral (3) and engineering and consultancy professionals value financial resources 1 or 2. This corresponds with the conclusion of Participant G:

> *"Technology developers receive sufficient financial resources, however financial issues arise during initiation of a tidal energy power plant. "*

For technology developers, there are various R&D subsidies available. For the implementation of a tidal energy (demonstration) power plant, firstly a more substantial amount is necessary and secondly, the R&D subsidies are not intended and accessible for these projects. The financial construction of a tidal energy (demonstration) plant usually consists of a subsidy (by the state, provincial government or a fund) in combination with a commercial loan and the feed-in tariff. The grant of the subsidy is often doubtful (Participant K, personal communication, 5 Oct 2017) and dependent on the permit, creating a process which takes years before final decisions are made, possibly resulting in failure. A difficulty during project developments (Participant H, personal communication, 28 Aug 2017) is the high 'cost of capital': the commercial loan provided by banks includes a high premium, because it is considered venture capital. Project developers are searching for methods to avoid this high cost of capital and a recent progress is found in the financial construction of the previously mentioned Tidal Bridge consortium. Due to the difficulties in obtaining finances for demonstration or commercial projects, financial resources are rated 2 out of 5.

The availability of human resources is generally considered well and the participants rate this function on average 4.1. Technology developers have no problem in finding skilled employees (Participant G, personal communication, 23 Aug 2017; Participant H, personal communication, 28 Aug 2017).

> *"There are sufficient students interested in tidal energy and additionally, young researchers dedicated to perform a PhD research on the topic (*Participant L*, personal communication, 4 Oct 2017).*

At the TU Delft, the Ocean Energy Platform is being developed, a network connecting academics occupied or interested in marine energy technologies. In November 2017, a new lectureship concerning 'Delta Power' is initiated at the Hogeschool Zeeland. Lastly, a Water Technology Excellence Centre has been announced as a collaboration between the province of Zeeland and Friesland (Participant L, personal communication, 4 Oct 2017). The expertise currently needed for offshore testing and demonstration (shipping, load handling, special port characteristics) is especially present in the Netherlands (Participant A, personal communication, 6 Oct 2017). Comprising these developments and the participant's ratings, human resources are valued 5 out of 5.

Overall, given the described problems in gathering financial resources, the overall function of resources availability is valued 3 out of 5.

4.3.3.7 Function 7: Creation of legitimacy

Tidal energy, due to being under water, has the benefit of having a smaller visual impact than wind energy. Resistance from the general public is considered lower than wind energy (Participant F, personal communication, 5 Oct 2017; Participant H, personal communication, 28 Aug 2017). Resistance, however, is present from specific groups focussing on impact on the environment. Concerns generally include: habitat loss, collision risks, noise and electromagnetic fields (Inger et al., 2009) and in the Netherlands the public attention is focussed on fish mortality. A knowledge gap exists on the effects of fish and mammals manoeuvring themselves through the turbine slot, creating resistance manifested in the government, NGO's and a nature conservation group. Whether the resistance is justified or not, can be made clear by an increased research on the fish friendliness. Currently, some larger companies are active in research regarding fish friendliness of their turbine. There is an international database concerning environmental impacts of marine energy technologies (Tethys), however it is disputable if this is known throughout the Dutch tidal energy sector and to what extent it is useful, since every tidal turbine is different hence having a different effect on the environment.

Fish mortality

The issue surrounding fish mortality in the Netherlands started several decades ago. It will be elaborated briefly, since it shows the challenges that arise regarding the delicate balance between water management and sustainable energy. Between 1988 – 2000, five large hydroelectric power plants were constructed at weirs in the Netherlands of which most in the Maas and the Nederrijn/Lek with a total capacity of 37,75 MW (T. Vriese, 2015). An obligation for implementation of a fish guidance system was present (e.g. fish ladder), however they were never implemented due to inefficiency of costs. The first research on fish mortality was performed at Linne, showing an average of 13% directly mortal passages. Indirectly, 40% of passages was estimated lethal (T. Vriese, 2015). Over the years, other studies exposed fish mortality with the most important causes being: barotrauma (rapid change in pressure), collision and shear (turbulence).

Around this time, due to several reasons, the eel population is strongly decreased and the salmon population is almost diminished. Both species are migratory and use the Netherlands as gate to the North Sea, inherently going through the hydropower stations in the Dutch rivers. The Dutch government initiated plans to strengthen the eel and salmon population in the Netherlands, including regulations on mortality by hydropower stations. Research was commenced and focused on an acceptable rate of mortality at hydropower stations. The mortality a population can take in general, is dependent on the species' condition, the migration behavior and the type of life cycle a species has. A population will grow until the maximum carrying capacity of a habitat is reached. A comparison can be made with fisheries and the so-called maximum sustainable yield, i.e. the annual maximum yield in order for the population to still be healthy. In the hydropower case, preferably the yield is 0%, however this is unrealistic. In general, it is found that the growth rate of a population is a logistic curve, with the maximum being the carrying capacity of a certain habitat. It is found that the maximum sustainable yield (MSY)(Gulland, 1971)is:

$$MSY = 0{,}5 * M * Bv$$

M = natural mortality
Bv = virgin stock biomass

Therefore, the highest growth rate of a species is found when the population is exactly half of the population at carrying capacity (Gulland, 1971). The part between half of the carrying capacity and the maximum population is called 'optimum sustainable population size', which is a healthy phase in which fluctuations of the populations are captured by the resilience, with no chance of extinction (F. T. Vriese, 2011). It must be said, however, firstly, this formula is basic and adaptions are made depending on population parameters and secondly, both eel and salmon population in the Netherlands are currently not at carrying capacity and it is unclear in what exact condition these populations are currently in.

A decree is active, stating that 10% cumulative population mortality by hydropower stations is accepted, however there is no scientific substantiation for this limit (van der Sar et al., 2001). This leeway, is intended for all methods of hydropower in the Netherlands, be it for energy production or testing practices (e.g. tidal turbines). Currently, however, this leeway (10%) is already exceeded by the five large hydropower stations mentioned before and therefore, new proposals for hydropower (including tidal energy) are only permitted when fish mortality is considered "nihil" or 0,1%. Permits for tidal energy demonstration projects are only granted when it is proven that the 0,1% limit is not exceeded, resulting currently often in a permit refusal. A catch-22 situation arises, since turbine manufacturers are not able to prove the fish friendliness of their turbines without testing.

The participants all acknowledge this knowledge gap and the subsequent resistance, valuating the function creation of legitimacy weak or neutral with an arithmetic mean of 2.6. Due to the obstructions in testing and demonstration, creation of legitimacy is valued at 2 out of 5.

4.4 Synthesis of results

In Table 8, a summary of the all results is presented and, for comparison, categorised in TIS functions, forming the answer to the last research question: 'How does the Dutch tidal energy Technology Innovation System relate with the European tidal energy Technology Innovation System and the wind energy Technology Innovation System?' The barriers in the Dutch tidal energy sector TIS are presented in the third column, the European developments in the fourth and the wind energy lessons learned in the fifth column. In this chapter, the action points are formulated on the basis of a comparison.

TIS Function	Function value	Barriers in the Netherlands	European context	Wind energy lessons learned (1-9)
Entrepreneurial activity	3	Currently, there is no commercial project developer within the Dutch tidal energy sector.	In recent years, larger engineering firms have entered the sector, creating more momentum in project implementation.	
Knowledge development	2	At research institutes and universities, there is a limited amount of research concerning tidal energy.		
		There is a gap between knowledge demand at the technology developers and the knowledge development at the research institutes.	Majority of the tidal energy patents arise from within the EU, showing substantial technical knowledge development.	(1) Knowledge consortia were formed between research institutes, universities and businesses
		Knowledge development concerning impact on the environment is lacking or insufficient for satisfying needs.	Knowledge development regarding impact on the environment is insufficient.	
Knowledge diffusion	4	Sufficient networks, however it is questioned whether the network learns enough from mistakes occurring in different projects	Sufficient networks	(2) Lack of communication between Dutch wind turbine developers has inhibited overall developments
Guidance of the search	3	No divergence of experimentation is visible yet, though it is questionable whether this is needed.	Divergence of experimentation is visible, with the majority of activities focused on a horizontal axis turbine.	(3) When upscaling a wind turbine gradually instead of in one go, the chance of eventually succeeding has shown to be higher.
		Larger technology developers do not perceive any guidance from outside their own company.		
		The role of the government concerning guidance is deemed insufficient.		
Market formation	2	A commercial market is absent due to a high LCOE of tidal energy. This is common for energy technologies in development in general, nevertheless a barrier.	A commercial market is absent. Focus is on testing and demonstration.	(4) It has been shown that the exploitation of a home market has been essential in the succeeding of all currently thriving wind energy industries.
		Planned demonstration projects are obstructed by a lack of financial security and uncertainty with regard to permitting and licensing.	Lack of understanding EU wide, because the technology is new. This results in high administrative burden for permits and finance.	(5) Bureaucracy and permit issues created a siting problem of wind turbines in the Netherlands.
		The connection of entrepreneurs with international markets is moderate		(7) The Dutch wind turbine manufacturers failed to export on the first markets, while Danish turbine manufacturers exported to Germany and Sweden.
				(6) Dutch subsidy programs resulted in an oversized Dutch wind turbine, unfit for the German market.
Resources mobilisation	3	Financial constructions for demonstration plants are challenging	European associetion (OEE) advocateS for a guarantee fund, creating financial security for investors.	(8) Financial resources are a necessity, however, it has been found that the availability of relatively more financial resources did not directly result in the success of some countries over others.
		A high cost of capital is perceived with tidal energy projects.	A high cost of capital is present for EU projects.	
		The SDE+ is deemed insufficient, given the phase of development of tidal energy.	Access to finance is deemed a major problem EU wide.	
Creation of legitimacy	2	A resistance towards the technology is present due to unknown environmental impacts.		(9) Two-bladed turbines have a higher visual and audial impact and were therefore abandoned.

The color emphasises urgency based on the function value. Legend:

TIS Function value = 2
TIS Function value = 3
TIS Function value = 4

Table 8. Synthesis of results. The color indicates the urgency of a TIS function in the Dutch tidal energy sector. Source: this work.

5 Discussion

This chapter presents a reflection on this study, including the interdisciplinary approach and the TIS method. At the end of this chapter, recommendations are formed on the basis of the results found in this study.

5.1 Reflection of method and reliability of results

5.1.1 Wind energy

In this thesis, the lessons learned from wind energy, together with TIS analysis of tidal energy, were used to create action points for the Dutch tidal energy sector. A corresponding phase of development in wind energy has been determined and used as a basis for the lessons learned from wind energy. This development phase, however, occurring several decades ago, was embedded in a different social setting with different challenges. Since the 1980s and 1990s, the world has seen automation and digitalisation, creating an inherent different world. This implies that socio-economic processes that were active three decades ago might not be present today or vice versa, new processes are affecting the innovation system. The lessons learned from wind energy are therefore not all-inclusive, but that was never aimed for. The lessons that are found are, nevertheless, valuable.

5.1.2 Tidal energy Europe

In the second part of this study, European developments have been analysed. This part, even though mainly used to create a context for the Dutch tidal energy sector, was relatively short. One participant has been used as input, together with desk study and literature research. Even though this was a high-level participant, taking into account more interviewees could have increased the reliability of this part. Strengthening the validity, however, is the fact that findings in the European and the Dutch sector to agree to a certain extend.

5.1.3 Tidal energy the Netherlands

The mapping of an innovation system is performed in order to create a system that reflects the realistic situation. However, it is inherently impossible to map all entities and potentially, elements are overlooked. The limitations harming the overall reliability of this TIS case study are the following: Firstly, TIS function values are created on the basis of the authors' interpretation, in accordance with previous TIS studies (Hekkert, Heimeriks, et al., 2011; Negro et al., 2007; Otto, 2009; Wieczorek et al., 2013). Even though greatest precision has been used, this might have resulted in subjectivity. Secondly, no participant from a government body has been taken into account. Remarks concerning the government lack a counter argument and could be one-sided. Lastly, the tidal energy sector is small compared to other sectors that have been subject of a TIS study, e.g. the offshore wind energy sector (Wieczorek et al., 2013). This implies the following: the precision of the study is relatively quickly affected. An interviewee which does not agree with other interviewees has a high impact. This is beneficial when this interviewee is right, however when he is wrong this is quickly hurtful for the precision of the study. A small sector also implies the following benefit: a relatively large share of the sector has been interviewed, increasing the accuracy. These shortcomings aside, the method has been a valuable method for creating insights in the development of tidal energy in the Netherlands that would otherwise not have been exposed.

5.2 Implications of results

5.2.1 Science

In this research an interdisciplinary approach is used to perform a research from the perspective of water science and management. However, the complex and interdisciplinary problems arising today, often demand a holistic approach. In this case, the conventional water science tools and methods did not entirely suffice for answering the research question and, therefore, a side step towards innovation was made. This step has been beneficial for the quality of this study and a similar approach can be recommended for other studies. Investigation through one discipline will not solve interdisciplinary problems.

5.2.2 The Dutch Marine Energy Centre

The action points presented in 5.3 show the implications for the Dutch Marine Energy Centre. Some of these action points are abstract, but others are more concrete and can be initiated and strived for by the Dutch Marine Energy Centre. One action point is: ‘turbine developers might limit themselves when assuming development should take place in the Netherlands’, which can be executed by making the Dutch entrepreneurs more aware of international opportunities. Other action points, for example ‘More research concerning tidal energy at research institutes is desirable’ is a society-wide action point, nevertheless can indirectly be strived for by the Dutch Marine Energy Centre.

5.2.3 Society

With its unique characteristics which are eligible at specific locations, tidal energy can play an important role in the renewable energy mix. The challenge, however, is to accept that this new form of sustainable energy production is currently in development and therefore in need of time and money, which, provided that economic feasibility will be reached, is repaid in the future. Also, tidal energy includes benefits that other renewable energy technologies lack (e.g. predictability), while currently costs are the only measure for comparison. A progressive view in terms of energy is necessary in order to acknowledge that the capability of providing a stable base load is a valuable quality in a world where the share of solar and wind energy is gradually growing.

5.3 Recommendations

The recommendations are based on the three most hampering functions in the Dutch tidal energy sector: Market formation, knowledge development and creation of legitimacy.

5.3.1 Market formation

The current high LCOE of tidal energy can be decreased by implementing demonstration projects. Currently, however, demonstration projects are hampered due to uncertainty with regard to permits and access to finance. In the European sector, a similar trend is visible: main obstructions are ‘red tape’ or redundant bureaucracy and formalities.

In wind energy, it has been shown that the exploitation of a home market is essential for the growth of the domestic industry, regardless of the home market size. In the Netherlands during the 1980s, the impartial attitude of the Dutch government resulted in permit and organisational issues from local authorities and therefore a siting problem. This siting problem turned out an important restraint on the testing and demonstration of wind turbines. Even though the underlying causes are different, a parallel with the current siting problem of tidal turbines is visible.

➔ Action point: Demonstration projects are necessary for further progress within the sector. Starting a home market is essential for the creation of a domestic industry.

The potential capacity for implementing tidal energy in the Netherlands is limited while the potential abroad is substantially higher, e.g. 12 GW in the UK (Burrows et al., 2009) and 2-5 GW in France (INNOSEA, 2016). The current phase of testing and demonstration of the technology creates an understandable focus on the Netherlands, however, technology developers should already keep an eye on the international market. An additional benefit of the international market is the fact that (offshore) resource locations are not directly in passage routes of migratory fishes. In the Netherlands, the potential locations are often overlapping with routes of migratory fishes. In other countries and at offshore locations, this is not directly the case, meaning potentially less impact on the environment.

A similar trend occurred in wind energy development in the 1980s: Dutch wind turbine developers shaped their turbine characteristics in order to fit Dutch subsidy regulations, however the turbines were inapplicable for the booming German market and therefore they failed to explore international opportunities.

- ➔ Action point: Turbine developers might limit themselves when assuming development should take place in the Netherlands: firstly, the Netherlands is a delta along with fish migration, inherent conflicting with tidal energy and secondly, the resource is better abroad.

5.3.2 Knowledge development

Knowledge development currently occurs at technology developers and for a small part at research institutes, however it is considered insufficient. Additionally, the knowledge development that is taking place at research institutes is not sufficiently aligned with the needs of the technology developers. Currently, a gap of knowledge on the environmental impact of tidal turbines halts testing and demonstration processes. In Europe, a similar gap of knowledge is visible when considering scientific publications. In other offshore industries, knowledge gaps that are of interest to multiple actors are addressed collectively by means of a knowledge consortium.

In wind energy during the 1980s, successive knowledge consortia were set up in the Netherlands, resulting in thriving wind energy R&D. Due to this, the Netherlands then became, and still is, one of the leading countries with regard to R&D in wind energy.

- ➔ Action point: Increased research concerning tidal energy at research institutes is desirable.
- ➔ Action point: It should be explored whether collective knowledge consortia could be set up to investigate environmental impacts of tidal energy.

5.3.3 Creation of legitimacy

Currently, Rijkswaterstaat does not allow testing of turbines in Dutch water bodies to take place at some locations. Guarding sensitive fish migration routes is desirable and concerns regarding additional fish mortality are justified; however, the current situation does not allow the verification of fish-friendliness.

It must be noted that public opinion and social impact could have an influence on the design and implementation. This message might not be accepted gratefully by technology developers, since this compromise might be at the expense of efficiency. It has been shown that the design of wind energy turbines has been guided not only by efficiency but also by audial and visual impact. In tidal energy, this matter is manifested in fish friendliness and the potential effect on the design and implementation is to be taken seriously. The weak legitimacy of wind energy in the Netherlands in the 1980s resulted in difficulties finding demonstration sites and therefore the market formation was limited.

- ➔ Action point: Small-scale pilots should be allowed for verification of fish friendliness of specific turbines, creating the possibility for implementation of quality standards. After this phase of experimentation and verification, the distinction between fish friendly turbines and non-fish friendly turbines will be clear, creating a knowledge base for further actions.

6 Conclusion

The water sector worldwide is traditionally focused on water safety, hygiene and agricultural problems, however given the current need for sustainability in order to combat climate change, the possible production of sustainable energy is a desirable extension of integral water management. Producing renewable energy by extracting it from water is a potential aspect of sustainability in integral water management. Tidal energy, a technology currently in development, is one of the methods to produce renewable energy from water.

The potential for cost reduction for tidal energy in combination with several unique characteristics has resulted in a worldwide interest in the technology in the last ten years. The global technical potential of tidal energy is estimated to be 1100 TWh/year, representing 4,5% of the current global electricity production. The resource of tidal energy, however, is concentrated on specific coastlines with narrow straits, headlands or sea mouths, resulting in substantial estimates for some countries including 12GW in the United Kingdom and 2-5 GW in France. In addition, tidal energy can pose valuable on locations where other renewable energy technologies run short. The unpredictability of the wind or the insufficient sunlight could render wind- and solar energy unfit to provide a base load on remote off-grid locations. Tidal energy, on the other hand, is highly predictable and can supply a base load four times daily, year round.

Over the last ten years, a rise in number of patents and entrepreneurial activities show a growth of the tidal energy sector, mainly within Europe. The Netherlands has a legacy in water engineering and also in tidal energy several Dutch pioneers are active. The Dutch tidal energy sector consists of 8 major technology developers, five knowledge institutes, test centers, governmental bodies and various organisations that are active in developing tidal energy. The water safety infrastructure in the Netherlands show a limited tidal energy potential of 120MW, however, the efforts of the Dutch tidal energy sector are focused on developing a commercial industry in order to exploit international locations. The aim of this research was to find action points that will enhance the developments of the tidal energy sector in the Netherlands. This study shows that the following processes require attention: market formation, knowledge development and creation of legitimacy, for which the following action points are constructed:

Action points: market formation

- ➔ Demonstration projects are necessary for further progress within the sector. Starting a home market is essential for the creation of a domestic industry.
- ➔ Turbine developers might limit themselves when assuming development should take place in the Netherlands: firstly, the Netherlands is a delta along with fish migration, inherent conflicting with tidal energy and secondly, the resource is better abroad.

Action points: Knowledge development

- ➔ Increasing the amount of research concerning tidal energy at research institutes is desirable.
- ➔ It should be explored whether collective knowledge consortia could be set up to investigate environmental impacts of tidal energy.

Action point: creation of legitimacy

- ➔ Small-scale pilots should be allowed for verification of fish friendliness of specific turbines, creating the possibility for implementation of quality standards. After this phase of experimentation and verification, the distinction between fish friendly turbines and non-fish friendly turbines will be clear, creating a knowledge base for further actions.

Currently, the future role of tidal energy and tidal energy turbines in society is unclear, creating ambiguity and friction in some parts society (industry, governmental authorities). Also, in the water management landscape, tidal energy is considered innovative and progressive. Eventually, water managers need to incorporate tidal energy in their work field, since tidal energy will become a prominent part of the physical environment. Already, the turbines in the Oosterschelde are controlled and operated by Rijkswaterstaat. The currently largest tidal range power plant (254MW), located at Sihwa Lake in South Korea, is initiated and controlled by a water company. Currently, however, the development requires sacrifices in terms of time and money from various sides of society. Questionable is whether the further development will take place in the Netherlands or whether other countries will take this share. The Netherlands, however, is a suitable and desirable location for development for the following reasons: Firstly, the Dutch water infrastructure, e.g. the Afsluitdijk, the Oosterscheldekering and the Brouwersdam are ideal locations for testing and demonstration. Secondly, the Netherlands has an established status with regard to water management and consequently, the exploitation of tidal energy worldwide could be added to the existing legacy of Dutch water technology and engineering. Currently, however, the tidal energy sector is very young and the exact relation with the established Dutch water sector is unclear, though not harmonious. This is manifested by the unclear role distribution and responsibilities in projects, ambiguity with regard to regulations and the overall bureaucracy. Visible, however, is the open and receptive attitude of the water sector: e.g. the realisation of the Oosterschelde project shows willingness from both sides. An increasing receptive attitude by the water sector in the Netherlands is necessary in order for the tidal energy developments to continue in the same rate as in Europe. In that way, professionals and companies in the Dutch water sector can export this new technology in the future as the most modern aspect of integral water management.

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7.1 Figures

7.2 Tables

Table 7. Institutions in the Dutch tidal energy sector. Source: this work.

Table 8. Synthesis of results. The color indicates the urgency of a TIS function in the Dutch tidal energy sector. Source: this work.

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Appendix A: Interview questions

List of diagnostic questions for the functional analysis of the Dutch tidal energy system (in Dutch)

F1: Entrepreneurial activities (ondernemende activiteiten)

Zijn er voldoende en juiste soorten ondernemers?

Welke mogelijke acties of gebeurtenissen kunnen bijdragen aan de prestaties van deze ondernemers?

F2: Knowledge development (kennisontwikkeling)

Is de hoeveelheid en het type kennisontwikkeling voldoende en afgestemd op de behoeften?

Welke mogelijke actie of gebeurtenis kan bijdragen aan kennisontwikkeling?

F3: Knowledge diffusion (kennisverspreiding)

Zijn er genoeg netwerken waarmee kennis zich kan verspreiden?

Welke mogelijke actie of gebeurtenis kan bijdragen aan kennisdiffusie?

F4: Guidance of the search (richting geven)

Zijn er genoeg en de juiste type actoren die richting geven aan het experimentele proces?

Welke mogelijke actie of gebeurtenis kan bijdragen aan deze functie van richting geven?

F5: Market formation (marktformatie)

Zijn de omvang van de markt en de aansporing of prikkels voldoende?

Welke mogelijke actie of gebeurtenis kan bijdragen tot marktvorming?

F6: Resources mobilization (beschikbaarheid van middelen)

Is er genoeg beschikbaarheid van financiële middelen en worden die goed besteed?

Is er genoeg beschikbaarheid van human resources?

Welke mogelijke actie of gebeurtenis kan bijdragen tot verbetering van de beschikbaarheid van deze middelen?

F7: Creation of legitimacy (weerstand doorbreken)

Is er weerstand tegen de technologie, het plaatsen van tidal turbines en de vergunningsprocedures?

Welke mogelijke actie of gebeurtenis kan bijdragen aan het verlagen van de weerstand?
Zijn de regelgeving, beleidsinstrumenten en vergunningprocedures ondersteunend?

Wat voor rol gaat getijdenenergie spelen in watermanagement binnen en buiten Nederland?

Appendix B: Structural analysis

Actors

Governmental bodies	Type	Description
Ministerie van Economische Zaken	National government body	
Ministerie van Infrastructuur & Milieu	National government body	
Rijksdienst voor Ondernemend Nederland	National government body	
Rijkswaterstaat	National government body	Responsible for issue permits inshore application
Provincie Noord-Holland	Regional government	Partly funded the Energiedijken consortium
Provincie Zuid-Holland	Regional government	
Provincie Zeeland	Regional government	Partly funded Oosterschelde project Tocardo. Partly funded Tidal Testing Centre Grevelingendam
Provincie Fryslân	Regional government	
Knowledge institutes		
Deltares		Delft3D/WANDA Computer models. Swansea Bay model.
NIOZ		Testfacilities, hydrodynamic studies, ecological impact studies. Hydrodynamics Wadden Systems research rojects (GETM/GOTM); . Part of the BlueTEC consortium
TNO		Applied research on acoustic effects, antifouling and corrosion.
ECN		Energizing delta's consortium; National Renewable Energy Action Plans (NREAPs); advisory for Duurzame Energie (SDE+) program
MARIN		Various testfacilities for ship hydrodynamics, propulsion, but also tidal energy. Recently, tests voor SeaQurrent en Tocardo.
Educational organisations		
Rijksuniversiteit Groningen		Research on ocean ecosystems. Theoretical models for SeaQurrent.
Universiteit Utrecht		PhD candidate (Sander van der Hees) on inter alia state aid aspects of tidal energy at Centre for Water, Oceans and Sustainability Law
Erasmus University Rotterdam		Research on organisation and governance aspects tidal energy. Part of the Energizing Delta's consortium.
Wageningen Marine Research		Research on fish behaviour and mortality. Impact assessment Blue Energy; Dynamic Tidal Power (DTP) consortium
TU Delft		Ocean energy platform. Part of the TiPA project (Horizon 2020). PhD candidate (Merel Verbeek) working on numerical modelling of hydrodynamic effects of horizontal axis turbines in the Oosterschelde basin.
Industry	Type	
Tocardo International B.V.	Technology developer	Two-bladed horizontal axis tidal stream turbine. Inshore application as well as floating offshore. Developing the Universal Floating System (UFS).Part of Tidal Bridge consortium and BlueTEC consortium.
Ronamic B.V.	Technology developer	Tidal range turbine
FishFlow Innovations B.V.	Technology developer	Horizontal axis tidal stream turbine (fishfriendly). Part of the Tidal Bridge consortium.
Pentair Fairbanks Nijhuis	Technology developer	Tidal range turbine + three-bladed horizontal axis tidal stream turbine.
Tidalys	Technology developer	Bankruptcy. Horizontal axis tidal stream turbine. Developing platforms, Electrimar1800 en Electrimar4200.
Deepwater Energy B.V. / Oryon Watermill	Technology developer	Vertical axis turbine.
Water2Energy	Technology developer	Vertical axis tidal stream turbine.
SeaQurrent	Technology developer	Tidal kite. Part of ForeSea project. Testing at Marin.
Schottel Hydro	Technology developer	Three-bladed horizontal axis tidal stream turbine. Part of Tidal Bridge consortium
IHC	Technology developer	Wave roter, vertical axis turbine.
Landustrie	Technology developer	Low-head tidal turbine
Strukton	Offshore contractor	Part of Tidal Bridge consortium
Bluewater (Energy Services)	Offshore contractor	Part of BLUEtec consortium
Huisman Equipment	Offshore contractor	Partly funded the Oosterschelde project. Constructed the structural array for Oosterschelde project.
Damen Shipyards	Ship construction	Part of BlueTEC constortium. Construction of BlueTEC platform.

Antea	Consultancy and guidance for project developers and technology developers	Project developer Testing at Kornwerderzand in close collaboration with Tocardo. Projectleader FORESE. Part of TTC-GD, Tidal Bridge, Dynamic Tidal Power (DTP) in POWER consortium
BT Projects	Project developer	Tidal Technology Center Grevelingendam (TTC-GD). Hydro electric powerplant Doesburg. Brouwersdam.
Dutch Expansion Capital	Investor	Part of 'Tidal bridge' consortium. Investor in Tidalys.
MET-Support		Creates technical standardization for tidal energy in co-operation with NEN: MET-CERTIFIED.
Nextco	Consultancy	
PwC	Consultancy	Part of Energiedijken consortium.
Supportive Organisations		
Dutch Marine Energy Centre		Network organisation
Energie uit Water (EWA)		Industry association tidal energy in the Netherlands
Netherlands Water Partnership (NWP)		
Op-zuid		Investor, public
MIT-zuid		Investor, public

Source: this work, as an elaboration on previous work by (Hoefnagels, 2016).

Networks

Project	Type	Status	Leden
Oryon Watermill TTC-Grevelingendam	Turbine testing	Planning	OP-ZUID (Europees Innovatieprogramma Zuid-Nederland), BT-projects, DWE
POWER	Consortium	Not active anymore	Consortium for feasibility research Dynamic Tidal Power (DTP). Imares Wageningen, Antea Group, Tocardo, Strukton, Arcadis, H2iD, DNV-GL, Pentair Fairbanks Nijhuis.
FORESEA	Subisidy program for testing	Active	Antea, DMEC, Tocardo, MET-CERTIFIED.
MaRINET2	Subsidy program for testing	Active	Marin, Maris, DMEC, total 39 organisations globally.
BlueTEC	Consortium	Completed	Bluewater, Damen Shipyards, Van Oord/Acta Marine, Tocardo, Schottel Hydro, Twentsche Kabelfabriek (TKF), Vryhof Anchors, Royal Netherlands Institute for Sea Research (NIOZ), Nylacast, the Tidal Testing Centre, and the Port of Den Helder
Energiedijken	Consortium	Completed	ECN, Deltares, Erasmus University, REDStack, Strukton/Antea, Tocardo, Energy Valley, Tidal Testing Centre.
Tidal Bridge	Consortium	Active	Strukton, Antea Group, Dutch Expansion Capital
Ocean Energy Platform	University network	Active	Platform connecting multiple researchers on the TU Delft who are occupied or interested on marine energy technologies.
Energie uit Water vereniging		Active	Industry associetion, consisting of 27 members.
Tethys	Database	Active	Database of academic literature on environmental impacts of marine energy technologies. Website: https://tethys.pnnl.gov/

Source: this work, as an elaboration on previous work by (Hoefnagels, 2016).

Institutions

Name	Type	Note
Energieakkoord	Agreement	14% share renewable energy production by 2020, 16% in 2023.
SDE+ Water	Regulation	Feed-in tariff Energie uit Water: 0,13 €/kWh
Besluit Rijkswaterstaat Vismortaliteit	Regulation	Fish mortality from new projects concerning ‘energy from water’ should have a ‘nihil’ impact (0,1% mortality of all passages)

Source: this work.

Infrastructure

The following tables depict all physical infrastructure concerning tidal energy. It is split into specific tidal energy infrastructure and general testing facilities that can be used for tidal energy testing, but are mainly used for other activities.

Name	Type	Status
Tocardo tidal array Oosterschelde	Demonstration site	In operation: 5x Tocardo T2 turbines with total capacity 1,25MW.
Tidal Technology Centre Grevelingendam	Demonstration site	Planned
Kornwerderzand	Demonstration site	Planned
DMEC Inshore demonstration site Den Oever	Demonstration site	Idle- license extension pending
DMEC Offshore Marsdiep site	Demonstration site	Idle

Name	Type	Status
TU Delft	Testing facility	Operational: wave flume, stream flume and stream tank
Wageningen University	Testing facility	Operational: straight flume and tilting flume
Hogeschool Zeeland	Testing facility	Operational: Stream Flume
Deltares	Testing facility	Operational: Atlantic Basin, Delta basin, intake and outfall basin and Scheldt flume
MARIN	Testing facility	Operational: Offshore Basin, Deepwater Towing Tank and Cavitation tunnel

Source: www.dutchmarineenergy.com