Understanding infrastructures: What is the mode of technological change in infrastructure sectors?

Innovation in the European high voltage direct current (HVDC) subsea cable industry since 2000.

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Having successfully defended the Jews, the golem turned on his maker, wreaking havoc in the ghetto, terrifying its inhabitants, and eventually attacking the synagogue he had been created to defend. (Kerstein, 2010)

The quote above represents how I felt writing this thesis. I created a golem and I lost control over it - again and again. However, like its mythological relative, the phoenix, after being destroyed, the thesis (and/or myself) rose back up again from the ashes. Countless hours have been spent reading different theories. Sometimes I would start writing just to get something down on paper – only to find myself rewriting it later. This, however, is how we are told it is. This is the way of writing an academic paper, and now, at the dawn of deadline, it must be delivered. As my professor Mom (from whom I may have inherited only limited academical skill) told me, a "good thesis is a delivered thesis". Although I suppose this thesis will never feel finished in my eyes, to me I am proud of it and of the amount of work I have put into it. Hopefully it will be of interest or inspiration for others interested in technological change in infrastructure sectors or the use of sectoral systems of innovation.

This thesis is a result of a battle between me and the golem, but the end result would be much worse without some wonderful helpers out there. These are the people I would like to send at least a few virtual high-fives: My classmates for many interesting discussions during class, and all our jokes and laughter in our reading hall. My parents, for your bottomless support and thorough proof-reading of my thesis. And last and foremost my supervisor, Allan Dahl Andersen, for motivating me, giving me constructive input and in general being a very patient man (let me know if you need more Norwegian lessons – I owe you!). Thank you all!

Abstract

To eliminate the problems of climate warming, several countries have devoted a great deal of time and money to reduce CO_2 emissions by replacing combustion energy power plants with cleaner technologies such as wind, hydro or solar power. However, with this energy transition new demand rises to the power grid. This new demand constitutes a major challenge both economically and technologically, yet very little research has been conducted on infrastructure transformation. This thesis seeks to explain how technological change comes about in infrastructure sectors. To explain the mode of technological change, the European HVDC subsea cable industry was chosen as a case unit. Using the sectoral system of innovation (SSI) perspective, this paper examines three dimensions of the European HVDC subsea cable industry, namely; (1) knowledge and technologies; (2) actors, relationships and networks; and (3) institutions.

This paper shows that infrastructure sectors evolve slowly due to the techno-economic properties of infrastructures. An example of this is the external systemness dependency on the functioning of the infrastructure service. This creates highly risk-averse customers and thus slowing down technological change. Homogenous demand and technology with high cumulativeness has also created a very homogenous firm environment that might also slow down technological change. This thesis ends by suggestions some policy implications to help facilitate faster technological change in the infrastructure sectors.

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1. Introduction

Infrastructure at the center stage of the energy transition

1.1 Background

The world is changing physically at an alarming speed. The ocean and atmosphere have warmed, vast amounts of snow and ice have melted, the sea level has risen and concentrations of greenhouse gases have increased. It is widely recognized by scientists that the rapid increase in climate change is mainly caused by man – for example by the vast amounts of carbon dioxide emitted through the combustion of fossil fuels (coal, natural gas, and oil) (Stocker et al., 2014). The dire consequences we face as a result of climate change have given rise to many new discussions of how to reduce our emissions. One obvious solution is to reduce the burning of fossil fuels and rather create energy by greener alternatives such as wind farms, hydropower or nuclear power. We call these changes in energy usage energy *transitions*. To reduce climate change we therefore need to understand what infuses and catalyzes energy transition. Much research has come as a result of this and within innovation studies a new branch has emerged, transition studies. However, within this research, the technologies in the transmission system transporting energy have remained largely ignored (Andersen, 2014).

This is worrying for several reasons. Firstly, the grids are in need of massive expansion and refurbishing to cope with the new situation that arises when few large power plants (concentrated in certain areas) are replaced by smaller and greener alternatives that are much more spread out. Examples of this can be taken from Germany, where nuclear power plants are replaced with wind and solar productions. This has technological implications for the grid.

Secondly, the grid does not only need upgrading because of increased power production displacement, but also because of increased variations in the amount of energy production. As there are no good ways of storing massive amounts of energy, the power produced must be similar to the demand. Coal or nuclear energy production is extremely reliable and also easily controllable. If one has too much power, one can decrease the energy production by burning less coal, or decrease the nuclear fission. If there is demand for more energy, production can be increased (Hawley, 2005). This means that the technical system operator operating the grid knows which power lines or cables need the right capacity for the larger currents. Because green energy production draws energy from local weather conditions (e.g. exposure to sun, wind, waves or waterfalls, to name a few), the energy created varies accordingly. This means that parts of the grid must be reinforced to cope with higher amounts of currents being transported from other areas. Again an example from Germany: if it's sunny in Bayern while there is no wind along the northern shore line, the solar panels in Bayern will create much energy while the wind farms in the north will not. Thus, there needs to be the necessary grid capacity to transport the energy created in the south to other areas of Germany, and vice versa if the weather is opposite. To further 'spread out' the climatic effects of energy production, there is also a need to integrate the power grids across Europe, which also raises new technological demands to the power grid as technical standards across borders are not harmonized.

Thirdly, reducing the cost of building infrastructure could decrease the cost of green energy production projects. As an example, the subsea cable connection to an offshore wind farm makes up about 25-50% of the total windfarm project cost[1]. The cost depends on the specifications of the project, for example the length of the cable (Delta[2]). Reducing the cost of cables could therefore be an extremely efficient way of bringing down costs on windfarms, and obviously also on cable interconnectors between countries.

Because of the new requirements, the new energy production demands from the power grid, the building of new and the refurbishing of old power grids are some of the biggest challenges in the transition to greener energy production. Therefore, to understand how policy makers efficiently can help facilitate energy transition, it is absolutely crucial that we understand how transmission infrastructures and their related industries function. In this thesis I will therefore look into how technological change comes about within a crucial industry supplying the grid infrastructure sector, namely the high voltage direct current subsea cable industry in Europe. Understanding this industry will be a small contribution to an overall better understanding of how technological change comes about in infrastructure sectors.

1.2 The case

In my thesis, I wish to examine how technological change comes about in infrastructure sectors. Our case for this analysis is the European *high voltage direct current* (HVDC) subsea

[1] The power converter is 20-25% and the power cables are about 75% of the total cost of the interconnection for offshore wind farms (Delta).
[2] "Delta" is a codename for one of my interview sources. See appendix 1.

cable industry[3]. The European HVDC subsea cable industry is an interesting industry to study for several reasons:

1. The European HVDC subsea cable industry has an important role to play in the transition to more renewable energy, as more cables are required both as connectors to offshore wind farms as well as interconnectors (cables) between countries to help even out the effects of variable energy.
2. The industry envisions a large market growth. The European Network of Transmission System Operators (ENTSO-E) has developed a ten-year development plan that estimates a demand of another 44 000 km of high voltage lines and/or cables by 2024. Another 4000 km of old lines and cables need refurbishing (ENTSO-E, 2014, p. 69).
3. This industry has not yet been analyzed from an innovation perspective.
4. The European HVDC subsea cable industry is a part of an infrastructure sector. Research suggests that innovation dynamics in infrastructure sectors are special, making the HVDC cable an interesting case for innovation theory about infrastructure and its sectors (Andersen, 2014; Markard, 2011).

Also, an analysis of empirical subjects published in the renowned journal *Research Policy* shows a clear tendency that innovation studies have had a focus on so-called "boys' toys" (for example computers, cars and TVs). There has been less research on other inventions that may also have had a large impact on people's lives (Martin, 2013). This might mean that the focus on high-tech boys' toys innovations may have "skewed our search for a better understanding of the innovative process with respect to methodological tools, concepts, analytical frameworks, and models" (Martin, 2013, p. 172). With regard to this, research on a sector that is essential to the functioning of our everyday lives, namely electricity and the transportation of electricity, would be a valuable contribution to innovation research in general.

[3] I have tried to be consistent in my use of the name for this case unit, but if I some places have not written 'European" or written things such as the "HVDC industry" or the "cable industry", note then that I am still referring to our case unit, the European HVDC subsea cable industry.

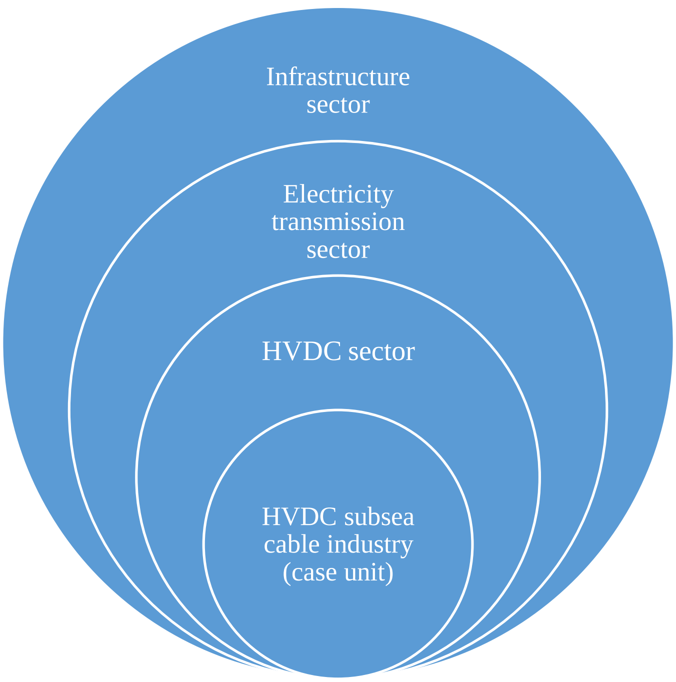
1.3 Research question

The overarching research question of this thesis is as follows:

How does technological change come about in infrastructure sectors?

This, however, is a very broad research question as infrastructure sectors may refer to multiple sectors with a range of different actors in each one of them. I define a sector as "A set of activities that are unified by some linked product groups for a given or emerging demand and which share some common knowledge" (Malerba, 2011, p. 385). This definition means that the borders of a sector could vary. It is unclear how closely linked products must be before they cannot be considered a part of the same sector. I conceptualize electricity transmission as one sector, because there is a common ground of knowledge for the transportation of electricity. However, if there are too many actors within a sector, this makes it difficult to fully grasp the interplay that goes on between the actors. This is too big a task for this thesis. Therefore, I have chosen to narrow the borders of this sectoral system while still staying within the definitions of a sector. I will therefore look at the HVDC sector, which is a part of an electricity transmission sector, which in turn can be defined as an infrastructure sector. It still has a range of different actors, but the scope is more manageable for a thesis of this size.

Figure 1: Diagram of sectoral systems in this thesis (my own illustration)



Within the HVDC sector there are several industries supplying different technologies, for example AC/DC converters, power lines or power cables. I cannot go into technological change in all of these industries. Therefore, my focus and therefore also my case for this study, is the *HVDC subsea cable industry in Europe*. To help answer my overarching research question, I have therefore narrowed it down to my case unit:

How does technological change come about in the European HVDC subsea cable industry?

1.4 The construction of the thesis

This thesis is divided into nine chapters. Chapter 1 explains why this research is highly relevant in our days' time of energy transition, and why the HDVC industry in particular was chosen as my case unit. The following chapter consists of a literature review, where I introduce the most relevant literature to help me answer my research question. Research related to technological change within sectoral systems of innovation and research on infrastructure in general is presented. Chapter 3 reviews the methodological choices of this thesis to provide transparency to my research and thus increase the reliability of the thesis. Chapter 4 is a contextual chapter which provides insights into the features of the HVDC industry. A brief history of the HVDC industry is presented as well as an overview over todays main technologies, the different actors, and market and technological predictions. In chapter 5 through 7, I use the sectoral systems of innovation approach as a classification scheme for my empirical presentation. The chapters are divided into 'knowledge and technologies' (5), 'actors and networks' (6) and 'institutions' (7). At the end of each chapter I discuss the findings in light of the theory presented in chapter 2. Chapter 8 summarizes and discusses these findings alongside earlier research on infrastructure sectors, thus linking together the various sections of the thesis. In chapter 9, I present my conclusion as well as my reflections on research discoveries, limitations of this study as well as suggestions of areas for further research.

2. Literature review

The theoretical background

This chapter begins with a definition of relevant terms I use in this thesis. Following this, the chapter is then divided in two theoretical frameworks. The first part describes how and why the mode of change (illustrated as the organization of innovation) varies across sectors. In this part, I introduce important concepts and findings of differences across various sectors, thus making a useful framework for analyzing the HVDC subsea cable industry. The second part of this chapter focuses on the literature on innovation in infrastructures. In this section, research is presented which shows that infrastructure is characterized by high systemness, high capital intensity and a slow moving technological change ratio. There have been published several articles on infrastructures, but there is little attention to the related industries that form part of this system or how technological change arises in infrastructures (Andersen, 2014).

To understand the dynamics of technological change in infrastructures, one has to include the industries that supply the technology related to that sector. The reason for this is that technical system operators (TSOs) operating the power grids do not make the technology themselves. Therefore, I conceptualize the HVDC subsea cable industry as embedded in the HVDC sector, which in turn is an infrastructure sector. There are many industries specializing in transmission technology, and one of them is the HVDC subsea cable industry. If this industry is a part of the HVDC sector which in turns is a part of an infrastructure sector, we would expect the traits of infrastructures to affect the HVDC subsea cable industry accordingly. Therefore, properties of infrastructures found in earlier research will be presented, so I can see if they fit with my empirical findings on the HVDC subsea cable industry later on.

2.1 Definition of key terms

In current literature, there is agreement amongst researchers that how technological change arises varies greatly across sectors. They provide different explanations, and the variables and methodology used also vary. An issue is for example the definition of a sector. Where does one draw the line for what is included in one sector? A chemical producer, for example, might supply and co-operate both a pharmaceutical sector as well as a telecommunications sector. It is therefore important to draw the lines of what is included in a sector so one does not compare apples to bananas. The word sector is, in classic economics, used to separate the economy into three components. The primary sector: the production of raw materials, e.g. a coal miner or a farmer. The secondary sector: transformation of raw materials into goods, e.g. a builder or a car manufacturer. The tertiary sector: service supply, e.g. consultants, shopkeepers or transport agencies (Kenessey, 1987). Markard (2011) uses sectors differently. He writes about *infrastructure sectors* and confines these sectors to physical networks in the sense of transmission and distribution grids. In his sectors, there are technologies, physical elements, organizations, suppliers and public authorities and institutions (Markard, 2011). Malerba (2011) introduces the notion of *sectoral systems of innovation*, where he defines a sector as "a set of activities that are unified by some linked product groups for a given or emerging demand and which share some common knowledge" (Malerba, 2011, p. 385). Others follow Keith Pavitt's renowned taxonomy and his use of the word sector as an equivalent of *industry*, naming *pharmaceuticals and biotechnology, chemicals, software, computers, semiconductors, telecommunications or machine tools,* all as different *sectors* (Malerba, 2011). In this thesis, I follow Malerba's school of thought when I talk about *sectors*. *Industry* refers then to a group of firms that supply a selected market. (Stiglitz, 1993:396). To avoid confusion or misunderstandings regarding such definitions, the table below presents a complete list of the key terms as defined in this thesis.

Appropriability	"Appropriability (of innovations) summarizes the possibilities of protecting innovations from imitation and of reaping profits from innovative activities" (Malerba, 2011, p. 382).
Competitiveness	"The possession of the capabilities needed for sustained economic growth in an internationally competitive selection environment, in which environment there are others (countries, clusters, or individual firms, depending on level of analysis) that have an equivalent, but differentiated set of capabilities on their own." (Cantwell 2005:544)
Cumulativeness	"Cumulativeness conditions capture the properties that today's innovations and innovative activities form the starting point for tomorrow innovations" (Malerba, 2011, p. 382). High cumulativeness means that a given innovative company is more likely to innovate in the future in a specific technology or along specific trajectories than non-innovative firms (Malerba, 2011).

(Infrastructure) industry	A group of firms that supply a selected market (Stiglitz, 1993:396). In this thesis, an infrastructure industry is an industry that supplies technology to its related infrastructure. References to the HVDC subsea cable industry (HVDC industry) refers to the producers of the cables.
Infrastructure sector	A sector is "A set of activities that are unified by some linked product groups for a given or emerging demand and which share some common knowledge*"* (Malerba, 2011, p. 385). An infrastructure sector in particular, is a "socio-technical system of fundamental importance to the functioning of society in areas such as water, energy, internet and transport. It consists of physical components and technologies as well as actors and institutions" (Andersen, 2014, p. 14; Jonsson, 2000).
Innovation	Joseph Schumpeter defined innovation as new combinations of existing resources. He distinguished between, on the one hand, new products, new methods of production, new sources of supply, exploitation of new markets and on the other, the reorganization of business (Fagerberg, 2005, p. 6). In this thesis, I will look at innovation in products and methods of production.
Path dependency	Path dependency explains how the set of decisions one faces for any given circumstance is limited by the decisions one has made in the past, even though past circumstances may no longer be relevant (R. R. Nelson & Winter, 1982; Wikipedia, 2015b).
Research and development (R&D)	"The standard research and development activity devoted to increasing scientific or technical knowledge and the application of that knowledge to the creation of new and improved products and processes" (Hagedoorn, 2002, p. 477).
Systemness	Systemness refers to the level of interdependencies among system components. If the systemness is high, it means that they cannot function without each other (Andersen, 2014).
Transition	In this thesis, I refer to *the transition to obtain a higher share of renewable energy sources*. An energy transition signifies

	fundamental structural changes in an energy sector (AT Kearney & World Energy Council, 2014).

2.2 Innovation and technological change

For technological change to happen, there must be some sort of innovation successfully implementing a new invention into the marked (Fagerberg, 2005). Even though innovation itself can be defined in a short sentence, "a new combination of existing resources" (Schumpeter in Fagerberg, 2005), innovation is not a simple thing. In fact, due to the complex nature of innovation, it is sometimes easier to say what it is not, than what it is. The old and outdated version of how innovation happens is *the linear model.* The linear model treated innovation and technological change as a linear product, going from invention (scientific discovery) to innovation (technological development in firms) and then diffusion (distributed and sold in the market). There were two main versions of the linear model, the "technology push model" and the "market pull model". In the former, the idea is that a new scientific discovery is what starts the innovation process, whereas in the latter a market need starts the development of innovations. Both versions of the linear models have been criticized for ignoring the many feedbacks and loops that occur in the different stages of an innovation. Today it is widely established that innovation has a much more dynamic lifestyle than what is suggested in these models (Godin, 2006).

2.3 How does innovation vary across sectors?

If innovation and technological change does not move along linear paths, then how does it move and come about? A much cited model today is the so called chain-linked model of innovation developed by Nathan Rosenberg and Steven Kline (Kline & Rosenberg, 1986; Smith, 2005b). The chain-linked model stresses three basic aspects of innovation:

- Innovation is not a sequential (linear) process, but one involving many interactions and feedbacks in knowledge creation.
- Innovation is a learning process involving multiple inputs.
- Innovation does not only depend on invention processes (in the sense of discovery of new principles), and such processes (involving formal R&D) tend to be under-taken as problem-solving within an ongoing innovation process rather than an initiating factor (Smith, 2005b, p. 150).

The work by Rosenberg and Kline shows that novelty not only implies the creation of new products or processes, but that also small changes may have large technological and economic effects. An example of this could be gradually optimizing a new machine to full performance. Over time, this might in turn have huge economic effects. Think of the gas combustion engine, a design that has lasted more than a century, but has been dramatically improved throughout the years. One can barely compare the early engines of the 20th century with the modern combustion engines of our time. Small and gradual innovations like these are called *incremental innovations*. Another major finding in their research was that input into innovation goes far beyond R&D activities. Mentioned here are design activities, engineering development and experimentation, training of new staff, exploration of market needs for new products, et. cetera (Smith, 2005b). Modern innovation surveys take these factors into account, but also implement findings from recent innovation research such as the *networking dimension* of innovation. This is the idea that collaboration and interactive learning is important for the creation of innovation, exemplified by involving and collaborating with other enterprises and organizations, as well as with the science and technology infrastructure (Smith, 2005b).

One of the most cited references on how innovation varies across sectors is Keith Pavitt's classic article on taxonomy from 1984 (Archibugi, 2001). Pavitt's taxonomy is, amongst other things, a critique of the older model (often called vintage model) of technical change (Fagerberg, 2005). The older model assumes that all technology is capital-embodied and enters the economy through investment (Pavitt, 1984). Pavitt argues that innovation happens in more ways than through R&D and attempts to develop a taxonomy, or classification scheme, that takes these other factors into account (Fagerberg, 2005). Pavitt uses a data-set on innovation in the UK that had measured 2000 significant innovations between 1945 and 1979. Using this data-set, Pavitt could not only measure the amount of innovative activity in different sectors, but also address the question of *how* innovations were created.

He identifies two sectors that serve the rest of the economy with technology, namely the "science based" and "specialized suppliers" categories. How these two sectors created their innovations, however, varied considerably. The "science-based" sector, created innovations through R&D and collaboration with knowledge institutions such as universities. "Specialized suppliers" created innovations through capabilities in engineering and knowledge sharing with their customers and users.

Pavitt's research shows that factors leading to a successful innovation differ greatly across sectors. This is important for policy makers, as one innovation policy might work well in one industry, but not in another (Fagerberg, 2005; Pavitt, 1984). However, leaning too much on taxonomies such as Pavitt's, may also be problematic. This may lead to a simplistic analysis and, in worst case, biased public policies (Lorenz & Lundvall, 2007). Renowned economist Christopher Freeman allegedly said, "Taxonomies may be dangerous as they put firms and sectors into rigid categories while reality is in a state of flux"(Lorenz & Lundvall, 2007, p. 3).

Pavitt's taxonomy and the chain-linked model demonstrates the complexity of innovations and points to the many different paths innovation and change might take. Indeed, research shows that innovation differs in terms of sources, actors involved, the boundaries of the process and the organization of innovative activities. Therefore, one cannot measure what matters for innovation and performance with a focus on the "representative firm". Doing so would capture only a part of the action that takes place and therefore identify only a few of the key variables that matter for innovation and performance (Malerba, 2011). For some innovations, research and development, and learning-by-doing could be the most important source. Others might emphasize competition and formal R&D joint ventures. Are patent system and public support for R&D the only relevant institutions and policies that matter for innovation? Do incumbents (large firms) with large R&D expenditures drive the sector? What is the role of universities? Do downstream markets play a role? All research on innovation shows that these vary greatly across sectors. It is therefore important to obtain data from several industries across different sectors.

2.3.1 OECD's R&D classification, Mark I and Mark II

There have been several attempts to classify different sectors based on their innovative capabilities. A traditional way to measure this is the ratio between R&D expenditure and output (Smith 2005:155; Hirsch-Kreinsen & Jacobson 2008:5-6). The OECD has used this calculation to classify businesses into three different categories (OECD 1984; 2002). The categories are labeled low-medium technology (0-3 percent), medium-high technology (3 to 5 percent), and high technology (above 5 percent). This classification simply measures the amount a given business spends on R&D, but does not assess how its innovation activities are organized or how technical change arises.

An example of classification based on the organization of innovation is the Schumpeterian Mark I and Mark II distinctions. Mark I sectors are characterized by a market of technological change where new firms and entrepreneurs play a crucial role in a game of "creative destruction". It is a situation where new ideas and technologies threaten the old commodity, and one where old competence and knowledge could become obsolete if new technologies replace them. This is co-called 'competence destroying innovation' (Metcalfe, 1998). Mark II sectors, on the other hand, are characterized by "creative accumulation" carried out by few and large companies with significant entry barriers for new innovators. Therefore innovation in Mark II sectors is largely incumbent driven (Malerba, 2011). High technological opportunities, low appropriability and low cumulativeness lead to a Mark I pattern. While high technological opportunities might still be high, if there exists high appropriability and high cumulativeness, this will lead to a Mark II pattern (Malerba, 2011).

However, a regime is not necessarily bound to one of the two Mark patterns. Over time, changes in a regime may turn a Mark I pattern into a Mark II. When an industry is young, knowledge is changing rapidly, uncertainty is very high and barriers to entry very low. The major innovators and key elements of the industrial dynamics have now become the new firms. After a while, as the industry develops, its technologies might follow defined trajectories: learning curves, economies of scale, barriers to entry, financial resources. All of these can become an important part of the competitive process. This in turns means that large firms, or even monopolistic incumbents, take over and, in turn, lead the innovation process. The change of Mark type can go both ways. If there are major markets, knowledge or technological market discontinuities, a stable sector with monopolistic incumbents (Mark II) might be replaced by a more turbulent sector with new firms using either new technology or focusing on a new demand (Mark I) (Klepper, 1996).

2.3.2 Sectoral systems of innovation

In economic, evolutionary theory, we find the term *technological regimes*. This is the idea that even though firms operate in uncertain and often rapidly changing environments, some regularities are assumed to be created due to the commercial and technological incentives and constraints firms face (Leiponen & Drejer, 2007; R. R. Nelson & Winter, 1982). The regularities are then divided into different technological regimes. Numerous empirical studies have contributed to the idea that firms in the same regime tend to organize innovative activities in the same ways (Malerba & Orsenigo, 1993; Malerba, 1999; Marsili & Verspagen, 2001; Pavitt, 1984). Within different technological regimes there are different learning and knowledge environments. This kind of environment "defines the nature of the problem that firms have to solve in their innovative activities" (Malerba, 2011, p. 382; R. R. Nelson &

Winter, 1982). The assumption that this knowledge environment plays a crucial role in the way the firms behave has also been verified in managerial and economic history literature (Malerba, 2011, p. 383). Knowledge and competence vary strongly across sectors, and earlier studies show that one can link basic firm innovative behavior and strategies to the underlying knowledge and learning regime. This has for example been done by Malerba and Orsenigo (Malerba & Orsenigo, 1993; Malerba, 1999). They link learning regimes in terms of opportunity, cumulativeness and appropriability of innovations to the type of basic innovative behavior (radical vs innovative vs imitative behavior) in sectors such as computers, biotechnology and semiconductors (Malerba, 1999). In fact, building on the theory of technological regimes as well as other evolutionary economic theories and innovation system literature (including the already mentioned Mark I and II), Franco Malerba introduced the notion of *sectoral systems of innovation (SIS)* (Malerba, 1999).

There are many ways to analyze technological change within different systems, but some have focus on national borders, such as national innovation systems, other on the technologies itself, such as technological innovation systems. This thesis tries to understand a certain sector, and therefore this framework seemed fitting for this thesis. The SIS approach contributes to the crucial idea that all technological or sectoral systems are not homogenous. The SIS perspective stands out from other system perspectives in the way that the conditions for innovations in one industry and in one country have much more in common with the same industry in another country than with another industry in its own country. Moreover, the SIS approach suggests that different industries may not have only different competitive advantages, interactive and organizational boundaries, but also different sources of innovation and user's needs (Tuncel, 2014). The sectoral system framework gives me the ability to understand a sector with respect to several dimensions, such as the type and role of agents, the rate and direction of innovation, the structure and dynamics of production, and in turn the effects these variables have on the performance (Malerba, 2002). A sectoral system framework focuses on three main dimensions: 1) knowledge and technological domain, 2) actors, relationships and networks, and 3) institutions.

2.3.2.1 Knowledge and technology

According to SSI perspective, any sector may be characterized by a specific knowledge base, technologies and inputs. The role of knowledge plays a crucial role in the sectoral systems by affecting "the rate and direction of technological change, the organization of innovative and production activities, and the factors at the base of firms' successful performance" (Malerba, 2011, p. 389).

Firstly, knowledge has different degrees of accessibility (Malerba & Orsenigo, 1993). Greater accessibility to knowledge implies lower appropriability. The level of appropriability affects the probability of protecting innovations from imitation and thereby raising the likelihood for revenues from the innovation. A high level of appropriability means that the protection of an innovation from imitation is likely, whereas a low level indicates widespread existence of externalities that can imitate innovations (Malerba, 2011). If turned around, with low accessibility and high appropriability, it is very difficult for newcomers to penetrate the market as knowledge and insight cannot not be easily obtained.

The source of knowledge may also be external to the sector, for example from suppliers, universities or research laboratories. Here technological opportunities play a role. Technological opportunities are measured in level and pervasiveness. The level reflects the window of opportunity for developing new technology from new information and therefore also the chance of successful innovation. High technological opportunities thus create strong incentives for companies to invest in innovation. This level varies, as an industry might go from high level of technological opportunities to more narrow technological opportunities as the industry (and the competition) matures. The pervasiveness of technological opportunities reflect how easily knowledge is applicable to other products and markets. A low level indicates that the knowledge is only applicable to a limited and specific set of products and processes, and a high level the opposite (Malerba & Orsenigo, 1993, p. 48). In some sectors, technological opportunities are strongly related to major breakthroughs made at universities, while in other sectors breakthroughs might come from in-house R&D. Not all external knowledge may be easily transformed into new artifacts. If, however, external knowledge is easily accessible and transformed, then innovative entry may take place, even if there is low internal knowledge accessibility within the sector (Malerba, 2011). If high absorptive capacity[4] is necessary the industry may be concentrated and formed by large, established firms (W. Cohen & Levinthal, 1989; Malerba, 2011, p. 388).

Secondly, knowledge may have a varying degree of cumulativeness. Cumulativeness builds on the idea that today's innovations and innovative activities form the starting point for

[4] By "absorptive capacity" we mean the ability of a firm to recognize the value of new, external information, assimilate it, and apply it to commercial ends (this is largely a function of the firm's level of prior related knowledge) (Wesley Cohen & Levinthal, 1990)

tomorrow innovations. High cumulativeness means that a given innovative company is, in the future, more likely than non-innovative firms to innovate in a specific technology or along specific trajectories (Malerba, 2011). There are three different sources of cumulativeness:

1) Cognitive sources: The learning processes and past knowledge constrain current research, but also creates new questions and new knowledge.
2) The firm and its organizational capabilities: These organizational capabilities are firm-specific and generate knowledge which is highly path-dependent. These implicitly define what a firm learns and what it can hope to achieve in the future.
3) Feedbacks from the market, such as "success-breeds-success": Innovative success creates profits that can be reinvested in R&D, thereby increasing the probability to innovate again (Malerba, 2011, p. 388).

High cumulativeness implies an implicit mechanism leading to high appropriability of innovation, because the knowledge is not easily accessible for entrants. Nevertheless, cumulativeness may be found at different levels, thereby affecting the industry differently. If found at local levels, high cumulativeness can be associated with low appropriability because there may be localized knowledge spillovers between local actors. Cumulativeness at the firm and technological level creates first-mover advantages and in doing so generates a high concentration of firms. This means that firms that have a head start can develop new knowledge based on existing ones and produce innovations of the incremental type continuously. Other dimensions of knowledge could be related to other areas, such as its tacitness, complexity, scientific base or its systemic features (Malerba, 2011).

2.3.2.2 Actors, relationships, and networks

Within the framework of sectoral systems of innovation, innovation is considered to be "a process that involves systematic interactions among a wide variety of actors for the generation and exchange of knowledge relevant to innovation and its commercialization" (Malerba, 2011, p. 385). These actors could be individuals (consumers, scientists, entrepreneurs) or organizations. The organizations may be firms, such as users, producers and input suppliers, or non-firms, such as universities, financial institutions, government agencies, trade unions, or technical associations. The different actors in a sectoral system are connected in various ways, both through market and non-market relationships. They can be connected through competition, processes of exchange, formal cooperation or informal interaction. Relationships between firms and non-firm organizations have been a source of innovation in many sectoral systems, such as biotechnology, pharmaceuticals, information technology and telecommunications (Malerba, 2011, p. 392).

Firms are the key actors in the use, adoption and generation of new technologies, and are continuously engaged in processes of learning and knowledge accumulation (Malerba & Orsenigo, 1993; R. R. Nelson & Winter, 1982). The level of firm heterogeneity is a result of the balance between selection (survival of the fittest), variety creation (innovation) and replication (easiness of copying inventions). Selection increases homogeneity, while entry, technological and organizational innovations are sources of heterogeneity. The already mentioned characteristics of the knowledge base also play a role in firm heterogeneity; ease of access to knowledge tends to increase heterogeneity, and vise-versa. The role of non-firms also varies; in some sectors, universities and laboratories play an important role; in others, one might find that venture capital companies are more important (Malerba & Orsenigo, 1999).

The role of demand in sectoral system is not seen as a static entity with undifferentiated customers, but as a group of heterogeneous actors that interact with the producers in various ways. Because of this interaction, the demand is also affected by the customer. The customer is, in turn, also affected by the knowledge, learning processes and competence, as well as by social factors and institutions. Therefore, the emergence and transformation of demand is an important part of the dynamics and evolution in sectoral systems (Malerba, 2011, p. 391).

According to Malerba, when using this system as an analytical framework, the most appropriate units of analysis are often not necessarily a single firm, but individuals, firms' subunits or a group of firms.

2.3.2.3 Institutions

In sectoral systems, institutions play a major role in affecting the mode and rate of performance, innovation and technology change. Agents' actions and interactions are shaped by institutions. By institutions we understand them as both formal (laws, rules, standards, regulations) or informal (norms, routines, common habits, established practices)(Malerba & Orsenigo, 1999). Institutions may affect sectoral systems in two ways. Either by *national institutions* such as the patent system or antitrust regulations, or by *sectoral institutions* such as sectoral characteristics of the labour market or sector specific financial institutions (Malerba, 1999).

How the agents are affected differs across sectors and might also vary from country to country. Some sectoral systems can become predominant in a country because the existing regulations of that country provide an environment more suitable for certain types of sectors than others. Regulation and liberalization/privatization industry has had major effects on the telecom industry in Europe. In France, some sectoral systems have grown considerably due to public demand (Chesnais, 1993). Local banks play an important role in some sectors, while in others, like software, standards and standard settings are important. National health systems may have a great impact such as in pharmaceuticals. (Malerba, 2011). Malerba recognizes that analyzing the role that institutions play on innovation production and distribution in sectoral systems is a formidable analytical challenge, because institutions may be more or less formal (patent laws or regulations vs. traditions and conventions) and their effects more or less binding on agents actions (Malerba, 1999).

2.3.2.4 Sectoral systems summarized: The dynamics of sectoral systems

The three elements, (1) knowledge and technological domain, (2) actors, relationships and networks, and (3) institutions, are closely connected. Changes over time in sectoral systems is therefore a co-evolutionary process comprising all three elements. This process involves technology, demand, knowledge base, learning processes, firms, non-firm organizations and institutions (Malerba, 1999, p. 23). Earlier work has discussed these processes at the general level, but Malerba claims that these processes are sector-specific (Nelson (1994), Metcalfe (1998) in Malerba, 1999). His argument is that one can observe these changes within a sector. For example, in sectors characterized by a system product and consumers with a homogeneous demand, coevolution leads to the emergence of a dominant design and industrial concentration (fewer firms). However, in sectors with a highly heterogeneous demand, or competing technologies with lock-ins[5], network externalities[6] and standards, coevolution may have another result. In such a case, specialized products and a more fragmented market structure may emerge (Malerba, 1999, p. 23). In addition, coevolution is often related to path-dependent processes. This means that local learning and interactions among agents and networks may generate increasing returns and irreversibilities that may lock sectors into inferior technologies (Malerba, 1999, pp. 23–24). The cases of sectors with competing technologies such as cars (and the combustion engine), multimedia (VCR, Blu-ray, etc.), and computers (and their operating systems) provide good examples of path-dependent processes.

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[5] By lock-in I mean that a certain technology is dominant not because of price or performance issues, but because of increasing returns to scale (the market dominance) (Arthur, 1989).
[6] By network externalities I mean the effect that the value of a product or service has, is dependent on the amount of users using it. For example a telephone or social media websites (Wikipedia, 2015a).

Changes in a sectoral system are therefore a result of the interplay between evolutionary processes such as variety creation, replication, and selection. The creation of new agents, both new firms and non-firms, is particularly important for the dynamics of sectoral systems and their degree of change. This is known as processes of *variety creation*. Variety creation may also refer to the rise of new products, technologies, and institutions, as well as new firm strategies and behavior. These could all take place through new market entry, R&D, innovation, etc. Not surprisingly, sectoral systems differ extensively in variety creation. Much research has shown that variety creation is strongly related to the knowledge base (the level, diffusion and distribution of knowledge), the presence of non-firm organizations (such as universities and venture capital), and sectoral institutions (such as regulations and labor markets) (Audretsch, 1996; Malerba & Orsenigo, 1999). There is also a great display in variation in the how easily new firms can enter a sector, and how much they can affect the sector. Selection plays a role in reducing heterogeneity among firms because it drives out inefficient or less progressive firms. This may be because of products, activities, technologies, and so on. Non-market selection could also play a role, if for example regulation or norms are changed.

2.4 Innovation in infrastructures

The link between a company's innovation decisions and its context has given rise to a range of attempts to conceptualize these contexts, for example through concepts such as national innovation systems or technological innovation systems (Fagerberg, 2005). However, one finds little research conducted on infrastructure sectors particularly, and the limited research on how change comes about in infrastructure indicates that infrastructures are special. Since the HVDC subsea cable industry is directly related to the infrastructure (in this case the power grid), we might suspect this industry to behave differently than others. This section reviews the limited research done in transition and innovation studies on infrastructures and discusses what we might expect from the HVDC subsea cable industry.

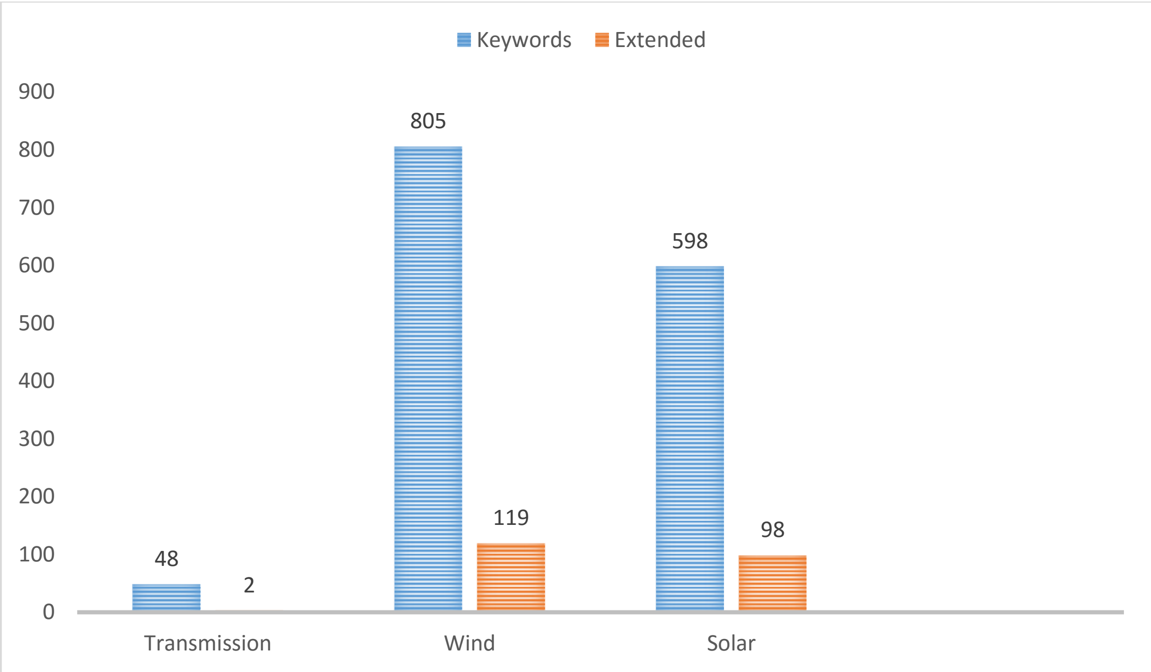
2.4.1 Research on infrastructure

As mentioned at the beginning of this chapter, I define infrastructure sectors as "A socio-technical system of fundamental importance to the functioning of society in areas such as water, energy, internet and transport" (Andersen, 2014). This could refer to roads, railways, power grids, water supply systems, telecommunications, et cetera. These sectors include "technologies, physical elements such as pipelines and plants, organizations such as utility companies, suppliers and public authorities and institutions such as regulations for grid access or quality norms" (Jonsson, 2000, p. 6). These sectors also encompass supply industries that provide these sectors with different sorts of technology.

Infrastructures have been studied in many ways; engineers might focus on technical efficiency, while economists concentrate on economic efficiency (Andersen, 2014; Markard, 2011). Within economics, researchers have also shown interest in the linkages between infrastructure and private sector productivity. In recent years, researchers have also studied infrastructure sectors from a management perspective and looked at organizational capabilities, strategic planning, risk management, etc. (Markard, 2011).

However, in a highly relevant field of study for this thesis, namely energy transition studies, infrastructure has been a neglected area, even though they are an essential part of our high-carbon economies (Andersen, 2014; Jonsson, 2000) (see figure 2). Some researchers argue that transition research in general suffers from "infrastructure blindness" (Andersen, 2014, p. 86; Bauknecht, 2011, pp. 32–34). Furthermore, they claim that the research focus within transition studies has been on the renewable technologies themselves, such as wind and solar powers, and not on the infrastructure system that connects these technologies to the economy (Andersen, 2014). This is a problem because infrastructure is not only vital to our economy; it is also a central part of our transition to more renewable energy (European Commission, 2007, 2014; Tawney, Bell, & Ziegler, 2011). Massive investments are namely needed in existing infrastructures for maintenance, refurbishing and expansion in order to cope with the new demand from the new green and variable energy supply. It is therefore essential to understand the drivers of and barriers to transformation in infrastructure sectors (Markard, 2011).

Figure 2: Number of articles on transmission, solar and wind technology within Transition Studies, 2000–2014 (numbers collected from Andersen, 2014, p. 77)



As figure 2 shows, there is evidently need for further research on infrastructure systems. Even if limited, what does existing literature on infrastructures tell us about change in infrastructures? According to Jonsson (2000), infrastructure is a socio-technical system. By this, he means that there are social and technical aspects to infrastructures; they consist of physical components and technologies as well as actors and institutions. Therefore, to understand how an infrastructure behaves, one has to take into account the actors that use, build and operate it, as well as the technical components that make part of it. His view is shared by Markard (2011). He argues that if you do not take a systemic approach there is a risk that certain processes or effects are highlighted while others are neglected; a "technological perspective might miss economic and regulatory implications, and vice versa" (Markard, 2011, p. 4). Therefore, to capture the entire dimension and understand the behavior of infrastructures, one must use a systemic approach (Jonsson, 2000; Markard, 2011).

The lack of research on infrastructure is noticeable in innovation studies as well. There, infrastructures have mainly been viewed as a static entity that gives direction to innovation activities. Therefore little research has been on infrastructure as an idiosyncratic sector in society (Andersen, 2014). An exception to this is a fairly recently published paper by Jochen Markard in 2011, and Allan Dahl Andersen in 2014. Markard developed a systemic approach to understand infrastructure transformation. In his research, he identified several key drivers for the transformation of infrastructure, including new environmental requirements, investment needs and capital intensity (Markard, 2011). The next section will summarize the traits of infrastructure that we do find in existing literature.

2.4.2 Properties of infrastructures

Based on various literature on infrastructure from both economics, transition studies and innovation studies, we can find traits that typically characterizes an infrastructure sector.

A) Indivisibility: Infrastructure must generally be constructed as a system or a set of complementary systems (Andersen, 2014; Smith, 2005a).

B) Multi-user: There are many users of the same supply system. The multi-user characteristic means that only one infrastructure system is required and that duplication is unnecessary. This is a key for establishing the dominance of a technological regime and therefore indicates a "first-mover advantage" for the first technology of that infrastructure (Smith, 2005a). The multi-user trait can also lead to network externality[7](Andersen, 2014).

C) Large technical systems: The above two points imply that infrastructures tend to be very large technical systems (Andersen, 2014; Markard & Truffer, 2006; Smith, 2005a).

D) Capital-intensive: The latter three all imply that infrastructure investments are very larger compared to most investments in other industries (Andersen, 2014; Markard, 2011; Smith, 2005a).

E) Generic: Infrastructure is a core requirement for many or all activities because it provides fundamental resources into all parts of economic activity (energy, information, transport, et. cetera) (Smith, 2005a).

F) Increasing returns to scale[8]: Because of the high capital intensity, infrastructure is subject to increasing returns to scale which leads to the formation of high entry barriers. This is why monopolies are common in infrastructures (Andersen, 2014; Smith, 2005a).

[7] Network externality may be defined as a change in the benefit or surplus a user of a system gains from using that system if the number of users increases. An example of this is for example a fax machine, as the fax machine increases in value if more people buy one (e.g. you can use it to reach more people).(Liebowitz & Margolis, 1994)

[8] E.g. reduction in cost per unit as a result of increased production

G) A public good: Infrastructure can be considered a quasi-public good that is non-rival and non-excludable and thus may have significant productivity spillovers to the private sector (Smith, 2005a).

H) Durable assets: Infrastructure is subject to a very long life time (Andersen, 2014; Smith, 2005a).

I) Systemness. Systemness is particularly strong in infrastructure sectors (Markard, 2011). Systemness is high if there are strong interdependencies among system components, which means that they cannot function without each other (Andersen, 2014).

What do these traits imply for my research? Due to high systemness, diffusion of new technology must probably be associated with a change in relevant standards and regulations. Standards are crucial for the direction of innovation and investment by equipment manufacturers (Andersen, 2014; Rosenwirt, 2012). However, the necessary change in regulation that must accompany new technology could also slow down technological change and therefore also infrastructure transformation. The external systemness (exemplified by the wider economy's dependency on a functioning infrastructure) could create strong risk aversion towards introducing new technology. High capital costs and complex system dependent technology could be barriers for new entrants, and could imply that new technology is mainly created by incumbents. If the external systemness creates strong risk aversion one would also suspect this to be a barrier for new entrants because of the customers lack of trust to entrant companies with a shorter track record than the established incumbents.

2.5 Towards a framework

This chapter has reviewed the most central and relevant literature on infrastructures and on sectoral differences for technological change. Because the aim of the thesis is to explain technological change in infrastructure sectors, I decided to do a case analysis of the HVDC industry. That this is a particularly interesting industry to study should be clear from the previous discussion.

How does earlier research on infrastructure fit into all of this? My research question is regarding technological change in infrastructure sectors. The HVDC subsea industry is my case and I define this as a part of an infrastructure sector (the HVDC sector). Earlier research indicates that infrastructure sectors are special, with a range of properties that I presented in section 2.3.2. The combination of these properties of infrastructures implies that "infrastructures generate stability and path dependency in both positive and negative ways to a larger extent than other sectors in society" (Andersen, 2014). Therefore one suspects that infrastructures only evolve gradually with incremental changes along established paths (path dependency), posing barriers to fundamental transformation of society at large (Markard, 2011). I hypothesize that these traits we find in infrastructure sectors should also be found in the HVDC industry because I conceptualize that this industry belongs to an infrastructure sector.

To do a thorough analysis of the HVDC industry, several theoretical frameworks were considered. These included national systems of innovation, technological systems of innovation as well as the multi-level perspective, but all were rejected because they provided too wide a lens for this particular case. They might better serve purpose for analyzing transitions in the past or for discovering general bottlenecks at a macro level. We, however, would like a closer look at the HVDC industry, and therefore preferred a lens with a 'narrower viewing-angle'. The sectoral system approach gives us a very useful framework for 'interrogating' the industry because it is divided into three categories with several parameters within each category. Following these categories and parameters, I can analyze my data, place them in the relevant areas, and thereafter compare them to earlier empirical findings from other sectors. Also, the sectoral system is designed to match different levels of disaggregation all depending on the goal of the analysis. Looking at what could be defined as an industry instead of a sector should therefore not be a problem as long as the boarders are clearly defined (Malerba, 2011, p. 387).

2.6 Conclusive remarks

In sum, this chapter started with a section that argues that innovation varies strongly across sectors and concludes that little research has been done on the cable industry and/ or industries related to infrastructure sectors. The second part of this chapter discusses the research literature on infrastructures and argues for applying systemic approach. Theoretically, this thesis is important for two reasons:

A) Given the major differences in the organization of innovation across sectors, the impact of governmental policies may drastically vary across sectors. There is therefore a need to study different sectors in great depth, both empirically and theoretically (Malerba, 2011). Studying the HVDC subsea cable industry gives us several clues as to how infrastructure sectors behave and are affected.

B) If we are to succeed in an energy transition, there are important bottlenecks within the (electric) transmission system that we need to solve. To do this, we need to understand how infrastructures changes. This chapter argues that to understand this one would need a systemic look. This thesis can then contribute to the understanding of one of most important the supply industries connected to infrastructures, namely the HVDC subsea cable industry.

Not all theories presented in this chapter will be used in the empirical and analytical chapters of this thesis. They do however give a backdrop as to why research on innovation in the HVDC subsea cable industry is useful. Another reason for the presentation of the literature in this section is the need for former insights in order to construct the research question, select an appropriate case and define a methodological approach.

3. Methodology

The choices of design and approach

This chapter presents the choices made with respect to research design, research objects as well as how the data was collected and analyzed. This will contribute to transparency and the reliability of my findings. I will first introduce the qualitative study approach and look into the case study as a method of research, before I present how and why this approach was chosen. I will also explain the process of data collection and discuss reliability, validity, biases and ethics.

During most of the course of writing this thesis, I was a research assistant on a research project about innovation in infrastructure systems in Europe. As it was my role as a research assistant to gather data on cable technology as well as the European cable industry, it became increasingly clear that it would be more efficient to write a thesis on the same topic. This way my work for the research project would contribute to my thesis, and my thesis would contribute to the research project. In all of the interviews the project manager lead the interview or was a participant. This was done because our informant’s competences were overlapping in our respective research areas.

3.1 Qualitative studies and case studies

Qualitative studies seek to understand casual relationships that are too complex to be discovered by quantitative designs (through for example surveys). Qualitative studies are used by a range of different schools, but common to them all is that they seek to answer questions that are not quantifiable, such as *how* and *why* questions. One can also look into to decision-making processes. Qualitative studies, on the other hand, seek to answer *what, where,* and *when* questions which indeed are quantifiable (Winchester & Rofe, 2010; Yin, 2009, p. 19). Since my research is a *how* question, the qualitative method is my preferred choice.

To be more precise, this thesis uses a qualitative case study approach. According to Gerring (p. 342 in Baxter, 2010, p. 81;) a case study is ‘an intensive study of a single unit for the purpose of understanding a larger class of (similar) units’. This fits well with this thesis because I seek to understand how technological change comes about in infrastructure sectors, but with the HVDC sector as my case unit. By using a case study approach the idea is that by interviewing a representative selection of actors from the HVDC subsea cable industry I can generalize to the rest of the sector and perhaps also the infrastructure sector. Also, a typical case study is designed to help our understanding of a contemporary system where the researcher does not have control of the behavioral elements (Yin, 2009, pp. 25–26), which is also the case in this industry. However, a case study is not necessarily a method, but rather an approach or methodology to research design. This is because there is the assumption that studying a case (or phenomenon) in depth is valuable on its own without specific regard to how the findings can be applied to cases not studied. This understanding may concern solving practical problems associated within a certain case, or broadening our academic understanding (theory) about the phenomenon in general, or both(Baxter, 2010, p. 82). This thesis touches upon both of these things. My aim is to understand how organization is organized in the European HV cable industry, which gives me an answer as to how this industry is organized compared to others. I have some theoretical hypothesis which I also would like to explore, such as if infrastructure traits define the organization of innovation activities within the industry. It will also be a contribution to theories of sectoral systems of innovation by testing these as a framework to analyze the HVDC subsea cable industry. Through this case study I therefore hope to expand both the empirical and theoretical understanding of relevant, similar or connected industries.

3.2 Research question and research design

As briefly mentioned in the former section, the research question has been continually modified as new empirical and theoretical information was uncovered. My starting point was developing theory to guide the research design. New discoveries were made by reading a wide range of theory (theories on sectoral patterns, transition, infrastructure, innovation systems, amongst others) and through dialog with my supervisor. According to Yin (2009, p. 10) using the time to take these tours and detours are a necessary and important part in a research process, and the time consumed has therefore perhaps strengthen the explanatory power of my research question. Early scoping interviews with different actors as well as a thorough documentary analysis were made to get an overview of the state of things in the industry. As my research question developed it became increasingly clear that the case study would be the most fitting as the cable industry proved to be the theoretically and empirically most fitting case to research. Though early research on websites and scoping interviews did provide a very useful backdrop, it was evident that there was little public information about innovation activities themselves. Therefore, to unravel information I had to conduct interviews with persons with expert knowledge in the industry. The units of analysis, in other words my informants, were carefully selected in dialogue with my project manager. I also identified other informants by talking to industry experts. After the interviews and document analysis the data was collected, organized presented and analyzed with the aim of contributing back to the literature from where my research once began.

3.3 Units of Analysis and Data Sources

My main unit of analysis, the unit I wish to look into and say something about, is the *high voltage direct current subsea cable industry* in Europe. The suppliers constituting this industry are the cable manufacturers and constitute my main data source. Since there is one industry (one main unit of analysis) this implies a single case study, accompanied with sub-units (the manufacturers and industry experts).

In collaboration with my project manager a total of thirteen interviews were done. Two interviews were done with DNV GL and TenneT, and one interview with CIGRE (International Council on Large Electric Systems), STRI, and Dong Energy. Six interviews were made with three different cable companies (one company was interviewed four times), but due to them wishing to be anonymous the company names will not be mentioned. It is my assessment to not give out which of the cable producers I interviewed, as the information they provided would be "easy to track" because of the very small HVDC market. In this market there are only a handful of established companies and potential entrants, as section four will explain in detail. When information from an interview is used, it will be noted by a parenthesis following a coded name: Alpha, Bravo, Charlie, Delta, et. cetera. See appendix 1.

In general, it proved very difficult to get the cable companies to talk about their innovative activities and therefore I only managed to interview three. My original thought for this thesis was that the cable companies would be my main source of input, but it turned out I would have to use data from other actors as well since the cable producers mostly declined my proposals for interviews.

3.4 The Collection of Data

According to Yin (2009), when looking at explaining a phenomenon it is an advantage to collect data from multiple sources of that phenomenon. He mentions six sources to acquire data; archival records, documentation, interviews, observation (direct and participatory) and physical artifacts (Yin, 2009, pp. 101–112). To answer the research question two sources of data gathering has been used: documental analysis and interviews. These were chosen because I needed hard data to argue why I expected the HVDC subsea cable industry to have a strong growth. The number of projects confirmed in the wind energy sector were found in documents from the European Wind Energy Association (EWEA), whereas data regarding cables to interconnector-projects were gathered manually from a range of websites. The mere size of the HVDC sector made it a tremendous job to get a proper overview of the different actors, partners and coalitions related to innovation activities. It was therefore necessary to interview persons that had many years of experience from the industry and therefore a good overview. Data by observation or participation would not be efficient enough time wise, because the innovation processes passes over very long periods of time. Also a few hours of participation would only show a small portion of the innovation activities within a firm and in turn of the industry. Physical artifacts, a technological device, a tool or instrument or some other physical evidence, can be collected or observed (Yin, 2009, p. 114). This was not deemed fitting for my research, even though models of cables were looked at to get technical insight into the build-up of a cable.

3.4.1 Interviews

According to Hay (2010), there are three forms of interviews: structured, unstructured and semi-structured. Structured interviews follow a standardized and predetermined list of questions, and the questions are asked in almost the same way and in the same order in each interview. Unstructured interviews are driven by the informant rather than the interviewer (or the set of questions). Semi-structured interviews follows a predetermined set of questions but the interviewer may diverge from these if the informant says something besides the questions that is worth while pursuing (Dunn, 2010, p. 102). When considering the different forms of interview techniques, it is important to reflect upon which questions one wishes to ask and what answers you are looking for. For example, when starting my thesis, I called different actors for an informal chat regarding different possible research questions. In these scenarios I used an unstructured method where I had written down some questions, but I was mostly interested in letting the informant, as an industry expert, lead the way to what they believed were the most relevant topics and question to pursue. This was because I wanted more insight into the industry and a broader understanding of how I could mold my research question.

Interviews are contextually sensitive (Patton, 2005) and therefore the interview guides were modified depending on the informant. For example, CIGRE, as a business expert, would not know the production capacity and the collaborations of a cable producer, but has knowledge of how the industry in general meets, and has an important role to play as a standard developer and could therefore answer questions to the development of new standards. Four interview guides were created (see appendix 2) for the interviews. For all of them the semi-structured method was selected. This was chosen because in qualitative method even though you are pursuing a consistent line of inquiry, the actual questions asked are likely more fluid than rigid (Yin, 2009). If a more rigid method was preferred, I would not have the possibility to follow up on issues that were not predefined in my interview guide.

3.4.1.1 The process of the interviews

To get a hold of informants I would first call the company and describe what kind of competence I would need for my interview. Most receptionists would then put me in contact with the right section in the company, where I would talk with a person who in turn might know who I could talk to. When, and if, I got the right person's contact information I tried establishing contact by phone (or email) to explain my project. If that succeeded I would send an email with a question guide as well as a description of the project in detail, underlining that information could be anonymized if they wished, and describe why it was important with the informant's contribution. If they accepted, I would then proceed to arrange a date for the interview.

However, as already mentioned, it was difficult to get the cable manufacturers to come for an interview. The high level of knowledge required about the industry demanded highly ranked staff with years of experience and thorough knowledge. Some of the cable manufacturers are very large companies where getting hold of personnel of a certain stature is quite difficult as they are often very busy. If they did have the time some would decline because the information was too classified to share, even if I argued the information would be disclosed in the thesis and anonymized. Unfortunately, most cable companies declined my request even though both myself and my project manager tried convincing them otherwise. As already mentioned, this thesis therefore also relies on expert knowledge of the industry from other actors besides cable producers.

For some I tried using the snowball method to get hold of new informants. This method consist of asking my informants if they can set us in contact with other informants (Thagaard, 2009). This proved to be a quite effective method to get a hold of general industry experts. The informants would usually name former colleagues that had moved elsewhere. With the informants' permission I could establish contact with the new informant by namedropping his or her friend / former colleague. The new informant would trust his or her former colleague's assessment of my research project being something worth helping and it would therefore be much easier for us to get replies and set a date for an interview. With this efficient method I made contact with new informants in CIGRE (twice), two cable companies (although one of them ultimately declined, unfortunately), and DNV GL.

As mentioned a total of twelve interviews were made. One was a quick conversation by phone with a written follow-up by mail, seven of these were made at the offices of the informants, and the rest by phone in my supervisor's office. Most of the latter eleven lasted about 1,5 hours. All of them were recorded by smartphones using various recording applications to the informants' consent.

After some interviews my knowledge and know-how of the industry and technological aspects rose. This meant that it was easier for me to have the capacity to follow the conversation and also take some notes during the course of the interview. The note-taking would be particularly useful if I had follow-up questions I needed for later on in the interview. Note-taking is also important if something the informant is saying is unclear or confusing. I would then take a note, let the informant finish his line of reasoning and then ask him immediately afterwards about what I did not understand. It is important not to let things pass by that you hope to make sense of later (Dunn, 2010). An obvious advantage of face-to-face interviews compared to the telephone interviews were that phone calls are of lesser quality and thereby less clear in tone that a real life interview, making it harder to hear what the informant is saying. Also, facial expressions make communication easier, as the informant might give away facial clues if they understand the question or not. About half of the interviews were done in Norwegian (and Swedish and Danish) and the other half in English. To be sure there were no major language barriers I would ask the informants if they preferred a Scandinavian language or English.

After the interviews the recorded conversation would then be transcribed alongside the already written notes to make sure no information was lost. Since the interviews were done alongside my project manager it was easier to have the capacity to take notes, also, the conversations between the two of us after the interview would give me the chance to clear misunderstanding or uncertainties that arose during the interview. There were no technical problems or loss of data during the collection process.

3.4.2 Document analysis

I have gathered extensive data from document sources on all my sub-units. This was largely also a part of my job as a research assistant, and as such I was already quite familiar with most of the technological terms prior to the interviews. The documents were mostly webpages, but also power point presentations from different seminars where new technology from different cable producers had been presented. Also reports made by the ENTSO-E, EWEA and Europacable were largely used to understand the market development and the traits of the different technologies. The documentary analysis was time-consuming as much of the information on cable producers' websites are made for engineers already trained in transmission technology. This is because the technology they produce is far from a normal consumer good, with usually just a handful, but very large, projects each year that are ordered by TSOs that already have expert staff trained in the field. The documentary analysis is, however, less time consuming than many other research methods (Punch, 2005, p. 184) and made me understand some of the dynamics of the industry which in turn helped us ask the right questions. Also reading documents as an additional source of data might strengthen the validity of the evidence. Documental analysis also has some strengths versus for example interviews. In interviews communication misunderstandings such as subjective coloring of the answers or questions (either verbally or by body language) or misunderstandings regarding questions could have major impacts on the answers given. With documental analysis it is solely the text and the researcher and this eliminates some of the variables in an oral interview. Still, however, the researcher might misinterpret data in documents. To avoid this, I would try to get crucial data from documents confirmed orally by my interview objects. Indeed, having many sources of data (called *triangulation of evidence*) can strengthen the validity of data (Yin, 2009).

Getting the data from all HVDC projects since the 2000 has also been a time-consuming effort. There are various data-sheets out there, but comparing them to each-other and also to HVDC cable manufacturer's websites, I recognized that none of them were complete with regards to the level of detail that I wanted. A thorough data-sheet containing (hopefully) all the HVDC cable projects since 2000 has therefore been a continuous work in progress as I discovered new projects. Included in this data-sheet are also some technical system operators (TSOs), installation and maintenance companies and energy production companies[9]. See appendix 3 at the end of this thesis for a screenshot of the database.

[9] Data was collected from energy consulting company 4C Offshores database on offshore windfarm projects as well as CIGRE's online HVDC project database. The data on interconnectors was collected from ongoing HVDC projects from the websites of ABB, Nexans, Prysmian and Siemens. The Wikipedia article on HVDC projects was also used. Other data was gathered by reading project descriptions at the TSOs websites.

3.5 The Process of analysis, reliability and validity

The empirical findings were quite systematically arranged already after transcription because I asked several smaller questions. Because of the multitude of questions, it was easy to track down information based on topic and no further coding deemed necessary. The empirical findings were analyzed using the theoretical perspectives presented in chapter two, largely using the categorization technique to interpret the data. I then put the data into different categories based on traits from sectoral system theory and based on traits found in infrastructure systems.

Reliability is achieved if the findings are consistent over time, meaning to what degree other researchers would achieve the same results given they use the same methods and are analyzing the same units as the previous researcher has done. High reliability also demands that the findings are coherent throughout the different sources in an analysis – that the sources all work in the same direction (Punch, 2005, pp. 95–96). Through my interviews it became clear that my suspicions as well as my findings in earlier document analysis matched with the data from my informants. My findings were coherent throughout my interviews as well. These findings help the thesis' reliability. Reliability may be improved further by more research on the innovation activities in the HVDC subsea cable industry. However, the industry dynamics may also change over time and thereby alter the results meaning that a different result than mine years from now does not necessarily imply low reliability. The worlds changes and so does data, therefore, to achieve high reliability it is also important that the research has been executed in a way that is reliable and trustworthy at that given time (Yin, 2009). The researcher can achieve this by being critical and reflected over the context and environment the data was collected in, and also being transparent on his research methods. It is also important that one is aware of how the informants as well as the researcher himself may be affected by their beliefs and experiences (Thagaard, 2009). I have tried to achieve high reliability by explaining my methods in this chapter, as well as being clear on when I recite informants and when I do my own interpretations in my analysis in chapter 5.

Validity refers to the correspondence between the gathered data and reality (Thagaard, 2009) and can be divided into four considerations.

1. Validity of data. How is the researchers own evaluation of how the data represents the phenomenon of research?
2. Internal validity. Does the study reflect the real-life phenomenon?

3. External validity. To what extent can the study be used to generalize to other settings?
4. Overall validity. Do the different parts of research logically fit together? (Punch, 2005, p. 29)

My own assessment is that I have strived to strengthen all of these considerations. Firstly, I used much time reading different theories to make sure my theoretical framework was fitting for my case. My theory has at least been rewritten twice and I am quite satisfied with the finished framework. The framework is a mix-up of two different schools of theories and could therefore be confusing, but I have indeed strived to make them logically put together for the reader. To reflect the real-life phenomenon, I have chosen what I deemed as the most representable sub-units as units of analysis. Both producers, consultants, customers and experts of the HV cable industry have been interviewed to give a thorough understanding and real-life illustration of the industry.

3.6 Biases and Ethics

A major concern for a researcher is the question of bias. This means that the researcher must avoid doing research to confirm preconceived positions (Yin, 2009, p. 76). Other examples of bad bias is choosing sources that do not reflect the whole industry, asking leading questions, misinterpreting data, or manipulating events (Yin, 2009, p. 102). To avoid bias, it is important that the researcher is constantly aware of bias and is open to findings that counter his hypothesis. A critical discussion regarding the researcher's theoretical framework and findings can help reduce the bias and in turn increase the thesis' reliability.

Ethical concerns are an important part of qualitative research because usually the research involves real persons (Punch, 2005, pp. 276–277). To ensure that ethical considerations are met it is important to ensure the well-being of all involved parts in the research. The informants must be chosen because they are assumed to be the best sources to illuminate the case and it is important to keep them well informed of the process (how will the information given be used) (Ragin & Amoroso, 2009). I have strived to have the highest ethical standards possible by being polite to informants, transparent about the process and also offer them anonymity.

4. Context

The European HVDC subsea cable industry

This chapter starts by giving an overview of the many abbreviations used in this thesis. It continues with explaining what a power cable is and why HVDC is an interesting cable technology. Then it explores the relevant history of the European HVDC subsea cable industry, the main technological developments and market trends within the last decades. To conclude, some of the features that might make the industry special are outlined.

4.1 Abbreviations

HVAC	High voltage alternating current. Alternating current is the most used form of current in modern transmission of electricity, bot at low, medium and high voltages.
HVDC	High voltage direct current. Today mainly used for high voltage transmissions over long distances.
LCC	Line-commutated converters. The older form of converting direct current to alternating current and vice versa. Uses thyristors and can only be turned on.
VSC	Voltage-sourced converter. A newer form of converting direct current to alternating current and vice versa. Uses transistors, and can be turned off and on.
MI cables	Mass impregnated cables have been in used since 1895. They consist of a conductor, a layer of paper impregnated with oil acting as isolation, and an armor sheet. Used for both AC and DC transmission.
XLPE cables	Cross-linked polyethylene cables are the most cable technology used in modern day AC

	transmission and is starting to be used in HVDC as well. Using XLPE on HVDC was first available with the introduction of the voltage source converter.
TSO	Technical system operator – usually a publicly owned company that is in charge of running, expanding and maintaining the national electricity grid.

4.2 Cable technology

A cable is not just a cable. Cables come in a wide range of sizes to accompany different uses, from transferring various data signals to electricity. There are simple thin cables that are based on basic technology that one, with a few tools, could create in your own living room. This thesis, however, focuses on high voltage power cables – made for high voltage direct current (HVDC). These cables have seen major improvements over the years and the most advanced HVDC cables are only being produced by a handful of actors worldwide.

My focus in this study will mainly be on HVDC cables as I see them as the most frequently used cable in the two markets we suspect will increase: cables for connecting offshore windfarms to shore, and cables for interconnectors between countries. This chapter seeks out to explain what is behind HVDC cable technology and why HVDC is interesting in comparison to the more common HVAC technology.

4.2.1 What is a power cable?

Power cables are a way of transferring electricity either underground or underwater from power plants to residential or industrial areas, or as means of exporting or importing power from other countries (interconnectors). Power *cables* are rarely visible to people, in contrast to power *lines* that are above ground and visible.

Power cables are categorized in different voltage categories, low, medium, high and extra high. Their respective voltage capacities vary between contexts and counties due to historical reasons. In this thesis I will use the capacity definitions made by Europacable (Europacable, 2014a). The categories and their respective capacity are presented in the table below.

Name	**Capacity (volts / kilo volts)**

Low voltage cables	50 - 1000 V
Medium voltage cables	1000 V to 36 ~ kV
High voltage cables	~ 60 kV to 150 ~ kV
Extra high voltage cables	~ 220 kV and upwards

In this thesis I will not differ between *high* and *extra high* voltage, and classify them both as *high*.

4.2.2 Why cables?

Traditionally, overhead power *lines* have mainly been used to transfer electricity, as most power plants were, and still are, on land. Power plants are usually located far away from residential areas to avoid local pollution and general impact on local environment. However, people often regard power lines as interference with local nature and lines have traditionally been frowned upon. With increased population and thereby more densely populated areas, keeping power lines hidden is an increased effort. Several countries are looking into replacing fossil power plants with windfarms, and environmental conditions may apply so these farms cannot be placed far away from populations. Cables may in both these cases be a part of the solution, as cables are underground or underwater and therefore have minimal impact on the environment.

4.2.3 Why direct current?

High voltage direct current is a way to transfer electricity with high voltage and direct current (DC) across long distances. An HVDC cable is an alternative to the more traditional alternating current (AC) systems, which most of the European grid exists of. AC has been the most preferred technology due to its ability to scale the voltage from high to low and back. This is done through induction, a physical property in AC current that does not work with DC. The transformation is done through transformers, which are inexpensive and easy to install close to the end users. The voltage in DC cables cannot be descaled with this technology and has to use more expensive converters at each end (to convert to AC). This means that shorter lines using DC are relatively expensive. Scaling is necessary because the voltage level needed for normal appliances is categorized as low (mains voltage in Europe is usually at 400 volts), while transferring power from a power plant is usually at least 50 kV and higher. The procedure of descaling the voltage from high to more manageable low voltage is therefore a major advantage with AC than DC (Tell, 2012).

This is not to say there are no advantages with DC over AC. One major advantage is that the loss of electricity in direct current (DC) cables can be as high as 60 % less than in alternating current (AC). Also, with direct current only two conductors are needed, creating a smaller and cheaper cable (Siemens, 2014). This makes the DC technology economically competitive for longer distances, where the costs of building extensive terminal converter stations (which are not needed for AC) are lower than what you gain from the lower manufacturing costs and lower electricity loss in the cable. As a result, for underground cables that are longer than 80 km, DC is often regarded as the cheaper and more efficient alternative for transferring electricity (Siemens, 2012).

According to Europacable the two technologies are as of now seen as complementary: AC power transmission is suitable for relatively short connections, while DC is the most appropriate technology for carrying high power over long distances practically without any loss. At present, Europe’s networks are based on meshed AC electricity grids. In the future, these will be complemented by a high power DC overlay network. While DC connections today are typically used to transmit or exchange power point-to-point, meshed or multi-terminal DC grids will become available as HVDC switchgear technology[10] gains market access (Europacable, 2014c).

4.2.4 The technology behind high voltage DC cables

Modern power cables come in different sizes using different materials, each adapted to its use. This is because the demands to the cable differs widely from each application. Common to them all is the buildup: a conductor (there may also be several in one cable) in the middle, insulation and then a protective jacket. The function of these layers is to prevent air-filled cavities between the metal conductors and the dielectric so that little electric discharges can arise and endanger the insulation material. The design and material used in a cable are determined by several factors:

[10] Equipment used to control, protect, and regulate the flow of electrical power in a transmission or distribution network. It is often located in substations, but can be associated with any electrical equipment that might need to be isolated for fault correction (e.g., if a voltage drop occurred in one part of the grid, it might be necessary to shut off the affected section to prevent the fault spreading), or for maintenance purposes. The main components of switchgear are circuit breakers, which interrupt high-voltage current to protect electrical equipment from excessive current (ABB, 2014a).

- Environmental conditions. Will the cable be exposed to sea water, sun, chemicals or extreme temperatures?
- How much voltage will it carry? This determines the thickness of the insulation.
- How much current will it carry – alternating or direct current? This determines the size and number of the conductor(s).

The buildup of the XLPE AC and DC cables is similar and they use the same technologies for sheathing and armoring. As with the AC cable, the cleanliness of the insulation is imperative, but with DC cables there are higher demands to the performance of the insulation because the semiconducting layers must be absolutely smooth to avoid buildup of electric discharges (Kreuger, 1991). For AC cables, plastic is most often used as the insulation material. For HVDC there are, however, three different insulation materials – all with different traits: Self-contained fluid filled cable (SCFF), mass impregnated paper insulated (MI) and plastic insulated (extruded XLPE, a stronger version of the regular XLPE used in most HVAC cables). There are still many SCFF cables in use in Europe, but all producers have stopped creating those. Therefore, this thesis will only focus on MI and XLPE cables.

HVDC systems have been in commercial use since the 1950s and the most widely used design is the use of MI cables and line-commutated converters (LCC) (BVG Associates, 2013). New converter technology called 'voltage source converters' (VSC) was developed in the early 1990s by Swedish and Swizz company ABB. The discovery of the VSC made it possible to use XLPE cables also in HVDC, because the strain on the cable when converting is much less when using VSC instead of the old LCC converter technology. The converter technology used is therefore crucial for what cable you can use in that system (Alpha).

Extruded XLPE cables are therefore the most modern of the three different technologies and are seen by several companies and organizations as the future dominant design of power cables (Prysmian Group, ABB, Nexans, Europacable). The first installation of VSC converters was done in Sweden in 1997, however on a power line (not a cable system) and with only 10 kV. This was done in collaboration with the local power utility, VB-Elnät. The power utility let ABB test the system on an existing 10 km long back-up AC line (Asplund et al., 1997). The first commercial subsea extruded HVDC cable was installed in 2002 between Long Island, New York, and Connecticut in the United States by ABB using VSC converters (Worzyk, 2009). The main advantage of extruded XLPE cables over their HVAC counterparts and older MI HVDC cables can be found in their highly reduced weight and dimensions. This means that the power (MW) transported per kilogram cable is higher for XLPE cables than other cables. When compared to HVAC, the difference is even greater because an AC cable system needs three conductors, whereas a DC cable system only needs two. Three-phase AC extruded subsea cables have approximately twice the weight compared to a pair of subsea HVDC extruded cables (ABB, 2009).

4.2.5 Technological developments since 2000

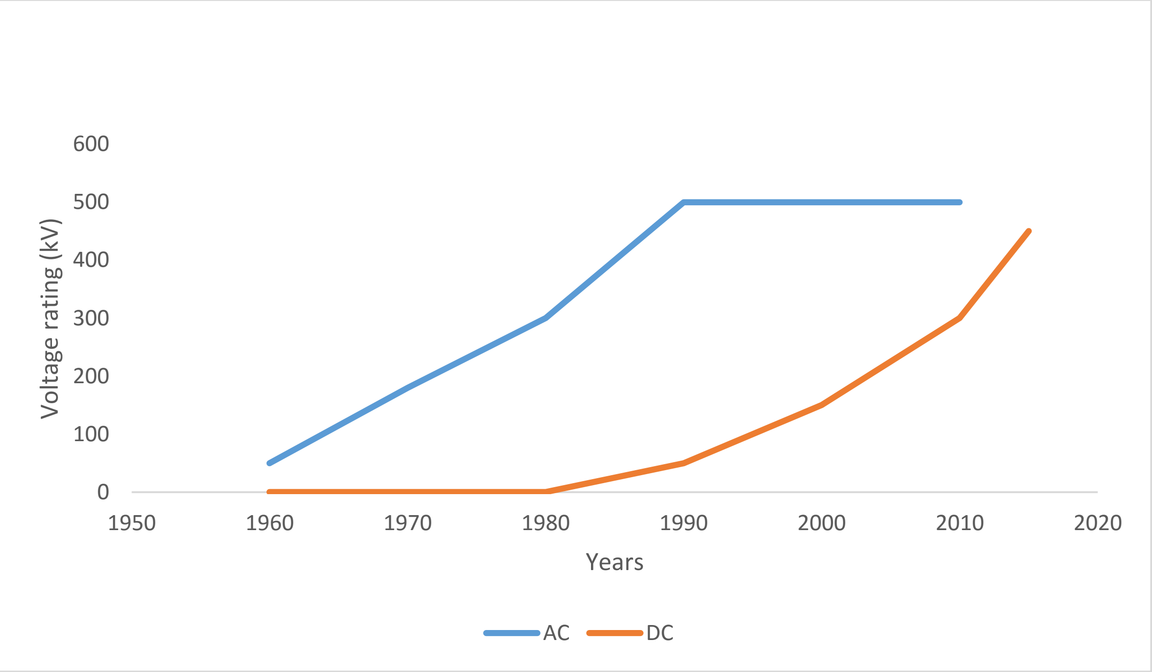
The main turning point in the HVDC subsea cable industry during the last fifteen years is the new isolation technique for HVDC cables, the extruded plastic (XLPE), that was made possible with the introduction of the new converter technology. This is cheaper to produce than the much older paper mass impregnated cable or the fluid filled cable which have been in use since 1895. The XLPE insulation technique has been used for HVAC cables since the late 1980s, but was first used for HVDC cables in 1998. This technology has seen a major increase in maximum capacity, increasing from around 100 kV in 1998 to 525 kV with the launch of ABBs XLPE HVDC cable in 2014.

For the development of the new 525 kV XLPE cable, a close collaboration between the R&D centers of ABB and Borealis[11] was established. Borealis were involved to develop a robust insulation material. A wide range of insulation materials including thermoplastics, cross-linked insulation systems, polymer blends, filled and non-filled insulations were studied. Finally, a new grade of non-filled XLPE insulation material with optimized chemical, mechanical and electrical properties was developed. Cables from model to full scale cables were produced and tested (ABB, 2014b).

[11] Borealis is Europe's second largest producer of polyethylene (PE) and polypropylene (PP) (two types of plastic) and the world's eighth largest producer. HQ in Vienna, Austria.

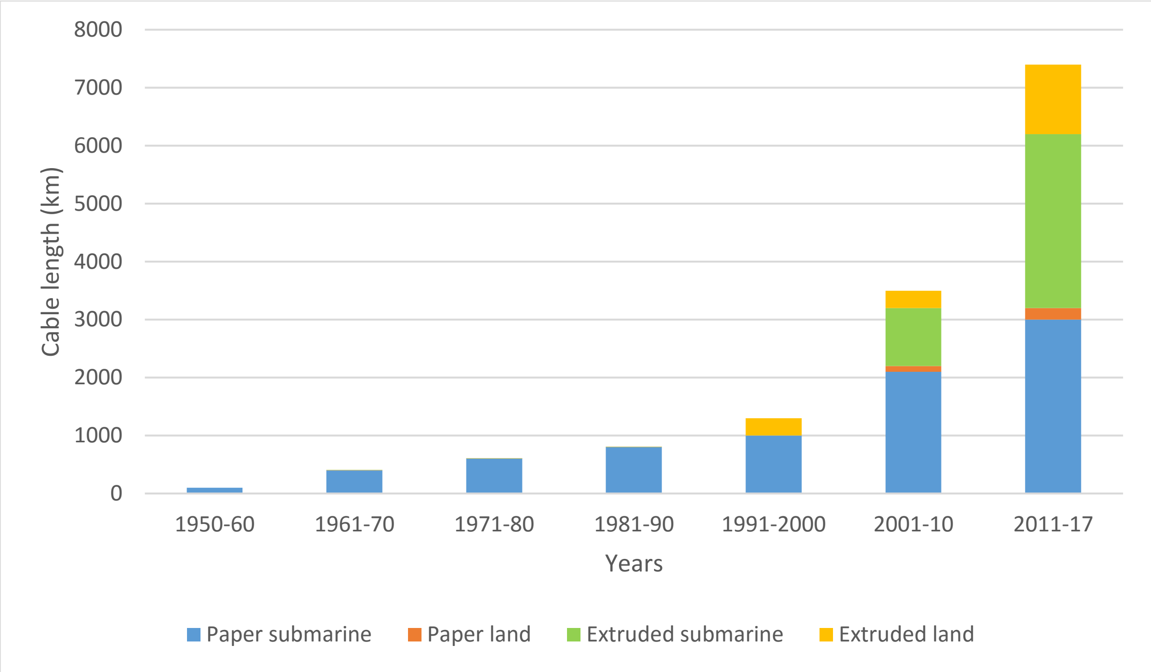
As we can see in figure 3, there was a steady increase in the voltage ratings of HVAC cables from the 1960s to the 1990s. From the 1980s to today HVDC has drastically increased in maximum voltage.

Figure 3: Evolution of voltage ratings of XLPE AC and DC high and extra high voltage power cables (Europacable, 2014b).



The trend in HVDC systems is to shrink the cable size, lower the cost and gain maximum voltage. As we see in figure 4, extruded cables, which are smaller than paper insulated cables, have been gaining the share of the market from almost nothing at the start of the nineties to over fifty percent today.

Figure 4: Increase in usage of HVDC cables and the different cable types (Europacable, 2014c).



4.3 Actors in the European HVDC industry

4.3.1 Producers

The high voltage cable industry in Europe is as of today dominated by a handful of actors. For large inter-connector cables (and the highest voltages) the main competitors are ABB (Swedish / Swizz), Nexans (French), NKT cables (Danish), and Prysmian (Italian), whereas General Cable (American, but with large manufacturing facilities in Spain and France) and LS Cable are seen as potential entrants by both customers and producers alike. Inter-connector operations are large and technically very advanced as there are extremely high demands to technological stability as well as high demands to the capacity of the cable. There are many uncertainties to installation as a result of the mere size of these projects (Delta). The companies competing for these projects are therefore not necessarily the same that compete for smaller projects with lower voltage. When looking at somewhat lower, but still high, voltages we can find many other providers such as Hellenic Cables (Greece), Parker Scanrope (Norwegian, recently bought by UK company Bridon)(Madshus & Reppe, 2015) and JDR.

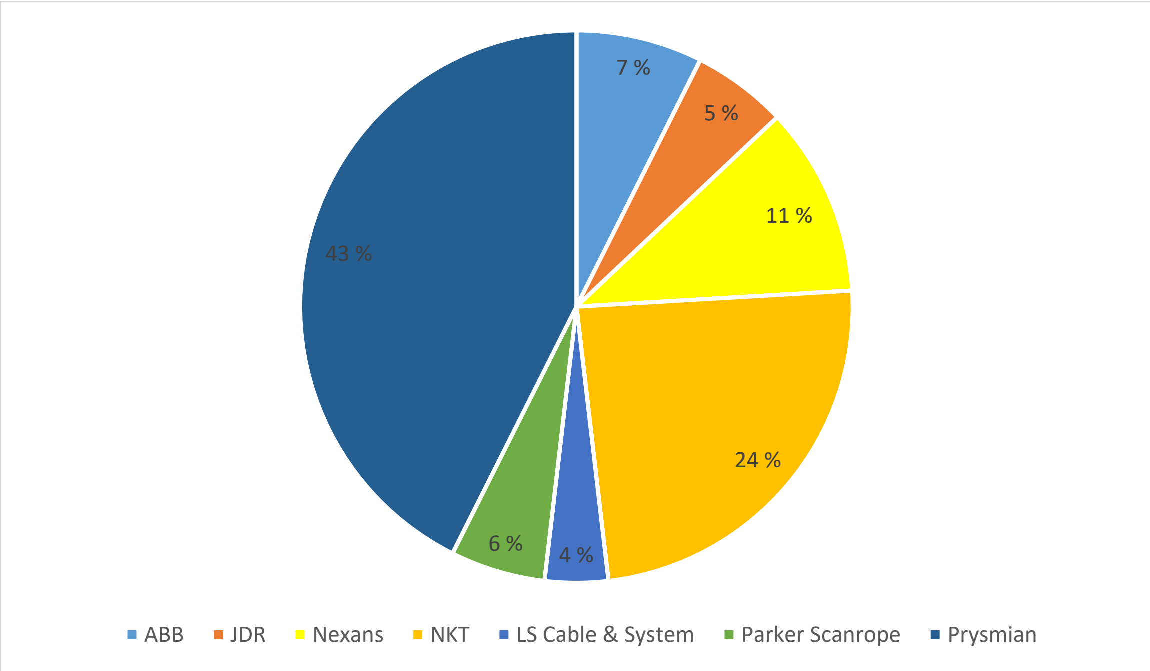
The sector that the HV cable industry is a part of consists of a range of different actors. There are the already mentioned cable producers, companies mostly constructing the cables and installing the cables, for example Italian Prysmian Group or Danish NKT Cables. Other cable producers also produce the necessary equipment around the cable, also referred to as the *cable system*, this refers to the necessary converter stations needed to either downscale the voltage to a necessary level, or converting from direct current (DC) to alternating current (AC) or vice versa. An example of a company producing cables and converter stations is ABB. Other companies only produce these converters and related equipment, but has no cable production. These companies will be discussed in more detail in section 4.1.2.

The cable companies that compete for the larger projects with the highest voltages, and sometimes with the more advanced direct current technology, are all large global companies that compete in several continents and have offices in most modern countries. Most of these companies' history stretches back to the late 19th century with the introduction of electricity. At that time the industry was dominated by a few large actors in each country, many governmentally funded companies. Through the years, companies have merged or been purchased, dividing the European market between a handful of actors (for further details see market share in section 4.1.1). Since 1999, the industry been exposed to several scandals related to cartel activities. For about ten years from 1999, 11 cable manufacturers had agreed allocation of important high-voltage power cable projects in the European Economic Area, including large infrastructure and renewable energy projects such as offshore wind farms. These companies were sharing markets and allocating customers between themselves almost on a worldwide scale. The European Commission imposed a total of 302 million Euros in fines for these companies. The companies were ABB (Sweden and Switzerland), Brugg (Switzerland), Exsym (formerly SWCC Showa and Mitsubishi Cable. Japan), J-Power Systems (formerly Sumitomo Electric and Hitachi Metals, Japan), LS Cable (South Korea), Nexans (France), NKT (Denmark), Prysmian (at the time called Pirelli), Silec Cable (formerly Safran: today owned by General Cable), Taihan (South Korea), and Viscas (formerly Furukawa Electric and Fujikura, Japan)(Wind Power Monthly, 2014).

4.3.2 Producer market share

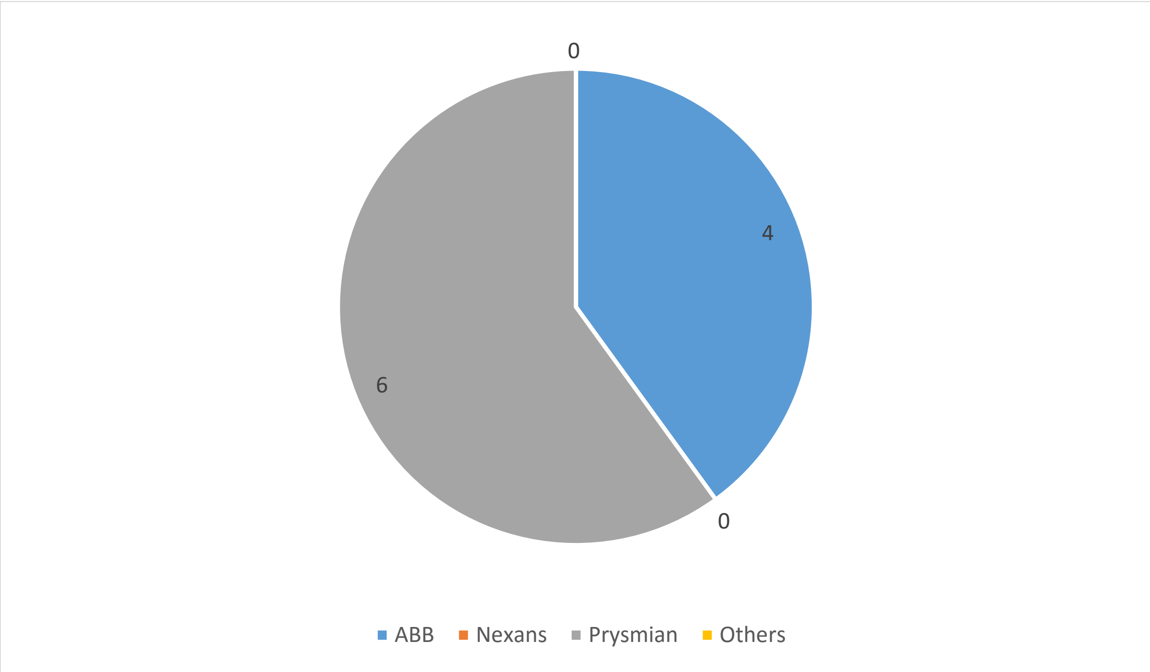
As we see in figure 5 there are perhaps more actors than suspected when looking at the different producers making power export cables for offshore wind farms. This is because many of these farms do not need HVDC because they are close enough to shore so AC will do.

Figure 5: Share of export cable suppliers from offshore wind farms in 2013 and 2014 (both AC and DC) (European Wind Energy Association, 2014a, 2015).



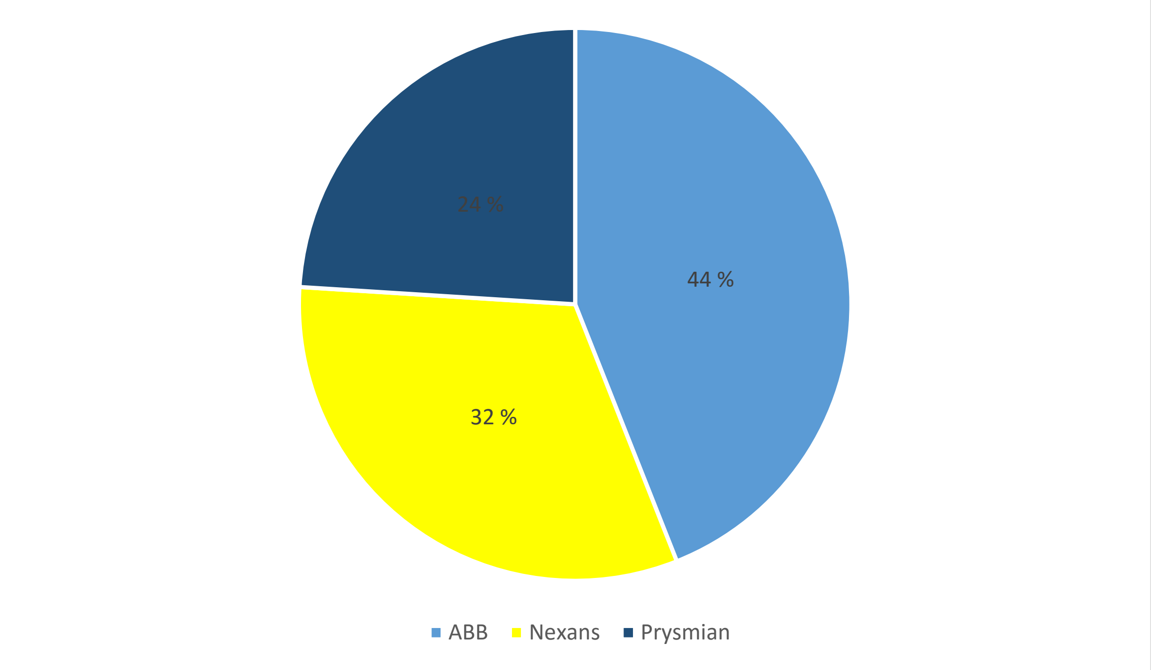
If we look at the market for HVDC export cables for offshore wind farms (figure 6), we find that only two cable suppliers (ABB and Prysmian) have delivered or are confirmed as a cable supplier in the time period 2000 - 2020.

Figure 6: Share of export cable suppliers from offshore wind farms using HVDC since 2000 to confirmed projects 2020.



If we look at the other expected growth market for HVDC (figure 7), the interconnector market, we find one other actor, the French company Nexans.

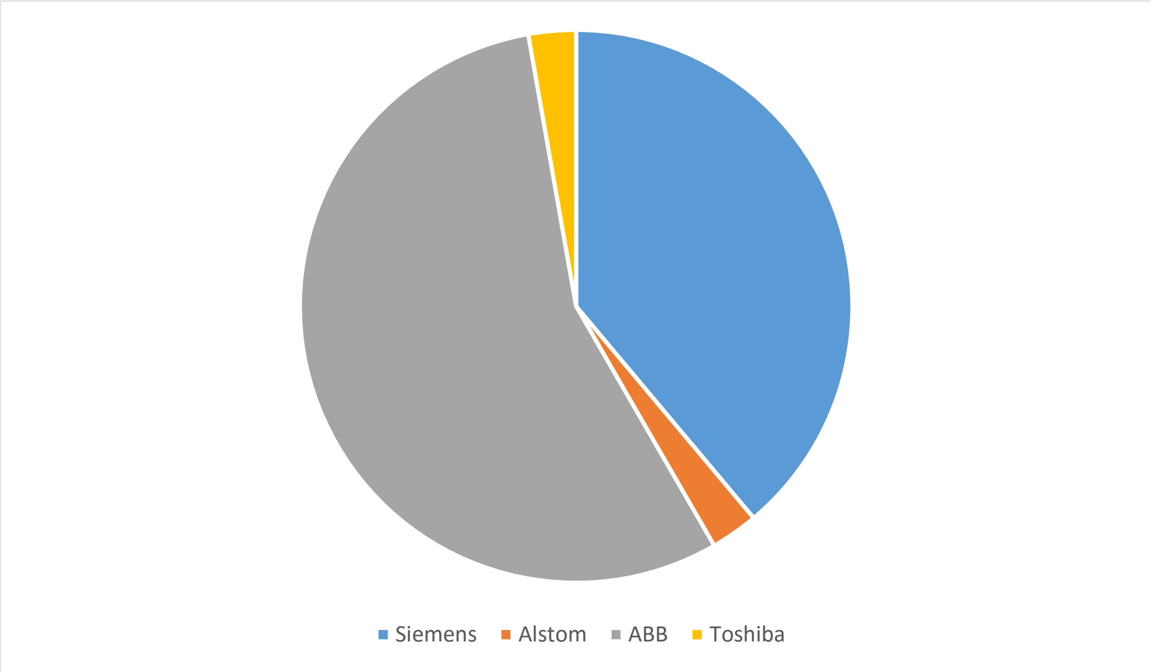
Figure 7: Market share between cable producers of completed or confirmed HVDC cable interconnectors Europe 2000 – 2020 (European Wind Energy Association, 2014a, 2015)



4.3.3 Other actors in the HVDC cable sector

As mentioned in the former section, there is a range of actors in the HVDC sector. Some companies are very much connected to cable companies because they produce the necessary converter stations for a cable system, but they do not produce the cables themselves. An example of this is Siemens and Alstom. When looking at larger HVDC projects in Europe, there are mainly three actors, ABB, Nexans and Prysmian. The only one of these companies producing the necessary converter equipment is ABB, which means that they are the only company that can provide the whole system. When Nexans or Prysmian are the cable producers we usually see a collaboration between them and a converter producer, in almost all cases, Siemens. See figure 8 for an overview of converter producers.

Figure 8: Overview of converter producers in HVDC systems above 50kV since 2000 to confirmed projects 2020[12]



Other companies in the supply chain provide subsea services with digging, installation and maintenance of cables. There are also companies within the chemical industry connected to the HVDC subsea cable industry. These companies typically collaborate with the cable producers in research and production of new chemicals and materials in the insulation around the cable (Alpha). An example of this is the collaboration between ABB and chemical company Borealis when developing the new 525 kV XLPE cable (ABB, 2014b) (more about this in chapter five).

Other companies are related to the development of standards or testing. In standards the two main actors are CIGRE (International Council on Large Electric Systems) and IEC (International Electrotechnical Commission). For testing equipment or external experts for supervising projects (consulting services), major actors are the Norwegian consulting and testing company DNV GL (fusion between *Det Norske Veritas* and *Germanischer Lloyd*), and the Swedish testing company STRI (India).

[12] Ibid.

4.3.4 Customers in the HVDC subsea cable sector

High voltage direct current cables are usually ordered by national governments to transport electricity from either a country to another or from a power source to a population. Thus, the customers are mainly national transmission system operators, so-called TSOs. There are a few exceptions, for example in Norway where the energy company Statoil (the Norwegian government is the major shareholder) ordered a HVDC cable to electrify one of their oil platforms. See table 1 for an overview of completed HVDC cable projects in Europe and their buyers since 2000[13].

Table 1: Overview of completed HVDC cable projects since 2000 in Europe.

Year	Name	Nations	Function[14]	Customer	Customer type	Kilovolts (KV)
2000	SwePol	Sweden / Poland	Intercon.	Svenska kraftnät (51%), Vattenfall (16%), PSE (33 %)	TSO	450
2001	Grita	Italy / Greece	Intercon.	Terna	TSO	400
2002	Moyle	Scotland / Northern Ireland	Intercon.	Mutual Energy	Energy company	250
2004	Troll	Norway	OOG	Statoil	Energy company	60
2006	Estlink	Estonia / Finland	Intercon.	Elering	TSO	150
2008	NorNed	Norway /The Netherlands	Intercon.	Statnett / Tennet	TSO	450
2009	NordE.ON 1	Germany	OWF	Tennet	TSO	150
2009	Valhall	Norway	OOG	BP	Energy company	150
2010	BritNed	UK / The Netherlands	Intercon.	National Grid	TSO	450
2010	StoreBælt	Denmark	Intercon.	Energinet	TSO	400
2011	Cometa	Spain	Intercon.	Red Eléctrica de España	TSO	250

[13] This chart is a small part of an ongoing database I constructed as a part of my work as a research assistant. Data was collected from energy consulting company 4C Offshores database on offshore windfarm projects as well as CIGRE's online HVDC project database. The data on interconnectors was collected from ongoing HVDC projects from the websites of ABB, Nexans, Prysmian and Siemens. The Wikipedia article on HVDC projects was also used. Other data was gathered by reading project descriptions at the TSOs websites. See appendix for screenshot of the data-sheet.

[14] OWF = Offshore windfarm.
OOG = Offshore oil / gas
Intercon = Interconnector.

2011	SAPEI	Italy	Intercon.	Terna	TSO	500
2011	Fenno-Skan 2	Sweden / Finland	Intercon.	Fingrid Oyj	TSO	500
2012	Borwin1	Germany	OWF	TenneT	TSO	150
2012	Romulo	Spain	Intercon.	Red Eléctrica de España	TSO	250
2012	East–West Interconnector	UK / Ireland	Intercon.	EirGrid	TSO	200
2014	Estlink 2	Estonia / Finland	Intercon.	Elering	TSO	450
2014	Skagerrak 4	Norway / Denmark	Intercon.	Statnett	TSO	400
2015	BorWin2	Germany	OWF	TenneT	TSO	300
2015	HelWin1	Germany	OWF	TenneT	TSO	250

4.4 Market predictions and developments since 2000

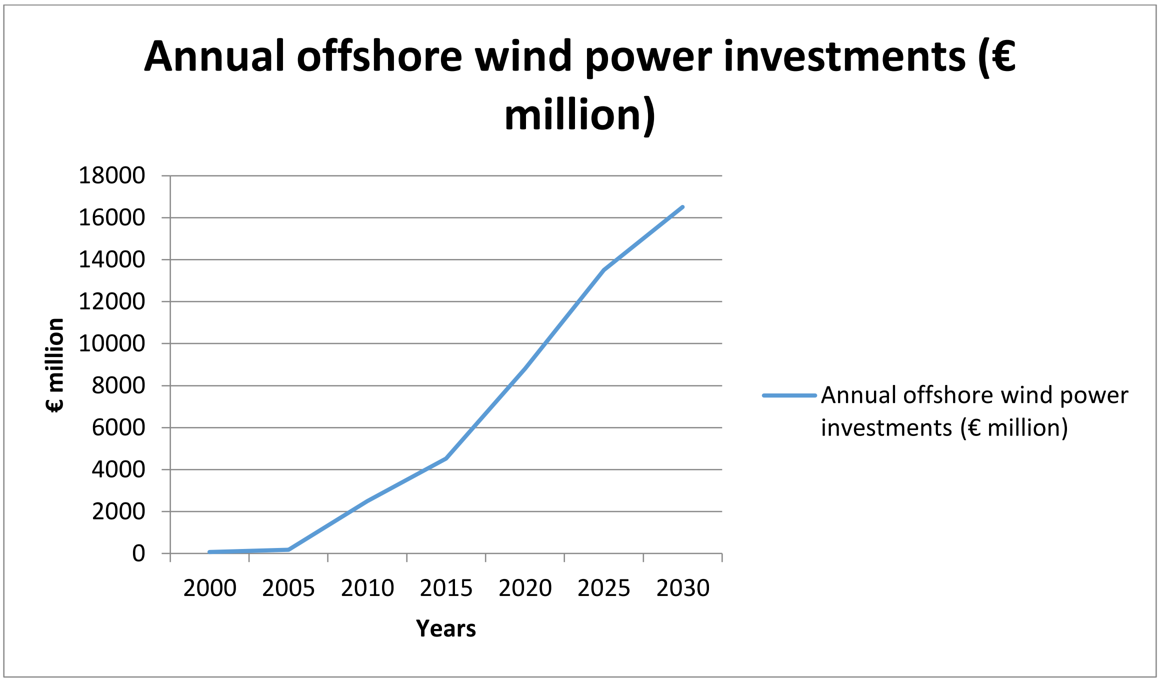
Because of the renewable energy transition there is reason to believe the HVDC subsea cable industry will continue to see major growth in the following years. There are two main reasons for this:

1. Due to the focus on renewable energy there has been an increase in installations of offshore wind farms. These farms need to be connected to the mainland power grid and thus there will probably be a rise in demand for off shore cables. This demand has been mainly for HVAC because the offshore wind farms have been installed relatively near shore and could therefore use AC. This seems to change, as with the VSC technology it is possible to use HVDC to connect wind farms. This allows windfarms to be connected further away from shore because of the reduced loss in DC compared to AC.

2. The renewable energy share of the total energy mix is getting larger. As a result of this, there is an increasing demand to mitigate the variable effects of the renewable energy. An example of this is connecting hydropower from Norway to Germany as a stabilizer when there is little wind (power) or sun (power) in Germany, and vice versa for dry years in Norway. These interconnectors are often characterized by great length and large voltage capacity. They are part of a large vision for a European-wide ‘supergrid’ as a key element of the transition towards higher shares of renewables. This demand is mainly for HVDC because cables are longer and require higher voltage

The market for HVDC cables has increased drastically since 2000. According to Europacable, a lobby organization representing 90 % of cable producers in Europe, from 2008 to 2011 alone there was a 40 percent increase in sales and production of extra high voltage power cables (Europacable, 2011, p. 1). At the same time as the sales of high voltage power cables are rising, so are the investments in offshore wind farms. In 2006 total investments in offshore wind farms amounted to about 250 million Euros. In 2013 the number was 6500 million (European Wind Energy Association, 2014b)(see Figure 9).

Figure 9: Estimated annual investments in Europe based on EWEA 2009 projections (European Wind Energy Association, 2009)[15]



The cable companies confirm this market increase. According to a cable company that wished to be anonymous, the market size for HVDC in 2007 was about 0,5 billion dollars. Since 2007 it has been 3-4 billion dollars each year. Roughly 50 percent of this market comes from Europe (Echo). The company expects the market to be worth 4-6 $ billion annually over the coming 10 years. Some estimates are much larger, but cable companies are often very conservative in their market assessment. This is because they have learned that there is "much political talk, and related uncertainty, about these projects. Often they are not realized" (Head

[15] Note to figure 9: In July 2014, the EWEA proposed new scenarios due to the financial turbulence since 2005. Three scenarios are presented as, low, central and high scenarios, all considering different economic and political outlooks. The central scenario for 2020 is 12 % lower than the numbers presented in the EWEA 2009 projections. These numbers are, however, not based on annual investments but in means of installed TWH (European Wind Energy Association, 2014c).

of global sales, cable producer, Delta). The same company said they used to have 0.5-1 HVDC projects per year on average, which means that work efforts lump together in time. Now they have up to 20 projects at the time and running full power for much of the time (Delta). Another cable producer say they have doubled the amount of staff on HVDC since 2010 and that they've also invested in expanding the factory's production capacity with machinery (as well as staff) (Echo).

Between 1991 and 2000 there were almost no investments in the Norwegian grid. After 2000, however, the grid industry has been growing rapidly. Investments in the Norwegian grid industry has grown with 10-15% each year the last five years (Echo). The producers say they do not think it will increase at the same rate the next years, but believe investments will remain high. Statnett (TSO in Norway) has said they expect the level of investments to remain at this level the next ten years. Last year Statnett invested six billion Norwegian Crowns, or about six hundred million Euros in the grid. These investments include transformers, substations, wires, control systems and cables (including HVDC). When you invest in big HVDC projects (inter connectors) you will also have to invest in local grid to ensure and enforce the supply to the HVDC cable (Echo).

According to the cable companies (Bravo, Delta, Echo), the older cable system using LCC converters and MI-cables will see a market growth because there is a steady increase in the demand for HVDC interconnectors. It is predicted that customers will prefer the old technology because it is still considered the more stable of the two and also has higher capacity than the VSC converter / XLPE cable combination. However, all of the companies believe XLPE will be the future technology when looking twenty years ahead, and all of them are thus investing heavily into that particular technology with both R&D and expansion of production capacity (Bravo, Delta, Echo).

After the introduction of VSC and XLPE, a representative (Charlie) said, DC has become even more important because of its two major advantages for offshore installations:

1. With LCC technology, you need a high fault level on both sides of the DC link, which means high installed capacity. With LCC you cannot have a so-called black start (starting without a high backup voltage in the system), but you can have that with VSC. On a wind farm you do not have a high fault level (high installed capacity), so you need a black start. Because there is no other generation, VSC is needed (Golf).

2. VSC converters are much smaller in size than their LCC counterparts and this is a crucial factor for keeping down costs on offshore windfarm platforms (Bravo, Delta, Echo).

Because offshore windfarms often are too far ashore for AC, the need for green energy, mainly wind, drives the VSC /XLPE technology. Also, with the decommissioning of nuclear plants the need for more wind power is estimated to grow (Golf). In Germany they will need many HV cables because the grid needs extensive refurbishing, but due to many residential areas they can't always use lines. Some parts will have to be cables (Charlie).

The DC counterpart, AC, will also continue to see major growth, but, HVDC producers claim, there are different market dynamics with far more producers competing for the same customers (Bravo, Delta, Echo). HVDC is a more confined business area than HVAC. The market fluctuates a lot because there are few projects totally, even on a global scale (Echo). Even though DC has seen exponentially the largest growth the last years, there is still a market for both technologies because they have different pros and cons (Charlie).

Consultant company DNV GL believes the HVDC technology certainly will change because the need or necessity will drive the market to use additional technology like the VSC converter, or for commercial advantages will push to higher voltage on merchant links (point to point, inside Germany, between countries, etc.) if not wind farms. The need for displacing thermal or nuclear power stations. Or events will happen (disasters, failures) which will push to circuit breakers (DVG GL).

4.5 Conclusive remarks

As this chapter has outlined, we can characterize the industry with some key properties: There are very few firms (3-5) capable of delivering HVDC subsea cables, the customers are mainly TSOs or governmentally owned power companies and there are very few HVDC subsea projects per year (1-3). However, demand has risen, producers and buyers alike expect growth, and so does intergovernmental organizations such as ENTSO-E. Also, technology wise the HVDC industry has evolved quickly the last years, with the XLPE cable evolving from 50 kV capacity in 1990 to 500 kV capacity in 2014.

5. Empirical findings and analysis part 1: Knowledge and technologies

Knowledge and technologies in the European HVDC subsea cable industry

> "We are going towards a greater degree of distributed power generation. The distribution of electricity demand is also more spread out than before. There is also greater immigration to cities. Today electricity is used in more areas (electric vehicles, heating) than before. Maximum consumption is thus higher and the grid is subjected to a wider geographical extent. There are also climatic changes, we see that there is more rain and thus higher production than before. Combined, these factors mean that the grid is subjected to other forces than before. These factors make the grid (built before 1991) not adapted to the current situation. To solve this, you can either let the grid be as it is and insert technology that facilitates the loads, or you can upgrade the grid."
>
> - Sales director, cable producer (Foxtrot)

The following three chapters describes and discusses my empirical findings from my interviews. The information is sorted into the theory and methodology outlined by Malerba's sectoral systems of innovation, firstly in this chapter; knowledge and technologies, secondly (chapter 6); actors, relationships and networks, and thirdly (chapter 7); institutions. At the end of each chapter I discuss the findings in relation to the framework outlined by Malerba. I choose to do it this way because it was easier for me to get a proper overview of the data by discussing it at the end of each 'category'. I believe this is also easier on the reader. This way one does not need to backtrack far to get to the empirical findings that are discussed. The discussion of how these findings in total affect the mode of technological change and how this industry is affected by being in an infrastructure sector is discussed in chapter eight.

As already presented in the theory chapter, the role of knowledge plays a crucial role in the sectoral systems by affecting "the rate and direction of technological change, the organization of innovative and production activities, and the factors at the base of firms' successful performance" (Malerba, 2011, p. 389). Uncovering the knowledge bases and the forms of knowledge is therefore crucial for answering my research question (*how does change come about in infrastructure sectors?*). To have a certain structure over the vast amounts of data gathered that fit into this category, I have divided them into three sub sections: "New technologies and trends", "Knowledge bases" and "Developing and testing a new product".

5.1 New technologies and trends

5.1.1 Deeper sea cables

A big challenge for cable manufacturers is that the forces the cable must withstand varies from one installation to the next. One of these variables are for example how far down from the surface the seabed is located - the deeper you go into the ocean, the higher the forces are. So far, interconnectors and offshore HVDC installations have been made on the Norwegian shelf and the Baltic Sea. The Norwegian shelf is roughly 500 meters below sea level, the Baltic sea around 100 meters deep. The Mediterranean, however, is between 1600 and 2000 meters deep. If offshore windfarms or interconnectors are to be made in the Mediterranean, this will be a big issue (Charlie).

5.1.2 Dynamic cables

There is an increasing demand for dynamic cables because more and more offshore platforms are being connected to the main land electricity grid. With offshore energy installations, you most often have a floating platform. This means that the cable will be subjected to movement, and it will hang, while most cables lie still on the seabed or underneath the ground. This means that the cable must handle a new set of forces compared to before. XPLE cables are more suitable as dynamic cables because they are made of plastic. They are more flexible than MI cables which are made of paper (Alpha, Echo).

5.1.3 Extruded cables (XLPE) vs. mass impregnated cables (MI)

Everyone in the business believes XLPE cables are the future. However, it might take longer to get there than initially expected. According to one cable producer:

> "Everyone is interested in the new XLPE 525kV, but there are still no buyers. What will be the first project? For example, in Nordlink or NSN I don't think the customer would want to go for new technology in such a big project. Statnett wants proven technology. Tests aren't enough." – Acting R&D manager, cable producer (Charlie)

Another producer argues:

> "Ten years ago, everyone thought the MI cable was a dead-end, but today we see that the XLPE cables still aren't close to what we can achieve with a MI cable, considering both reliability as well as voltage capacity." – R&D Team leader, cable producer (Echo)

Because customers won't take the risk with the new and unproven technology that is XLPE, one of the producers believes MI cables have the largest potential for growth the next fifteen years. Also, there are very few producers that can make MI cables (ABB, Nexans and

Prysmian), and the production capacity in the world is very low. On longer distances, one needs MI because the customer usually wants very high voltage capacity. However, in the long term, this producer argues, MI will be substituted by XLPE because of it's cheaper production cost (Echo). The XLPE cable should be cheaper to produce because the plastic is easier, from a manufacturing perspective, to isolate the conductors than wrapping paper around it (as with the older MI cable). With regards to installation costs, the difference isn't much since they have to send a cable ship anyway (Bravo).

Almost everyone I talked to mentions the XLPE and VSC duo as the most important technological invention since 2000 in the HVDC industry. However, this does not mean that the more proven and much older MI technology has stood at a standstill. The MI cables have seen smaller, incremental changes through the years and are slowly increasing in voltage capacity. In Europe the highest is so far 600 kV and producers say they can squeeze even more out of this old technology. This might delay XLPE's dominance even further (Echo).

5.1.4 Joints

A long cable cannot be installed in one shipping simply because a long enough cable won't fit on a boat. Therefore, a cable company needs to make several trips and the cable needs to be laid down in several parts. These cable parts are then joined together by different joints. These joints used to be extremely time consuming to install as one had to manually wrap paper around the conductors by hand. The whole insulation (on the joint part) would be rebuilt. This would be done on a moving boat and was quite time consuming. With new extruded solutions there are prefabricated joints which are much quicker. According to one producer a joint installation with MI would take six hours, while the new extruded joint solution only takes half an hour (Alpha). At sea this might not matter as much as on land, because roughly 100 km of MI subsea cable can be laid before one needs a joint. On land, however, you need many more joints and therefore joint installation time makes a big difference (Echo).

5.1.5 The relationship between AC and DC

During the last twenty years the relationship between AC and DC has changed. AC is anything but dead, and there are still technological developments and many relevant uses for AC. There are some new uses, such as how far you can push AC before going to DC, and also new uses such as moving cables for platforms. However, the last years HVDC has become cheaper and has, in an increasing amount of cases, been cheaper than AC for longer distances (Alpha).

From the producers' perspective it does not matter if the customer wants DC or AC.

> "If a DC cable is cheaper than an AC cable, we install a DC cable. It's as easy as that. We want to offer the customer the best system and cables for his needs. Usually customers have their own experts and have decided on beforehand which technology and what product they would like. Sometimes we are included at an early stage to give advice."– Market intelligence executive, cable producer (Bravo)

According to an anonymous industry expert, the cable companies are not indifferent when selling AC or DC systems. The informant tells us that this is because when they create an AC system a lot of the revenues go to the conductors and the equipment (steel structures) to put a line up in the air, and Alstom, Siemens and ABB are not in that business.

> "The DC producers want to push DC because in that technology there is less competition. Also, there is a smaller revenue base in AC so they do not want to push new technologies in AC. The goal is therefore to sell more DC and basically kill AC. General Electric is now buying Alstom. They are trying to get into high voltage DC business. They are looking at that as a growth opportunity. They can also sell AC, but they may be more inclined to promote DC if they get Alstom. The AC technologies are being de-emphasized by the suppliers. This is for business profitability." – Former leader at CIGRE committee (India)

5.1.6 Future bottlenecks?

There is wide consensus in the industry that the primary concern for bottlenecks in the HVDC market are on the production capacity of HVDC cables (Alpha & Echo). Bottlenecks in installation and services have been observed, mostly related to offshore installations, according to Dutch/German TSO, Tennet. Also, if the plans of the European network of transmission system operators for electricity (ENTOE) are to be fulfilled, the production will have to increase drastically, one producer says. There simply is not enough production capacity at the three HVDC cables producers in Europe today (ABB, Nexans and Prysmian) to meet the demand expected up to 2025 (Echo) The companies say that this is due to the large amount of time it takes to produce each meter of cable. Also, when the cable is produced, it has to be tested thoroughly before it can be installed and shipped (Alpha). As an example, one producer says he does not think a sole cable company has the capacity to deliver enough cable for Statnett's two big projects in 2020: Norway – Germany (NordLink) and Norway – England (NSN). However, producers also say it's difficult to justify investments in production capacity because ENTSOEs plans are generally uncertain. (Echo) Also, because the customers are reluctant to use the new XLPE technology, it is mainly on MI cables that the production capacity is insufficient (Echo).

One AC cable producer trying to get into the DC market says that in five years, one might see other cable producers such as: Hellenic (Greek), NKT cables (Danish), LS Cable (South Korean) and Viskas (Japanese) on the European HVDC market. Because of this, this producer doesn't see production capacity as a problem, but is worried that there might be a lack of "system engineers" that can manage complex HVDC projects. The producer believes the industry must take responsibility and affect local policy makers to educate more (Foxtrot).

An industry expert from CIGRE says the need for higher voltages might be a problem not for the cables technology itself, but for installation reasons because the cables are getting so large.

> "The higher the power - the bigger diameter they need in the copper and insulation. The bigger the diameter of that cable the heavier it will be. Producers can only manufacture and ship a limited number of feet of cable. The bigger it is, the smaller the bending radius will be, and they need bigger reels to ship it. Particularly if they put it on a ship, they would need to divide the cable into many, many sections. This means they have shipping constrains that limit what they can do." – Former leader at CIGRE committee (India)

5.2 Knowledge bases

5.2.1 Technological and financial barriers

It's not easy to get into the HVDC market. Firstly, there are huge amounts of investments needed. Secondly, you need a long track history of technology, research and development to be able to enter.

> "Cable technology by itself is not rocket science, but when you are moving at the borderland of how much strain plastic and chemistry can handle, you really should know what you are doing." – Senior sales and marketing executive, cable producer (Alpha).

Also, the automation and the manufacturing line to make an HVDC cable is very advanced. The technology behind this is difficult to access because even if some of the different processing machines are accessible from sub-suppliers, they must be put in a system to create the cables. Some of the producers even produce their own machines instead of relying on sub-suppliers. The very basics on how to produce a cable is known, but beyond that the production techniques vary from one producer to the other.

> "It is a long leap from producing simpler lower voltage cables to high voltage cables. Even though in recent years the market has been growing, the amount of producers has decreased." – Senior Sales & Marketing Executive, cable producer (Alpha)

In addition to financial and technological barriers, the customers are very risk-averse and will not buy a technology from a firm where that technology is yet to be tested. Therefore, a barrier is also made by the lack of HVDC project experience for the newcomer.

A potential entrant company says that in general, an HVAC company would want to move into HVDC. According to this company "it is basically a matter of company strategy and philosophy at which markets you want to be in". According to him, the entry barriers to the HVDC market are high, but the winnings in that market are also higher. He compares HVAC to a National Football League while HVDC is like the transnational Champions League. Champions League is very difficult and expensive to enter (large investments and complex technology), it is difficult to succeed (get orders) but at the end you also have bigger prizes (contracts and profits, longer cables). If you are in a national league, then you need to invest heavily in building a new team to get into the Champions League. HVAC is a commodity while HVDC is a niche product with larger profit margins. Therefore, he says HVDC is an attractive market that their company wants to be a part of (Foxtrot).

For possible entrant companies it is a problem that a production plant cannot produce both HVAC and HVDC. In order to produce HVDC, it is therefore necessary to build a new production plant. A new plant will need to be certified and tested under a number of standards. In addition, the products (cables) must undergo stringent tests under the supervision of external observers. This involves a 1-year test and associated in-house pre-tests. One potential entrant company has worked with DNV GL in this process and has estimated that the set of tests to go through plus time used to establish a skilled HVDC team of engineers imply that it takes 3-5 years to set up a new factory, at a cost between 150 and 200 million Euros. This is a major investment for most firms. As a firm you therefore need to be absolutely convinced that this is what you want to do in the long term. Moreover, the established HVDC companies have many other markets besides HVDC cables. They are thus able to survive mistakes and/or bad years while smaller AC companies may go bankrupt if a HVDC project fails (Foxtrot).

According to a representative from CIGRE, the most likely next entrant in the European HVDC market is a Chinese company because they have a strong internal demand for HVDC. Also, when the Chinese bought converters for an 800 kV HVDC (line) project, they insisted that the European cable producer set up factories for semiconductors and transformers in China. Therefore, much of the technology was then acquired by the electric power research institute in Beijing and then transferred to Chinese producers.

> "The manufacturers are in a way short sighted because they are giving away the technology, but then again if they do not do it, their customers will." – Former leader at CIGRE committee (India)

5.2.2 Access to skilled personnel

> "In DNV GL 2011 we were 20 experts, and in 2020 we will be 40. The critical mass of HVDC experts in the world is maximum 230. These are the engineers who know anything of value of HVDC schemes. It is a small niche of people in a high growth market. It is almost impossible to recruit engineers. We have problems recruiting good people." – Head of section, DNV GL (Golf)

Most of the producers as well as the customers (TSOs) agree that recruiting is one of the most difficult and crucial issues. This is especially due to the massive growth of HVDC project in the past years. It is also difficult because there is no formal education for HV cable workers, and therefore the customers and HV producers both need to train their own personnel. They look for people with the right basic educational background and then have to spend years training them.

> "We need to train new people at the same time as we are taking in new projects. There is education within HVDC, but it's within this company. They are usually educated electrical engineers and they come to us and spend another two-three years to study HVDC. To meet our demands, we are hiring experts from all over the world." – Cable producer (Alpha)

> "In Sweden, and in Europe in general, there is a lack of electrical power engineers. This is particularly acute for people with HVDC experience." – STRI

However, another producer says that it is at the time becoming easier getting qualified engineers than before, because the oil and gas industry, who are looking for people with much of the same background, is struggling. One of the producers says that there is a lack of metallurgists in the market (Echo).

The basic training for HV cables is used for training both HVAC and DC, because even different there are many of the same physical laws and restrictions that apply to the cables (Alpha). Therefore, an engineer working with AC can go on to work with DC cable.

> "From a production point of view AC and DC are very similar because they use the same production equipment for the screening and the jacketing. With the old paper impregnated cable HVDC technology it was different. With those cables one needed to paper wrap the conductor, with the new extruded

plastic insulation you can use the same manufacturing line. The material defines what equipment you are using." – Cable producer (Charlie)

MI demands more craftsmanship and therefore requires more expertise. So it is easier to go from AC to DC extruded (XLPE) than to DC MI (Echo).

In addition to electrical engineers, the cable producers have several material engineers such as polymer chemists, polymer engineers and metallurgists. The cable producers usually have a heavy academic staff in that field, with several engineers with Ph.D. degrees on a team. However, the producers do not make the materials for the cables, they look into how the material reacts to different strains and voltages. These companies have had extensive experience with polymer from AC for many years and the challenges in DC are not very different (with only slightly different voltage etc.). The experience they have from AC is therefore important (Echo).

For entrant companies, moving an engineer from DC to AC is a major difficulty. According to them, an engineer cannot easily be transferred from HVAC to a HVDC XLPE/MI cable production. Because of this, they are trying to hire external people with HVDC experience. However, there are very few of them around. The result is that they try to train their existing engineers to learn HVDC by establishing strategic collaborations with "knowledge centres" across Europe, particularly technical institutes and universities. They are forced to establish such relationships as they don't have experience in-house to transfer to the new engineers. According to one entrant company, the investment in human capital is very high (10-15 million Euros to start up) (Foxtrot).

For the TSO TenneT, detailed knowledge of the performance of the HVDC equipment and of potential interferences with other equipment is crucial. Because of this, Tennet has expanded the HVDC group in recent years. The department for DC interconnections at TenneT was created three years ago when it became clear that several new projects would come. It then made sense to concentrate the competence and experience within TenneT. Over the last two years, TenneT has continuously hired HVDC people from DNV GL. It is not a problem to get good people, partly due to their good relationship with DNV GL. TenneT is in general concerned with building internal competence during projects to minimize the need for external support in the longer run. TenneT has a few HVDC experts internally who can be involved in up to two projects at a time. In addition, the main competence need for HVDC projects is "project management skills". This approach is the same for HVAC and HVDC. In general, TenneT focuses on operation of the link rather than the technological content of it. The TSO in Belgium (Elia) is now starting its first HVDC project (called Nemo). Tennet has several HVDC projects under its belt and therefore Elia is asking TenneT for advice on these matters (Juliett).

5.3 Developing and testing a new product

5.3.1 Developing a product

The basic innovation cycle in the HVDC industry starts from a basic idea. Then, the feasibility of the idea is assessed and filtered down. Eventually, very few projects are left. In such a process one can go from one hundred ideas to one. A typical innovation process starts with new insulation material and the creation of a certain length of cable. For the insulation material producers use engineers outside of their main factory, but the project as a whole is driven from the producer's HQ. Creating a cable is a prolonged qualification process, therefore a big part of developing is testing. This has to do with mechanical and electrical tests which are created by CIGRE and IEC. After that one can initiate a long-term test, or a so-called one-year test. During this test the cable will be tested with a constant current and voltage for a whole year. All of the HVDC producers I talked to had their own test facilities (Alpha, Bravo, Charlie, Echo).

> "It is important to do high voltage testing and go to full scale as quickly as you can, because you can see things there that you cannot see on a small scale. Already at the beginning you have to look at the whole system to get the whole picture." – Market intelligence executive, cable producer (Bravo).

With material testing and small-scale testing, and especially on full-scale design, it's not unusual that producers find patents that other HV cable producers already have registered. Then they may have to design in a slightly different way. (Bravo).

> "We always have to do a new qualification test even if the design is exactly the same as in a previous project. It has to do with insurance, all customers seek certification of their specific design although it is similar to a previous project we have done." – R&D team leader, cable producer (Echo).

In some projects cable producers may experience that they have to make small modifications to the design. They may then need to do a new qualification test. With smaller modifications they do not need to run a new one-year test. This is necessary only if they make drastic changes to the cable system or manufacturing units such as change factory, increase cable current capacity, or change the insulation material (Echo).

Feasibility studies are important for producers to show not only that their technology works, but also to gain further knowledge on the cable system for that project as well as setting up budget estimates.

> "For us, feasibility studies are a part of our marketing. With a feasibility study we will gain more knowledge on how the cable system should be, we can help with budgeting cable prices and isolation. We either do it for free or we rent out a team that may help the customer." – R&D team leader, cable producer (Echo).

Largely, the HVDC cable producers produce parts for the whole transmission system. However, they buy the materials for the cable from other manufacturers, but the producing of the cable is done at the producers' factories using their own machines and equipment. They make the transformers from scratch and they design and develop the control and data systems (Bravo).

5.3.2 Research & development (R&D) organization

One cable producer say they have different R&D departments. Some are global corporate departments which in turn are multi-tech departments. They screen technological developments broadly and identify interesting activities for their company. Each technology branch within this company interacts with corporate R&D in development of ideas and projects. While corporate R&D has a time perspective of 20-30 years, the R&D teams behind HVDC focus on maximum five year periods (often two to three years). Corporate R&D also actively establishes links with universities and external environments while the local R&D group interacts with the production team for feedback on how to improve the production process. The local R&D groups may occasionally hold workshop meetings with buyers to evaluate the potential market for various project ideas. In such meetings you find representatives from both corporate and local R&D. Occasionally local R&D departments have interactions with people from universities but this is rare. It is more common to have industrial PhDs who work with and are mainly financed by the cable producer (Charlie, Delta).

It's not an easy operation to increase voltage capacity in a cable. All of the producers have struggled with the very high voltages. Especially with currents over 320 kV you get other types of forces and mechanisms to deal with, and one must design the joints and cables in an entirely different way. Thus, the development work with extruded cables are projects that span over several years. In addition, cable companies still focus on the older MI technology.

> “On subsea cables for example, we often use a lead sheath for armouring. Now our maximum depth is at 1200 meters. But if one wishes to cross the Mediterranean, the cable would have to withstand forces down at 2500-3000 meters. This means the cable would need another armament. At the same time as they are pushing boundaries on the XLPE they are also trying to push the MI technology with aims to get to 600kV or higher.” – R&D team leader, cable producer (Echo).

The customers expect a life range of 30 to 40 years for cables. Therefore, the producers must construct something that is robust enough to meet those expectations. Because of this, the producers tell us that much of what they do on R&D is margin testing. Based on those tests they estimate the lifespan of a new cable. This requires long tests and much operating experience.

> “With the new XLPE technology, the insulation materials are so highly stressed under load that we need to understand the phenomena in order to design the cables, splices, terminations and terminate the seams. It is anything but trivial, it requires lots of internal tests. When we finally make a qualification test we have perhaps already made fifty tests in advance to define the margin on the different kind of items that are inside a cable, after which we may have to do a redesign and come up with a solution.” – R&D team leader, cable producer (Echo).

Technical development with one of the producers primarily happens in three different processes, namely qualification processes, R&D experimentation, and delivery projects. In delivery projects the steps are smaller than in R&D, so there is less material testing in the supply projects. If they are to deliver a cable that they have already delivered for a similar project, but maybe this time at somewhat deeper depths, they think that they have enough margins, and that they don’t have to take all these steps on material testing over again.

> “Technology development usually happens between projects. We will never offer a solution until we are fairly confident that we can deliver a good solution. The commercial risk is enormous because problems can rise along the way.” – R&D team leader, cable producer (Echo)

A Head of Section at DNV GL tells us that the mode of technological change in transmission grids is extremely slow. He uses the story of HVDC voltage source converter technology as an example.

> “ABB developed the technology in the mid-1990s. In 1997 they set up a 10 km test /demo line in Ludvika. They invited a group of international experts to come see and test the technology. ABB did this to convince TSOs. Usually manufacturers apply their newest technology in small projects or insert it in existing projects to run tests and to demonstrate (at a cost of 50-100 million Euros). After 2-3 years of operation without problems, TSOs might be sufficiently convinced that it is OK to try it out. Then, after 10 years since first demonstration, the technology was applied in large scale projects.” – Head of Section, DNV GL (Golf).

5.3.3 Overseeing a project

One cable company sees a structural shift in the market around 2007. Before 2007, there were so few HVDC projects and the overall market was so small that one could send one's top engineers to follow each project. Hence, in this period it was common to have R&D projects within the overall HVDC projects as the firm felt confident that issues could be solved and buyers trusted in the firm's ability to solve them. After 2007 the project portfolio has been so big that it is impossible for this producer to allocate top engineers to follow each project. Instead these engineers oversee several projects (Delta).

All HVDC grid connection systems are designed for the individual transmission requirements (e.g. transmission power, number and length of AC and DC cables, turbine type of the connected wind farms, etc.). A TSO mainly specifies high-level / general technological requirements for HVDC projects such as whether it should be AC or DC, or LCC or VSC. Besides that, TenneT mainly lists "functional requirements" and leaves specification of technological details to the supplier (who also bears the full risk of faults) (Juliett).

There are often more difficulties than expected with the big HVDC projects. An example of this could be the many North Sea projects where the installation has been more difficult than projected. Siemens has published numbers where they have lost 120 million Euros in offshore connections the last years (Echo). Another informant told us that "delays are the rule rather than the exception in HVDC projects". They can be due to capacity issues, transport, technology, etc. Also it is very difficult to test software systems in isolation. In the current practice, software and hardware only meet at the installation platform because assembly takes place on the seas. This often leads to various types of problems (Golf).

5.3.4 Investment cost

> "Developing a cable system like a VSC system (with XLPE cables), is a multimillion-dollar investment. You need high power labs, high voltage labs, testing facilities, and substantial manufacturing and design technology capabilities. Neither of these are possible to do in collaboration with a university. All the cable producers would develop this in-house." – Former leader of CIGRE committee B4 HVDC and power electronics (India).

It is difficult to set a fixed price per meter in HVDC as every project is different. A cable is also sold including the cost of installation, which also affects the price (Echo).

5.4 Summary and discussion part 1

My theoretical framework emphasizes the important role that knowledge plays in the transformation of sectoral systems. I looked for such signs of transformation by asking for instances of technological break-through that have happened since 2000. The main response was that the most important breakthrough was the combination of the new HVDC converter technology (VSC) that enabled the use of new cable technology (XLPE) in HVDC systems. The converters were invented by ABB, while the cables were made in collaboration with the chemical sub-supplier Borealis. According to many of my sources, this sub-supplier has regular meetings with all of the three main HVDC competitors. Borealis is seen as an important partner in developing new cables, because of their high knowledge of plastic. Therefore, they have become a very important source of knowledge for the novel XLPE HVDC cable technology. The XLPE technique for isolating cables has been used for many years in HVAC, and as such we understand that Borealis has been an important ally for many years before the use of XLPE in HVDC cables.

There seems to be very high cumulativeness in the HVDC business, exemplified especially by the HVDC MI cable. This cable has been, and still is, incrementally improved over sixty years and is only offered by three companies. This implies that the knowledge base is highly path-dependent. However, good feedback from the market has resulted in cable companies reinvesting profits in continual R&D resulting in incremental improvements over the years. The high cumulativeness implies very high levels of appropriability, because knowledge is not easily accessible for entrants. As Malerba (2011) argues, this has created first-mover advantages and a high concentration of firms. There seem to be low levels of technological opportunities partly because the technology behind cables is very mature – it is based on old technology dating as far back as the late 19th century with the introduction of both AC and DC cables (albeit with much lower voltage) (Tell, 2012). The low level of technological opportunities is underlined by the high levels of appropriability, as well as the high investment-costs needed for developing and testing HVDC cables.

Firm knowledge heterogeneity is very low in the HVDC industry, with only a few companies competing in the same cable technology. Some of the companies provide other services as well, such as converter equipment, but the knowledge base connected to converter technology is vastly different from that of the cable technology and therefore none of the cable companies (which did not produce converter technology) were interested in moving into that technology. There are some technical differences between the cables from the different suppliers, but their performance is usually about the same, and the technical development points in the same directions (all of my interviewees claim that XLPE technology is the future).

Many of my sources said that the extruding process necessary to make a XLPE HVDC cable is very similar to constructing an XLPE HVAC cable. Constructing the older and more proven cable technology, the mass-impregnated paper cable (MI cable), is seen as very different from constructing both of the former two. It needs vastly different processing machines to wrap the paper around the conductor. Since the new XLPE HVDC isolation material and the processing techniques are much more similar to HVAC cables than the old MI HVDC cable, the new XLPE HVDC system can thus lower the technical barriers for HVAC entrants. The 'new form' of cumulativeness goes from paper to plastic isolation, meaning that the cumulativeness of AC cable knowledge (which is based on plastic isolation) is more relevant than before. Also, access to necessary knowledge could be easier than before because Borealis is a central dialog partner in developing this new plastic material. Borealis' cumulative knowledge of XLPE isolation technology could therefore have spillover effects to other cable producers. In Schumpeterian terms, the XLPE cable technology can be seen as a "knowledge destroying" innovation (Schumpeter, 1942). With time, it will render much of the knowledge base related to the MI cables obsolete.

The XLPE / VSC duo was initiated and developed by a cable (and converter) producer mainly to gain a competitive advantage over other producers. The VSC converters are smaller and lighter than older HVDC converters and are thus more suitable for other applications such as installation on offshore wind farm platforms. The XLPE cables are also lighter and smaller than MI cables, but their main advantage is that they are much easier to produce. However, as of today, XLPE is more expensive than MI on voltages higher than 320 kV. On lower than 320 kV, XLPE is cheaper. Because of the rather small price gap, customers still choose the older and more proven MI technology. However, all producers agree that the XLPE is the novel technology, and with time it will be much cheaper than LCC/MI. It will certainly become the main technology in cable productions. The XLPE can be seen as an incumbent driven innovation since no major collaborations with universities were made, and most R&D and testing were made in-house at the cable producer. This indicates that the technological opportunities are related to in-house activities and are therefore internally based from firms, not from external sources such as universities.

Dynamic cables were also mentioned as a technology change that has happened the last fifteen years. This innovation could be seen as necessity driven/market pull. In this case, the Norwegian government wanted to send electricity from land to offshore oil and gas platforms to reduce CO_2 emissions (the alternative is creating energy on the platform by using oil or gas). Constructing subsea cables is routine for HVDC suppliers, while creating a dynamic cable from the seabed up to the platform is not. Therefore, I was told, the HVDC companies collaborated with offshore installation companies to learn about the forces that the cable needed to withstand. This, as well as the example with Borealis, shows that the HVDC companies can adapt to new surroundings and technologies by collaborating with knowledge sources external to the sector.

Overall there seem to be very low levels of accessibility in the HVDC knowledge base. An example of this is that there exists no formal education to be an HVDC engineer. All of the HVDC cable producers interviewed said they would normally hire an electrical power engineer and then proceed to give him/her an in-house education program of 2-3 years to specialize in HVDC. Another example, according to several of my sources, is that there are very few engineers in the world with solid HVDC knowledge, DNV GL estimated the number to be “maximum 230”. The two HVDC producers, DNV GL, the entrant company as well as the TSO, all told of problems recruiting people with good knowledge of HVDC. There is a rise in demand, while there are only a few skilled persons in the world. For an entrant company this could be a bigger problem because they do not have the necessary in-house knowledge to train ‘fresh’ engineers. On the other hand, established HVDC firms see recruiting (and training) of engineers with low levels of knowledge of HVDC as a business as usual routine.

There is little or no collaboration with sub-suppliers, the chemical producer Borealis being one of the few exceptions. One of the HVDC producers orders processing machines from a sub-supplier and collaborates closely with them, but the other one makes their own processing machines from scratch. This makes it harder for newcomers to gain knowledge of the cable producing process by possibly collaborating with sub-suppliers. Also, the HVDC companies are so large that they have their own training programs, R&D facilities, test-labs, as well as internal R&D internships and exchanges across international offices. This has also been found in industrial machinery companies (Malerba, 2004; Wengel & Shapira, 2004)). This means that knowledge mostly arises and stays within the company.

The incumbent HVDC producers are extremely secretive. We can see this both in the difficulty of finding informants for this thesis, but also in the lack of collaborations they have with universities. As one informant told me, research in universities is published and made available to the public, while a cable producer would want these technologies commercialized before publicized. This makes it hard for cable producers to collaborate with universities as they are not willing to share their research.

However, there are some examples that may indicate that accessibility is rising for potential entrant companies (such as the HVAC actors). The new HVDC XLPE knowledge pool is more similar to HVAC than the older HVDC MI, making HVAC knowledge easier applicable to HVDC. Also, there seems to be a displacement of HVDC knowledge from in-house TSOs to consultant companies. Several of my informants confirm that there was a shift around 2007 when consultant companies became more important than earlier on. Because consultant companies are available for hire and their knowledge therefore is obtainable, this trend could increase accessibility to the HVDC knowledge base. There is also a rise in test-labs at research institutes and consultants which could displace knowledge further. This could lower the investment costs needed to test and develop new cable systems as one could rent the expertise and testing facilities instead of having to investing in new equipment and the skills to use it.

6. Empirical findings and analysis part 2: Actors and networks

Actors and networks in the European HVDC subsea cable industry

As is presented in the theory chapter, within my framework, innovation is considered to be "a process that involves systematic interactions among a wide variety of actors for the generation and exchange of knowledge relevant to innovation and its commercialization" (Malerba, 2011, p. 385). Different actors in a sectoral system are connected in various ways, both through market and non-market relationships (Malerba, 2011). This chapter highlights the HVDC cable producers' connection with other actors in the HVDC subsea cable industry.

6.1 Collaborations with other cable producers

It's not unusual for cable producers to collaborate with each other in projects. According to one of my informants there is an ongoing discussion around the TSO's in Norway (Statnett) next big project, the interconnector to Germany and to the United Kingdom. The discussion is whether cable production capacity will become a bottleneck. My source, a Senior Sales and Marketing Executive at one of the cable producers, says he does not know of any producers who have the capacity to manufacture these cables on their own, so projects of these magnitudes are usually divided between two producers. When this has happened before it has not been because of production bottlenecks, but because TSOs collaborating on an interconnector wanted different cable producers. An example of this is the NORDNED project. In this interconnector between Norway and the Netherlands, the national TSOs wanted two different cables. Therefore, there is a joint between these different cables on the Dutch/Norwegian border. This cable was made by Nexans and ABB (Alpha).

6.2 Collaborations with sub-suppliers

A major sub-supplier for all the cable producers are the material suppliers. The cable suppliers mainly need paper or plastic for the insulation, or copper or aluminum for the conductors. A big part of cable cost goes to the material.

With the new extruded cables, the biggest difference is that it is isolated with extruded plastic instead of oil impregnated paper. To create the correct plastic type, all of the producers say they are collaborating with one major plastic producer: The Austrian chemical company Borealis. Two producers say that collaborate with Borealis all the way when developing new cables, and that they have continuous meetings with them (Charlie, Echo). Borealis has testing facilities that are better at testing chemical reactions in some particular areas. Before starting a collaboration with Borealis in a certain project, the cable producer and Borealis will write a non-disclosure agreement defining the scope of research and agreeing that both companies will have access to the research.

The producers say they would like to have several plastic suppliers because it could press down the price of plastic and it would also be more reliable to have several suppliers in case of error. At the time, however, it is mainly Borealis which has the necessary know-how and materials to be able to supply the cable producers. For the time being, DOW, an American chemical company, is closest to achieving the same plastic performance as Borealis. Accessing the sub-supplier industry for HV cables is difficult because the customers demand the same qualification test of sub-suppliers as they do for the cable producers. Therefore, only internationally recognized companies are considered when cable producers are looking for new sub-suppliers (Echo).

One cable producer creates its own manufacturing and processing machines, while another invests in machinery produced by other suppliers. This company has close dialog with these sub-suppliers and says that the most recent manufacturing line is installed by this sub-supplier.

> “Those who delivered the extrusion line have long operating experience and a number of important suggestions on how to set the various parameters of the production line. Therefore, we have several development projects with them. This has been important for AC and it continues to be important for DC.” – R&D team leader, cable producer (Echo).

One producer says that even though they only have one supplier on plastic, they are generally not too worried about bottlenecks on the supply side. This producer says they have good solutions for finding alternatives if it should happen, and that there have been no problems getting hold of aluminium or copper. However, due to the price increase in copper, it might look like a shift now, where aluminium takes over. In general, all use of raw materials and metals are based on world prices. Borealis has the same rates to everyone – in other words, on the material side the competition is not an issue.

6.3 Collaborations with universities and research centers

One of the cable suppliers says they do not have collaboration with universities and research centers with regard to R&D. They support them, but they are not involved at all in the supplier’s product development. This company also says they have not had difficulties hiring a sufficient number of HVDC engineers. However, they find that many engineers have limited knowledge of HVDC, but they are tutored by the cable producer. This company hires electrical engineers, physicists, and chemical engineers. My informant tells us that many universities shut down high voltage labs and discontinued education because of the increased focus on IT during the nineties. He now thinks high voltage is becoming popular again. This company is, like all HVDC cable producers, a large company with offices across the world, and as such they have many internal R&D internships (Charlie).

Another producer seems to have closer collaboration with universities. They collaborate with several universities, as well as a major independent research organization. This company also says they have a great internal environment within the company, having internal internships and R&D projects between different regional offices and research centres. Research with universities or research organization may be difficult because the latter two would want to publish all data, while secrecy is very important for cable producers. It has therefore happened that collaborations between a cable producer and universities had to be terminated. Still, this company has at least one meeting a year with local universities and research institutes. Some of the research projects are funded by the producers themselves, while others are funded by national research councils or EU funds. There may also be exchange of engineers between the research institutes and the cable producer. But because the HVDC environment is quite small they do not see the need for a systematic exchange policy and rather have exchanges on an ad-hoc basis (Echo).

6.4 Collaborations with consultants and test-labs

Usually the cable companies have a third-party consultant who either participates during testing of a new cable or a third party consultant who tests the cables independently. The early R&D tests are usually made in-house without consultants, while the one-years tests and qualification tests usually have a third party present. Companies worth mentioning here are Sats (Norway), STRI (Sweden), Kenetics (Canada) SPI (Statens Provningsanstalt, Sweden), Germanischer Lloyd (German, now a part of DNV GL) and DNV GL. Sometimes it is a demand from the customer that the producers do an external test, but usually the external actors are at the cable producer’s facilities when they do tests. Most HVDC producers have their own full-scale test facilities for new products. Test facilities of manufacturers are often better than those of third party labs and as such most tests are made in-house. Several producers and industry experts say that the trend the last ten years has been that customers (TSOs) come to tests with a third party consultant instead of their own experts. Before 2005-

2007, they say, the TSOs were more engaged in project specifications and had more engineers of their own involved in the process (Charlie, Echo). Third party consultants are an important discussion partner if irregularities should happen.

The TSO TenneT say that they, as an EU company, must follow the EU rules for procurement. This means that the call for tenders must be public and distributed in EU channels. Afterwards there is a pre-qualification process where applicants are assessed according to financial robustness, technological capabilities, proven track-record and experience, price, and other factors. In this phase, TenneT receives support from third party consultants (DNV GL in this case) – this is exclusively in the early phases of the project. Other than that, TenneT has not experienced a strong need for external consultancy support in managing its HVDC projects. They say the market for consultants is mainly in the Middle East and North Africa where TSOs have limited experience. In Northern Europe, TSOs are competent. However, if governments order independent investigations, consultants must be used. The current role for consultants in HVDC in Europe is thus limited (Juliett).

According to DNV GL, there is a strong demand, or there should be, for third party consultants. This is because each producer is technology specific in the way that they promote their own technology.

> "When a customer puts a HVDC system inquiry on the market, they usually get three offers. Each customer prepares their own specifications and their own technology. There are huge variations of supplier's offers to customers. It is as if there is no customer specification. For customers to make a technical evaluation and qualify a grid, the offers need to be synchronized with respect to each other and most of all to the customer's specifications. Also the commercial offers need to be reviewed so that we are comparing apples to apples when looking at the price. Customers can do it themselves, but this is not an expertise that is normally resident in a TSO. It is however a part of our daily business." – Head of Section, DNV GL (Golf).

DNV GL believes that cable producers will stop testing in-house, because, they claim, cable producers do not have the capacity. DNV GL are investing 70 million Euros in upgrading testing facilities. This is a response to market needs and also to strengthen their position (Golf). According to a possible HVDC entrant company, DNV GL almost has monopoly on consultancy on offshore grid installations with a combined competence portfolio on HV equipment and certification services (Foxtrot).

6.5 Collaborations with other actors

Other collaborators worth mentioning are companies that have expertise on building platforms for the oil and gas industry. When creating dynamic cables, two HVDC producers have significant collaboration with oil producing companies and oil consultant companies. According to their specifications, the cable companies needed to develop new cables that met the new demands required by this new use. The offshore industry has experience in how much a cable will be affected by the environmental surroundings so the cable producers could calculate how strong the cable needed to be to last at least forty years (Alpha, Charlie).

Another important actor are banks. If a TSO is building a link, there is always a bank included in that project. Banks normally asses the risk of a project, and thus the price of a loan, in specialized departments of the bank which also receive advice from consulting engineers. Specialized banks exist for this but they are often subsidiaries or part of larger banks because the risk involved in such projects are very big (Foxtrot). A bank may also require insurance of the entire link. Here there are massive differences between a land and a sea cable. On sea it takes longer to find a fault and fix it, because a boat must be sent out. Even simple repairs could cost several million Euros. Because of this, the insurance companies demand much documentation on the operating experience of cables to ensure few faults.

> "Without insurance, a bank may not be willing to fund at all. It is easy to think immediately of new and exciting technology when considering HVDC systems, but one has to consider financing and insurance as well." – R&D Team Leader, cable producer (Echo).

6.6 Relation to customers

All of the cable companies say that TSOs are conservative when considering new technology. It is difficult to convince a buyer to take a risk on a new technology. According to my informant from CIGRE: "Utilities in some parts of the world are becoming more and more risk-averse. They pick an older more proven technology because of the perceived risks of the newer technology" (India).

Both of Statnett's two major projects (to Germany and England) are both, from their side, specified as paper insulated cable (the old technology) with a 525 kV system voltage. This, a producer tells us, is not because of the price but because of operating experience.

> "The first high voltage cables that were used in Norway were paper insulated cables. They were installed in the 30s and they are still working. Because of this, this technology is highly proven and very reliable." – Senior Sales & Marketing Executive, cable producer (Alpha).

This might also be because customers have negative operational experience with the use of polyethylene (plastic). In the eighties, plastic cables were produced and installed, but the insulation was not tight enough and microscopic parts of water slowly entered into the plastic. This phenomenon in polyethylene is called "water tree”. These small ‘trees of water’ would create partial discharge. Over time this would eventually increase and you could get arcing. This happened in several cables in the Oslo fjord, resulting in the TSO needing to dig up and exchange the cable (Echo).

According to DNV GL, TSOs are conservative, but in a way they also drive technology by steadily ordering higher capacity lines, and sometimes ordering projects that demand new technology (like the offshore wind farms far away from shore that needed DC). They think that technology will grow towards DC grids in cities and towns where you have a DC grid instead of AC grid.

> “The power industry is extremely conservative if you compare with for example telecom. When a new mobile device is launched, you have buyers running to test it, and soon you will see numerous blogs and reviews of the product. This takes place within weeks. In transmission technology the first thing a customer asks you when you showcase a new technology is: “Have you proven that it works for long times under different types of stress”? Your product may work well for 20 years, but if it faults in year 21, you have a serious fault which renders your product unsuitable.” – Head of global sales, cable producer (Delta).

6.6.1 Collaborating with customers in projects

Customers have usually decided what voltage they want before ordering a system. Some customers are pressured from their government; they need power from A to B, regardless of technology. If a producer gets a project, there are many upcoming interactions with the customer. The buyer and the producer agree on what kind of testing they need before installation, and representatives from the customers are usually represented during these tests. A short test (two months) called a type-test is required on all projects. Very many companies also have some business points on all of the processes of production. For example, before a producer can start a certain machine, they will have a meeting with the customer (or a representative) who then will be going through a check list. These lists cover for example that all design documents are approved by the customer, the machine has been set up by the right rules, and so on.

There are no standard sizes on HVDC projects, and the cable producers design the system for each project. Economies of scale at the project level are thus very difficult. However, scale economies at the component level can be done (Delta). Because the system varies, the installation of the cable system is a big part of the project, subsea as well as on land.

> "If I go to a new project in India, four out of five questions will be about the installation. How should it be performed? How much infrastructure do we need to change?" – Acting R&D Manager, cable producer (Charlie).

According to several of my sources, there was an important change in buyers that happened around 2007. Before 2007 there was a small group of people working with HVDC, and relationships with TSOs or buyers were often personal and "trust-based". Since 2007, however, there has been an increase in activity in the market resulting in more competition, more professionalism (at arms-length), and most projects are run under a much heavier time pressure than earlier. Moreover, TSOs now have significantly less internal HVDC competence compared to earlier. This complicates trust-relations due to augmented asymmetric information between the two. Because of this, buyers now increasingly employ third party consultants when performing feasibility studies, technology choice, when they decide testing, and so on (Charlie).

In the larger interconnector projects, the TSO is involved in many of the meetings and the processes.

> In a major interconnector project, we use nearly 50 000 engineering hours. There are many tests to be made, a cable to be produced, and a few thousand pages of documents that need to be discussed with the customer. There is also the interface between the cable, the installation, and sometimes even the interface between the two different cable companies (or the converter supplier). So, there is much engineering and technical work that includes the TSO, which is done in the project. – R&D team leader, cable producer (Echo).

6.6.2 Collaboration with customers between projects

So if customers are risk-averse and are not willing to test new technology, how do technologies in HVDC progress? Usually, it is a cable company working with a good customer. We're told that ASEA (now ABB) worked closely with the Swedish power board with testing new technology in a new project. In projects like those, the cable producer takes all the (financial) risks. Cable producers need a demonstration plant, because no one will buy anything unless you already have something installed. This "catch 22" is a problem because no manufacturer can afford to just build a project and make it operate without getting any funding from anybody. Therefore, they work with a friendly utility to do things. In France, for example, cable producers work with EDF (the TSO in France) (India).

One cable producer says they need their own HVDC link as a testing facility where there is room for malfunctioning. The producer is interested in paying for all of the equipment and installation, but only a TSO can approve this. Still, they say, TSOs are not interested because they see no need for it. “Why should I help you with this new product when my network is perfectly fine without it?”, the cable producer’s R&D team leader rhetorically asks (Echo). In addition, most TSOs are generally very busy with solving other problems and have “no time for play”. Here the informant implies that EU projects may play an important role in the interest of the collective industry. These projects may play a role as substitutes for conventional pilot-projects and may do so at a much larger scale (lengthier and involving more actors and thereby creating a new community). An example of a project like this is the “Best path project” that works on developing a framework that can make equipment from different suppliers work together without problems.

A cable producer says they have a good relationship with Statnett, National Grid, Interna, and other major TSOs. They are constantly trying to achieve cooperation, but TSOs are very aware of their role, so they are reluctant to associate themselves too much with a vendor. So much cooperation is often more generic development and casework. They also have a discussion forum where they try to meet once a year. But we’re told that from a competitive viewpoint, it is not trivial to cooperate strongly with solely one customer, as the TSO can be accused by competitors for favoring some of them (Echo).

It is extra difficult to introduce new technology if the producers deal with someone who does not have previous knowledge about the technology. In these cases, the customer will hire consultants to work with the supplier to make sure the technology really works, but there still has to be a basic trust between the two because of uncertainties related to new technology. It is therefore important that the producer is a known supplier with a good reputation. Also, producers could convince buyers to do projects with new technology if the price is lower than with proven technology (CIGRE).

Statnett has in-house people who are very good, and they can take their time and fund the efforts of doing long feasibility studies (ten-year study for the cable to the UK and Germany). However, many TSOs have now reduced the staff they have available for such work. As a result, many would have to rely on consultants and manufacturers when they buy something (CIGRE).

New technology is always combined with risks resulting from the lack of experience. Therefore, TSOs are aware of this and normally very careful with using new technologies. To overcome this, the cable producers talk to the TSOs and show them the advantages of their newest innovation (Juliett). According to one of my informants, a common way for suppliers to bring in new technology would be to offer other technologies than what the TSO is asking for. The cable producer would try to convince the TSO to try the newer technology, but would at the same time lower the price because of the higher risk (CIGRE). TenneT says these technical opinions of the cable producer are very important because the technology supplier knows his system best. Despite that, they always try to get a second or even a third opinion (Juliett).

Even though suppliers say they are waiting for an adventurous TSO to install and run their new HVDC technology, TenneT says that TSOs can only be adventurous up to a certain degree. The transmission grid is, due to its importance, no place for experiments. However, to stimulate technology development, a TSO can act in different roles. In an active role TenneT tries to give their ideas, needs and problems to the suppliers and try to find solutions with them. They also have the role of experts to discuss the practical benefits of new technologies with the developers. Full scale testing is normally done by the developers and is no option for TSOs.

TenneT says that the five factors, price, technological edge, available capacity, company reputation/experience and previous transactions and trust, are all equally important to them. For the Nordlink cable there were applicants from Asia including China and Japan. But they didn’t pass the pre-qualification due to lack of a proven track record, i.e. experience with similar projects over time. TenneT is however certain that these actors will gain the necessary experience in other projects (probably outside Europe – China has a large home market) and be able to compete in 1-3 years (in both cables and converters).

At TenneT there are two types of projects: business case projects and necessity driven projects. In business cases, the investment is made on the basis of specified dates for commissioning and decommissioning, and functional requirements that can create a revenue stream in the period in between. This implies that only proven technology is applied. This means that other similar installations exist. Some minor technical details, but not larger aspects may differ. It is for example discussed whether suppliers will be allowed to install a section (30-40 km) of new 525kV XLPE cable in a subsea cable project. This would be a way for suppliers to accumulate experience with a new product. TenneT says that in principle this could be acceptable, because at the end of the day it is the responsibility of the supplier if faults or delays occur in the project – also after installation (Juliett).

An example of a necessity driven project is the offshore wind projects in German waters. These are not business case projects, but necessity-driven projects as part of the Energiwende (Germany's transition to more renewable energy). These projects have thus induced several innovations (Juliett).

> "It is absolutely crucial for us to have a group of technology experts to carry out technology choice processes as we as transmission grid operator are the only company which has a view on the complete picture. The awareness for this has risen in the last ten years." – Head of DC interconnector department, TenneT (Juliett)

For new power producers the importance of reputation and experience could be a big barrier. TenneT says that competition is important for them, but that track record is worth more than 'encouraging competition' by risking new companies in big cable projects. Buyers will therefore test new producers by giving them "test-orders" or smaller projects to see how they perform with regard to quality of technological components and project execution (Foxtrot). Overall competition hasn't changed much the last ten years, but on the global scale competition is stronger in cables than in converters (which remain dominated by European firms). Several Asian cable companies are in the European AC subsea cable market, and TSOs are therefore familiar with and know them – so it will be easier for them to enter the DC market (TenneT).

6.7 Summary and discussion part 2

Firms are the key actors in the SIS perspective. They are the key actors in the use, adoption and generation of new technologies. The level of firm heterogeneity is a result of the balance between selection (survival of the fittest), variety creation (innovation) and replication (easiness of copying inventions) (Malerba, 2004). In the European HVDC subsea cable industry there is an extremely homogenous environment of firms. Over the years, selection has led to the acquisition of smaller firms resulting in only a handful of large producers that have projects all over the world. The role of variety creation (innovation) and replication also explains the homogenous environment. Innovation and technological opportunities are, as argued in the first part of my analysis (part 1), low, because knowledge accessibility is low. Knowledge accessibility is so low that entrant companies cannot find skilled personnel in universities. DNV GL tell us it might not be easier to find them elsewhere either. Their estimated number of skilled HVDC personnel worldwide is at most 230 persons. There are however signs that the heterogeneity is increasing. Test-labs and consultants are used at a higher rate than before and, with the increased demand, it is also expected that Asian HVDC cable producers will enter the European market when they have developed more HVDC experience in their home countries (such as China, Japan and South-Korea).

We find properties that we expect to find in infrastructure sectors, such as the high capital-intensity. DNV GL and a possible entrant company estimate that a new factory costs between 150-200 million Euros. Then another 10-15 million Euros need to be added in human capital to obtain the necessary knowledge, and another 50-100 million Euros to create and demonstrate the first HVDC project. Even if a company overcomes these obstacles, success is not guaranteed, because customers are extremely risk-averse. As the TSO Tennet told us, "competition is important, but track record is worth more" (Juliett). Together, these entry barriers explain why there are so few actors in the HVDC industry.

Cable companies mention that they want more plastic producers in order to have a reliable source of supply and maybe lower prices (more heterogeneity). However, for the moment there is only the American chemical company DOW who is close to acquiring the same competence as Borealis. Also, there are significant barriers for a chemical producer to enter this market. The sub-suppliers must go through the same tests as the cable producers. Therefore, only internationally recognized companies are eligible to enter. This could hinder further diffusion of knowledge between sub-suppliers.

One of the HVDC producers produces their own processing equipment and therefore does not rely on sub-suppliers to deliver machinery. Another producer, however, does. They said they have close dialogue with these suppliers and that they have been important for AC and will be so for DC. This could raise the accessibility of knowledge for new entrant companies.

Universities play an important role in educating engineers with base knowledge of electricity and transmission, but there is no formal education within HVDC or cables. There is some collaboration between producers and universities when it comes to guest lecturers, but universities play no role in R&D processes. New knowledge is therefore mainly developed by the cable producers' in-house R&D departments. As mentioned in Part 1 of the analysis, this limits the accessibility to knowledge within the industry.

Consultants and test-labs have plays an increasingly important role the last ten years. Before 2006, a producer says, "the TSOs were more engaged in project specifications and had more engineers involved in the process". Due to the TSOs decreasing knowledge of HVDC, a TSO today usually brings an external expert to supervise tests instead of an in-house expert. The rising importance of a third opinion has influenced the cable companies, and today third-party consultants are widespread. They either participate in the cable companies' testing of a new cable, or they test the cable themselves. Early R&D tests are however done without consultants. The rise of these consultant companies could also increase accessibility and lower entrant barriers. Professionalization of the industry whiskers away the earlier trust-relationship between customer and producer, meaning it may be easier for new producers to convince buyers of their technology.

Another important actor are banks. The banks are important because of financing, and they may also require insurance of the whole cable system. The insurance companies require much documentation of the operating experience of cables (to ensure few faults). If there is too much risk involved, insurance companies may refuse to insure the link and thereby financing could be impossible. This may be part of the explanation why TSOs are so risk-averse.

One of the strongest relationships in the HVDC industry that we find, is between the cable producers and the customers. There are several reasons for this. One is that there are very few HVDC cable producers out there, and the only customers are more or less national TSOs. This means that through the years, the TSOs have had many encounters with more or less the same companies – and vice versa. Also, there are very few projects on a worldwide basis, they are extremely costly, and they take years to finish. All of this results in long processes of procurement with many meetings between producer and customer. The regular meetings continue after procurement as well, with testing, installation and maintenance of the system.

Customers have usually already decided what voltage they want before ordering a system. Some customers are pressured by their government, saying they need power from A to B, regardless of technology. This, however, does not mean that cable producers can install whatever technology they like. The TSOs have a tremendous amount of power over innovation in the cable industry. Since they are the only customers, they create a monopoly situation in each country. The commodity that the TSO deals with is electricity, and there are no important performance issues related to that meaning we can't have faster electricity. However, stability is very important as electricity is extremely important for the functioning of our economy and we therefore cannot risk blackouts. Therefore, the TSOs put stability above everything else when assessing technology. This means not only that the technology itself must be proven in test-labs, it must be proven in full-scale, and preferably over many years in a real commercial project. Also, the cable producers advertising this technology must be a well-established company with many projects behind them. Because of the mere size of these projects, delays under installation are the rule rather than the exception, and therefore the TSOs do not want to take chances on newcomers with short track records. This fits very well with Malerba's theories: homogenous demand leads to a dominant design (the MI cable and the old LCC converter) which in turn leads to industrial concentration (again, only three HVDC MI producers in Europe). Therefore, developing the new XLPE system took many years, because producers could not get TSOs to try this technology. Even though the advantages of the new technology are many, the technology was not proven enough in real-life projects.

We know that emergence and transformation of demand is an important part of the evolution in sectoral systems, and this is clearly the case with the VSC / XLPE. The first high voltage HVDC XLPE in commercial use in Europe happened with the German Energiwende (German transition to more renewable energy). With the Energiwende the need arose for several offshore windfarms on the edge of the German coast. The suggested offshore windfarms were so far at sea that HVDC was the only viable option. The problem, however, was that with older HVDC technology, one could not have a 'black start' (meaning no power) at the one end. This was obviously needed, because windfarms do not always produce (enough) power. Therefore, the Dutch / German TSO Tennet was forced to try the new VSC / XLPE duo. There a black start is possible - meaning that they can be installed on offshore windfarms. This example shows that a new demand created the possibility to evolve new technology in the HVDC industry.

This is not to say that TSOs take no risks with all new projects. There has been a massive increase in voltage capacity in HVDC systems over the years. This has happened by cable producers having regular meetings with them, showing them their new technology and trying to convince a customer of the increased performance outweighing the increased risks. In addition, third party consultants are hired to make sure the technology really works. Also, producers might offer new technology at a lower price to compensate for increased risks. Today Tennet is discussing trying a new 525 kV XLPE HVDC subsea cable in a short section (30-40 km). This way the producer could accumulate experience and test their new product. The TSO Tennet says this could be acceptable as long as faults or delays are the responsibility of the cable producer.

7. Empirical findings and analysis part 3: Institutions

Institutions in the European HVDC subsea cable industry

Institutions play a major role in the rate of performance, innovation and technological change in sectors. Institutions include norms, routines, common habits, established practices, rules, laws, standards and so on that shape agents cognition and action and affect the interactions among agents (Malerba, 1999). This chapter outlines and discusses the different institutions and their respective effects on the industry.

7.1 Patents and disclosure agreements

Patents are becoming increasingly important in HVDC. This is because there is an increasing amount of players and activity. One cable producer says patents will continue to become important because it is easier for new players to go into DC with the new extruded cable type (because it is more similar to AC than the more different classic paper insulated cables) (Charlie).

Another producer says that they use both patents and publications when trying to protect their inventions. Both of them make sure that their specific design is not copied by other companies (Echo).

Disclosure agreements play an important role in the development of new technologies, such as for example the insulation material for the XLPE plastic done in collaboration with chemical producer Borealis. Non-disclosure agreements are also signed between test-labs, consultants and customers (Charlie, Echo).

7.2 Standards

> "Standards are very important for how you test equipment. In addition, if you want to procure something competitively you have to refer to standards for a buyer to buy your new equipment." – Former leader of CIGRE committee B4 HVDC and power electronics (India).

There are no standards on a complete HVDC cable. The first standard for a HVDC cable will come in 2016. CIGRE has a few documents on HVDC, but there are no standards on the cables. Cable producers say there seems to be a demand in the market for more standards because there are customers who want additional testing. Additional testing to comply with (potential) standards does not add much to the total price, unless customers want long-time testing (Charlie).

This is not to say there are no standards when manufacturing a cable. A TSO (or even public authorities) such as TenneT will specify which set of standards from IEC or CIGRE that applicants must comply with. If the standard is not adequate, ad hoc specifications are made. The director of sales at a possible entrant company says that there have been important changes in the "standard setting paradigm" over the last 5-6 years. HV cables in general and HVDC in particular have gradually undergone a "professionalization" which has accelerated in recent years. In the "early days" producers could more or less freely make contracts and set terms for quality, tests, installation, and quality. The entrance of DNV GL in HVDC reflects that things are changing. Now there is a larger demand for formal risk assessment and management. This is driven by the energy transition; my informant says (Foxtrot).

7.2.1 Developing standards

Currently there are competing standardization activities led by different TSOs, consulting companies and cable companies. These standards are either developed by IEC or CIGRE. In CIGRE there are various industry experts in different study committees. These experts represent their country, not their company. There is a meeting every year and it takes three to four years before a study committee will put down a practice. Some of these practices are taken up in the IEC. There are also standards in 'grid codes' that are developed in ENTSO-E which TSOs also are a part of.

A potential entrant company in the standards regime is DNV GL. DNV GL published two HVDC "recommended practices", last year[16].

> "The suppliers have standards and practices, procedures that work well in the industry for them one by one. They are all established, have a long track record and their own activities, but there are differences between them driven by their own technological preferences. It does work well; it is however not uniform - it is supplier specific." – Head of Section, DNV GL (Golf)

A cable producer told us that DNV GL has a very clear goal to become an alternative to the IEC and CIGRE, "They want to create their own guidelines and recommendations so that

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[16] RP-1: "Subsea Power Cables in Shallow Water Renewable Energy Applications", Feb. 2014. (DNV-GL, 2014b)

RP-2: "Qualification procedure for offshore high-voltage direct current (HVDC) technologies", Aug. 2014. (DNV-GL, 2014a) they can send a consultant team afterwards" (Echo). This producer told us that IEC and CIGRE are the associations which are recognized in the industry. In CIGRE there is a big session every two years in Paris. At the last one, DNV GL asked to cooperate with the IEC and CIGRE in forming standards. This was rejected by CIGRE. According to my sources, there are many in the cable and power industry, as well as several other actors, who do not want DNV to create their own standards.

> "DNV GL want to make the tests more rigid so that they can sell testing. CIGRE and IEC have always been organizations that have been promoting the industry as a whole, making a good set of rules that benefits everyone. DNV GL is a much more commercial type of player who want to steer the direction in a way where they can sell their tests and consulting services. We, and most cable companies I've talked to, do not think that is a good idea. You take the focus away from what you want to achieve with standards and standardized tests. They are more than welcome to join the study committees or working groups, but we do not want to create a separate DNV GL library." – R&D Team Leader, cable producer (Echo)

Some producers do however see a point with DNV GL and have participated with developing the two papers on recommended practices. Some power producers have complained that processes in IEC and CIGRE are slow, and DNV GL is recognized by cable and power producers and TSOs as much quicker at finishing recommended practises. Cable companies say there might be use for DNV GL in HVDC, but on other areas than cable testing. A cable producer told us he sat in one of the committees at DNV as a representative for Europacable, but "only because Europacable wanted to ensure that the report was a supplement and not a substitute for CIGRE and IEC" (R&D Team Leader, cable producer, Echo).

7.3 Politics and norms

The interest and lobbyist group Europacable has tried to convince stakeholders to accept the concept of partial undergrounding. Partial undergrounding is the idea that instead of sending power on land through lines, you can send parts of the power through underground cables. This could be done in sensitive areas where one, for various reasons, would not want visible overhead lines. Europacable has tried to convince buyers that partial undergrounding is a good solution because cables are very reliable and it is easier and cheaper to repair faults than many think. One can also reduce the electromagnetic field better than with lines. Also cables are not visual, and they take up less space.

The organization for TSOs in Europe, ENTSO-E is developing network codes which will have an influence on technology and grid security. Therefore, TenneT, as well as other TSOs, are actively involved in the development of such codes. Their own grid codes will be adapted accordingly (Juliett).

7.4 Summary and discussion part 3

Agent’s actions and interactions are shaped by institutions, like for example norms, routines, habits, rules, standards, et. Cetera (Malerba, 1999).

Chapter 4 showed a clear increase in HVDC projects the last years. Several of my informants claim that the rise in demand is driven by the energy transition. Formal instances such as state rules and regulations, especially in Germany, have initiated the expansion of greener energy, which in turn has demanded innovation from the HVDC cable industry. The building of large interconnectors is the result of public policy to help disperse the effects of the green (variable) energy (the transportation of energy from where the weather conditions create the most energy).

There are no standards on a complete HVDC cable, as the first standard for a HVDC cable will come next year. At the same time, there is an increasing demand for standards from the supplier. There are, however, many standards for manufacturing cables. A TSO will specify which sets of standards from IEC or CIGRE that applicants must comply with. There have been important changes in the “standard setting paradigm” over the last five to six years. It seems that HV cables in general, and HVDC in particular, have gradually undergone a professionalization which has accelerated in recent years. In the “early days” producers could more or less freely make contracts and set terms for quality, tests, installation, and quality directly with the customers. The entrance of DNV GL in HVDC reflects that things are changing. Now there is a larger demand for formal risk assessment and management from third-party consultants.

The standard regime is today set by various industry experts who work in committees either in CIGRE or the IEC. DNV GL wants to be a part of the standard setting regime. Informants tell me that DNV GL wants to make standards and recommended practices so they can profit from selling their consulting services afterwards. True or not, the expansion of standards could increase the dynamics in the HVDC industry. With today’s regime, company trust seems more important than neutral standards. The increase in activity implies that there is less space and time for trust-relationships which in turn creates a need for formalizing and systematizing relations between actors. If there are sufficient standards and competent consultant companies assessing these, it might be easier for a new customer that has the technology – but not the experience – to enter the market. This in turn might lead to a more heterogenic firm environment and thereby a more active innovation environment. Several of my informants said CIGRE and IEC take many years before they publish recommended practices or standards on new technology. With DNV GL, my informants tell me, the time it takes to develop a recommended practice or standards is much less. This could increase the speed of technology change.

8. Further discussion and implications

How does technological change come about in infrastructure sectors?

The three elements in SIS that I have covered both theoretically and empirically are closely connected. Therefore, changes over time in sectoral systems is a co-evolutionary process involving all three of these elements. In this chapter the empirical findings from these three elements as a whole will be summarized and discussed alongside former research on infrastructure sectors. The aim is to answer my research question: *How does technological change come about in the European HVDC subsea cable industry?* This helps me answer my overarching research question: *How does technological change come about in infrastructure sectors?*

8.1 How does technological change come about in the European HVDC subsea cable industry?

To answer this question, we first need to understand how knowledge acts and diffuses in the industry. From my theory chapter we know that according to SSI, low knowledge accessibility often leads to high appropriability. From my empirical findings we can say that there is most definitely low knowledge accessibility the HVDC industry, because there is no formal education for HVDC engineers and because there are very few experts available in the world. This has also lead to high appropriability (difficult to copy design and innovations) clearly shown by the fact that there are very few actors operating in the high voltages of HVDC. Risk-averse customers being afraid of new producers might also take the blame for the few actors. Further we must acknowledge that knowledge in this industry is 'internal' in the way that new technology is mainly driven from firms. There are, however, some exceptions such as the important collaborations cable producers have with the chemicals company Borealis. This company creates the plastic insulation for the plastic insulated cables (XLPE). There also seems to be a need for high absorptive capacity for firms to succeed in the business. We know that absorptive capacity is largely a function of the firm's level of prior related knowledge. The companies' knowledge must be said to be very high because of the high firm and technologically based cumulativeness in the industry. The need for high absorptive capacity tends to create industries with few large and established firms, which is clearly also the case in the HVDC industry. See the table below for a quick and very simplified summary of the different knowledge traits.

Knowledge traits	**Level / type**
Knowledge accessibility (high/low)	Low
Appropriability (high/low)	High
Source of knowledge (internal/external)	Internal
Absorptive capacity (high/low)	High
Cumulativeness (high/low)	High
Cumulativeness type (firm, technological, local)	Firm and technology

To further understand technological change in the SSI, I documented in chapter 6 the different actors, networks and the relationships between them. There I found that there are many interactions between several actors in the generation of innovation and its commercialization. There are interactions with the universities, but even if the basics of electrical engineering is thought in universities, the link must say to be weak, as there is no formal education for HVDC cables and most importantly: most research is done in-house in cable companies. Also there is a mismatch between the secrecy of the HVDC cable industry and the openness of universities. Universities would like to publish new research while producers would want new findings and knowledge to be kept internally in the company.

Amongst the more important collaborators are the banks. The banks demand insurance and thus that standards must be met to allow for financing. Sub suppliers such as the chemical industry, and consultants and test-labs are other important actors. My informants tell me that the industry is changing, with the increased use of third-party consultants for testing and construction of HVDC projects, and there is also an increase in the use of third party test-labs for testing of links. Firm heterogeneity is very low in the HVDC industry, but the increased use of consultants and third party test labs indicate that this may be changing. New actors such as DNV-GL could help displace HVDC knowledge from the incumbents to other actors as well, opening the HVDC “knowledge pool” for possible entrants.

The strongest network link is arguably between the customers (the TSOs) and the cable producers. This link has been, and still is, very strong. There are continuous meetings between these two, and R&D in cable companies seems very based on what is actually needed from the customers. A good example of this is the HVDC XLPE technology related to the VSC converter technology that was needed for the construction of German offshore windfarms. The technology was already available, but this infused the testing of this new technology in a real-life real-size project. I therefore argue that the governmental pull in Germany for greener energy production was the most important factor for implementing, and thereby a "commercial application", of the HVDC XLPE / VSC technology.

See the table below for a quick and very simplified summary of network traits found in the HVDC industry.

Network traits	**Level / type**
Link producers - universities	Weak
Link producers – consultants / test-labs	Medium (increasing)
Link producers - customers	Strong
Link producers - Sub suppliers	Medium / Strong
Link producers - financial institutions	Strong
Firm heterogeneity	Low

Finally, to understand technological change in the HVDC industry I reviewed the different institutions and their role in the industry in chapter 7. As Malerba also recognizes, the role of institutions is a hard analytical tool, as they can come in various forms and have a widely varying effect on the sectoral system. This thesis has only covered some of them, such as formal regulation, standards, disclosure agreements and patents. A further study could for example look into the role of informal institutions such as norms, routines and common habits.

In my discussion I speculate that standards are playing an increasingly important role in the industry as there is an increasing demand from both insurance companies and customers to use third-party consultants and test-labs. This could make patents more important because customers are wishing for a 'third opinion' which a good standards regime could offer.

Formal regulation (of the energy sector) is extremely important for technological change because the increased demand for greener energy has led to an increased demand in the amount of cables and the technology behind the cable (a great example of this is for example the use of XLPE VLC technology in German offshore windfarms).

See the table below for a quick and very simplified summary of the institutional traits found in the HVDC industry.

Institutional traits	**Level / type**
Formal regulation (of the energy sector)	Very important
Standards	Fairly and increasingly important
Patents	Fairly important

So how then does technological change come about in the European HVDC subsea industry? From the SSI perspective we know that changes in sectoral systems are a results of a coevolution of the three categories mentioned above. From this we can say that technological change comes about slowly and incrementally. This is because technologies are highly cumulative, and the knowledge regime is characterized by low knowledge accessibility, high appropriability, and internal sources of knowledge. Furthermore, there is a need for high absorptive capacity for firms. Together these factors put newcomers and challengers in a very disadvantaged position, and this is why the industry consists of a few large and established firms.

Who and what drives the technological change? According to SSI, firms are the key actors in the use, adoption and generation of new technologies. This is also the case in the HVDC industry where almost all R&D is developed by the cable producers and partly the sub-suppliers. I therefore argue that the main innovators are the incumbents - the large few cable companies that have the necessary technology to produce HVDC cables. Even though the new HVDC XLPE system was developed to reduce cost and therefore get a commercial advantage, it was first commercially applicable after new demand conditions from a new application – offshore windfarms far from shore. The construction of these windfarms is a result of governmental regulation of the energy sector in Germany. This chain of events shows how the cable producers are strongly shaped by demand foremost from projects from TSOs around Europe which in turn is created by governmental regulation (the role of institutions). The TSOs therefore create market-pull for new technology, however they also delay new technology because of their high risk-averseness, as shown in chapter 5 and 6.

How then can the rate of technological change be increased? There are some signs that the industry is changing to a more dynamic industry. The technological life cycles in the HVDC business are in general very long and could therefore prove to be of significant barriers for newcomers[17], as there are incremental changes to performance in HVDC cables related to the same knowledge regime (same insulation principles and build-up of the cable) and not vastly new ones. However, the introduction of the HVDC XLPE (extruded) cable is, in a way, an exception to this. My context chapter showed us that the XLPE insulation technique has been used for HVAC cables since the late 1980s, but was first used for HVDC cables in 1998. XLPE technique is therefore not a new thing on AC cables, but it's fairly newer in its application on HVDC cables – especially for higher voltages. This shift from the older technology, HVDC MI (mass impregnated) cables, to HVDC XLPE cables could give new firms a window of opportunity to enter the HVDC marked by "leapfrogging" over the older HVDC MI technology. "Leapfrogging" refers to a possibility for late-comers to catch up with established firms by leapfrogging over older technologies and thus bypass heavy investments and instead invest in the state-of-the-art technology of the new technological commodity (Keun, Seong-Jae, & Jia, 2009; Lin, 2011) . This could especially be true for HVAC companies because my research shows that the production techniques and the cable build up technology of the XLPE HVDC cable is much more similar to that of HVAC cables than the older HVDC MI cable. This implies that much of the knowledge behind HVDC cables should be easier obtainable for HVAC producer as the knowledge base is much more similar with the new XLPE cable.

The entry of third-party actors such as consultants and test-labs could also help disperse HVDC knowledge and thereby perhaps increase knowledge accessibility and increase firm-heterogeneity. Here the role of standards also plays a role, with increased standards it might be easier for new companies to enter the European market to prove for European TSOs that they have reliable technology.

In sum these changes can create higher firm-heterogeneity. We know that the creation of new agents, both new firms and non-firms, is particularly important for the dynamics of sectoral systems and their degree of change. This variety creation may also refer to the rise of new products, technologies, and institutions, as well as new firm strategies and behavior (Malerba & Orsenigo, 1999). In general, rapid technological change implies a great heterogeneity of actors in most sectors (Malerba, 2011, p. 390). Higher firm-heterogeneity could therefore perhaps raise the rate of technological change in the European HVDC subsea cable industry.

[17] Studies have confirmed that shorter cycle times of technologies implies a higher possibility and degree of technological catch-up and therefore a higher level of technological capability for new firms (Perez & Soete, 1988; Rho, Lee, & Kim, 2015)

The role of demand plays a large role in the performance of innovation in the European HVDC subsea industry. We know that a homogeneous demand usually creates a dominant design and industrial concentration (Malerba, 1999, p. 23). The TSOs in Europe thus set the pace by deciding which technologies to use and from which cable suppliers to order from. Therefore, to increase the innovative performance in the HVDC industry it is up to the TSOs to be more risk-willing both in terms of technological choices, but also when it comes to letting newcomers into the market.

8.1 How does technological change come about in infrastructure sectors?

The overarching research question of this thesis is as follows:

How does technological change come about in infrastructure sectors?

I argued in the theory chapter that the related infrastructure industries must be included in analysis of changes in sectoral systems. This is because at least in some industries, such as the HVDC subsea cable industry, the only customers are the TSOs, and the only tech-provider to that infrastructure are the HVDC cable producers. Thus, a technological change in that system cannot happened to one without affecting the other. If my hypothesis is right, we would expect many of the traits normally associated with infrastructure sectors to match the traits found in the HVDC subsea cable industry.

My findings are largely coherent with our hypothesis. The properties of the HVDC case unit largely matches former research on infrastructures. It is clear that there is an interaction between the industry and its surrounding sector affecting each other in different ways. It holds true that network externalities, indivisibility, scale and the multiuser property imply that infrastructure investments are highly capital intensive. As chapter 4 and 6 have shown, the projects are very large and highly capital-intensive. As argued in 6.7, this creates big barriers for new entrant companies because the initial investments needed for starting with HVDC technology are immense.

As argued in 6.7, TSOs are very risk-averse. This can be explained by the generic traits of infrastructure which means that they are a core requirement for many or all activities because it provides fundamental resources into all parts of economic activity (Smith, 2005a). This interdependency between the transmission infrastructure and the wider society generates strong risk aversion (Levitan, 2014). TSOs cannot risk black-outs and therefore chooses well-proven technology over newer technologies and also chooses suppliers they know well. This is seen for example in chapter 6 with the TSO TenneT saying “competition is important, but track record is worth more” (Juliett).

Like former research on infrastructure has shown systemness is usually very high in infrastructure sectors. This is also true for the HVDC industry because all the cable projects are being installed in a system of an established technology (the power grid). In these systems there is strong interdependency between the technical components. This means that regulatory change must accompany technological change to maintain grid stability in the process (Andersen, 2014). As one producer put it: “If I go to a new project in India, four out of five questions will be about the installation”. Systemness is extra profound in cases of interconnectors, as different countries may have different network codes and standards. This impacts negatively on technological change because of issues related to path dependency. As suspected, in sum these properties mean that technological change in the HVDC industry has evolved gradually with incremental changes.

9. Conclusion

Main findings and contributions

9.1 Main findings and contributions

I have attempted to fill a void in the innovation studies literature, where research on infrastructure sectors has been scarce. Also, there has been little research on the HVDC industry, and as such this thesis has empirically been a contribution to new knowledge about the innovation dynamics in the HVDC cable industry in Europe and theoretically by advancing the emerging area of infrastructure research within innovation. With emphasis on qualitative interviews and document analysis, the knowledge and technologies, actors and networks, and institutions in the European HVDC cable industry have been mapped. The European HVDC cable industry was chosen as a case unit to help answer our overarching research question: *How does technological change come about in infrastructure sectors?*

I conclusion change in our case unit, the European HVDC subsea cable industry, change comes about by:

(I) Change is slow and incremental moving along predefined paths. This is due to the high systemness and interdependencies of infrastructure sectors. This means that the wider economy's dependency on the infrastructure creates highly risk-averse customers reluctant to take risks in new technology.

(II) There is mainly incumbent driven innovation as almost all technological break-troughs and innovations the last twenty years have been done in-house at cable companies. This thesis reveals that high capital cost, the importance of trust between customer and cable companies, as well as a knowledge base which has low level of accessibility, has led to a homogenous firm environment with very few producers. This further slows down technological change.

It is difficult to conclude on something in particular regarding the mode of technological change of infrastructure sectors (in general) other than that my findings in my case unit were coherent with my hypothesis. The properties of infrastructure are found in my case unit, but much further research on other infrastructure sectors is needed before a conclusion can be made.

9.2 Limitations, further research and policy implications

Although I do believe that the findings in this thesis provide a fairly accurate description of the European HVDC subsea cable industry, more research is required to fully uncover the industry. Examples of this is that I miss a few HVDC cable producers, and also the lack of insurance companies and banks. The reason for the former is that a couple cable companies declined my offer for an interview due to secrecy issues. The role of banks and insurance was discovered late in my data gathering and therefore I did not have the time to find a bank or an insurance company for interviewing. It would also be interesting to look deeper into the role of public policies. This thesis revealed that public policies play a huge role for the HVDC industry, and as such it might be interesting to go further into the role of national and European institutions (including the TSOs).

The overarching question in this thesis is a very broad one, and therefore this thesis only presents an early contribution to the literature surrounding the transformation of infrastructure systems. The scope of a master thesis poses some restrictions to the amount of empirical data it is possible to gather and analyze. The link between the surrounding infrastructure sector and the European HVDC subsea cable is apparently strong as the properties of infrastructure found in earlier research is also found in the industry. This means that the European HVDC subsea cable industry is strongly linked to infrastructure sectors. However, further research must be done on other industries in the infrastructure sector to confirm if these changes coincide with other findings.

Infrastructures will continue to be a central part of our economy, and thus understanding infrastructure sectors is a very important issue. In the introduction of this thesis I also argued that infrastructure transformation is especially crucial in our days because of the new demands the energy transition requires from the infrastructure. This thesis reveals the main obstacles to quicker technological change and a better innovation environment in the European HVDC subsea cable industry. There are some signs that the industry is moving to a more dynamic industry, such as the increased importance of standards or the use of third-party firms such as consultants or test-labs, or the introduction of the XLPE cable that has a more open knowledge pool. However, as long as TSOs remain extremely risk-averse it is difficult to introduce new technology. The high interdependency of the surrounding economy, however, makes it so that this risk-averseness is understandable. A solution could be if the TSOs could involve themselves in research collaborations with cable producers, and especially new ones moving into HVDC. This way it might be easier to test new technology and also for newcomers to enter the marked. This could lead to a more heterogeneous marked and increase technological change in the European HVDC subsea industry. This must be seen as crucial in our transition to greener energy, as more efficient - and then perhaps less expensive - cables could dramatically bring down costs on offshore-windfarm projects as well as in general the building and refurbishing of the power grid in Europe.

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Appendix 1 – source codes

Code	**Company type**	**Company name**	**Title**
Alpha	Power cable producer	Anonymous	Senior sales & Marketing Executive
Bravo	Power cable producer	Anonymous	Market Intelligence Executive
Charlie	Power cable producer	Anonymous	Acting R&D Manager
Delta	Converter producer	Anonymous	Head of Global Sales
Echo	Power cable producer	Anonymous	R&D Team Leader
Foxtrot	Power cable producer	Anonymous	Director of Sales
Golf	Consultant company	DNV GL	Head of Section
Hotel	Consultant company	DNV GL	
India	Branch organization	CIGRE	Former Head of Committee
Juliett	TSO	TenneT	Head of DC interconnector department
Kilo	Energy producer	DONG energy	
Lima	Consultant company	Stri	

Appendix 2 – interview guides

Interview guide HVDC cable producers

Time, name of interviewee, his\her profile and expertise.

1. **Cable Technology**
    a. What are the most important technological changes in HVDC subsea cabling over last 10 years?
    b. Which are the main technological barriers remaining for HVDC cabling? What direction of technological change do you expect for the next 10 years?
    c. Overlaps in technical competence for producing / improving different technologies. Can the same engineer easily move between?
        i. HVDC versus HVAC cables?
        ii. How does your company consider the markets for HVDC and HVAC? Complementary or competitive?

2. **How are innovation activities organized?**
    a) Where are R&D activities concentrated geographically?
    b) How does your company work to introduce new HVDC cable technology (incl. new designs)?
        - Can you describe a typical process?
        - From technical component to complex end product?
        - Are patents important?

    c) Collaboration: In relation to processes of R&D and innovation/commercialization activities, does your company interact with other actors? For example:
        - Buyers
        - Sub-suppliers? Component suppliers? Firms from other industries? ICT? Materials?
        - Universities & Research centers?
        - Certification companies?
        - Test labs?
        - Others?

d) Frequency & time of innovation activities
   - In projects or continuously between of projects?
   - Standardized versus project ad hoc technical solutions

e) Do HVDC cable firms typically have own full-scale test facilities for new products?
   - In HVDC converters (and the like) companies often contract external facilities to test components. Also the case for cables?

f) The role of (conservative) buyers: how to convince them to use novel technology?
   - How important are feasibility studies?

3. The importance of "standards" or "quality assurances" for innovation and introduction of new technology in the market?

a) To which degree do industry standards play a role in your industry? Why?
   - Important for buyers?
   - Does it affect relationships and interaction with suppliers?
   - Can requirements from standards affect R&D processes?

b) Which are the most important standards for HVDC cable technology?
   - Technical stability, security, combining components from competing suppliers?

c) How are such standards developed?
   - Who are the main actors?
   - How does your company interact with these processes?

d) How are standards given authority?

Interview guide CIGRE

Time, name of interviewee, his\her profile and expertise.

1. **Areas of technological innovation and competencies**
    - Can you describe in a general way the most important innovations within HVDC over last 10 years? (besides the HVDC VSC/Light)
        i. Converters
        ii. cables
    - Which main technological challenges remain for HVDC looking forwards?
    - Overlaps in technical competence for producing / improving different technologies. Can the same engineer easily move between:
        i. HVDC versus HVAC?
2. **How are innovation activities organized?**
    - Can you describe a typical process from patent to power system? From technical component to complex end product?
    - Frequency & time of innovation activities
        - In projects or continuously between / independent of projects?
        - How long time does an innovation project run?
        - How is the day-to-day R&D work combined with selling novel technological systems? Is there a tension here?
    - Collaboration: In relation to processes of R&D and innovation/commercialization activities, do HVDC cable firms interact with other actors? For example:
        - Buyers
        - Sub-suppliers? Component suppliers?
            - Firms from other industries? ICT? Materials?
        - Universities?
        - Research centers?
        - Competitors?
        - Others?
    - Do HVDC cable firms typically have own full-scale test facilities for new products?
    - The role of (conservative) buyers: how to convince them to use novel technology?
        - How important are feasibility studies?
3. **The importance of technical standards for innovation**
    - To which degree do industry standards play a role in your industry?

- Technical standards for equipment manufacturers
    i. Certifying reliability of technology/product
    ii. (in)compatible technologies from different manufacturers?

Interview guide cable producers

Time, name of interviewee, his\her profile and expertise.

1. Utviklingen av HVDC

• De siste årene har vi sett en stor økning av HVDC-prosjekter i offshore vind, hovedsakelig i Tyskland. Er dette en interessant teknologi for dere, hvorfor / hvorfor ikke?

• I hvilke prosjekter har dere brukt denne typen teknologi?

• Hvordan har HVDC utviklet seg siden 2000 sett fra deres synspunkt?

2. Deres teknologiske vurderinger av HVDC kabel

• Hvordan forsikrer dere om at ny teknologi rent faktisk fungerer bra? Tekniske standarder? Tillit til produsent?

• Trenger dere selv betydelig kompetanse på teknologien for å kunne vurdere dette? Eller bruker dere tredje part?

• Hvilken rolle spiller feasibility studier innen teknologi-valg og valg av leverandør?

Er det kabel-produsent der ivaretar etterfølgende drift og vedlikehold? Er dette en stor kostnad`

3. Samarbeid med kabelbransjen

• Vi vet at kabelbransjen har behov for å teste ut fersk teknologi i fullskala og trenger derfor å samarbeide med kunder for å få til dette. Har dere samarbeid med kabelbransjen i å teste ny teknologi?

• Hvordan har dette samarbeidet utartet seg?

4. Teknologiske og produksjonsmessige flaskehalser

• Vi har kollegaer i Sverige som med fokus på offshore vind har påvist at flere typer flaskehalser kan forventes å oppstå langs verdikjeden etter hvert som ekspansjonen av fornybar energi progresser. Opplever dere flaskehalser knyttet til kabelbransjen når dere bygger ut nye prosjekter? (tekniske flaskehalser, flaskehalser knyttet til levering, flaskehalser knyttet til kostnader).

5. Konkurranse i kabelbransjen

• Selskaper som leverer høyspentkabler i Europa er svært få, spesielt om man ser på undersjøisk og HVDC-kabler (ABB, Prysmian, Nexans). Har dere noen oppfatning om hvorfor det er så få aktører i Europa?

• All den tid ENTOSE og flere TSOer peker på et enormt behov for kabler frem mot 2030 skulle man anslå at det europeiske marketet er interessant for nye aktører. Vi vet dere har gitt en kontrakt til LS Cable fra Sør-Korea. Er det andre aktører på vei inn? Hva tror du det vil ha å si for markedet (prissetting, og så videre)?

Interview guide Tennet (TSOs)

Time, name of interviewee, his\her profile and expertise.

1. **Technology choice / technology procurement**
   - Can you explain how the choice of technological design and components is done in a HVDC project?
   - How important is it that you (buyer company) have a group of technology experts to assist you in the technology choice process (1 = not important, 2 = useful, 3 = crucial)?
     - Has this changed during the last 10 years?
   - How does Tennet interact with 3rd party specialists (certificates, standards, tests, technology qualification) in the decision making process?
   - Could you say that there is an additional risk for the buyer in purchasing "new technology" (unproven under real-life circumstances)?
     - What, if anything, do technology suppliers do to convince buyers to buy their newest equipment?
     - Suppliers say that are waiting for an adventurous TSO to install and run their HVDC hybrid breaker technology and 525kV XLPE cable. Is this a typical situation?
   - One could say that it is in an individual TSO's interest to stimulate technological development that might reduce cost / improve performance of technology. Do you participate in technology development collaborations with the HVDC industry (cables and converters)?

- What role you have in such a collaboration? Advice? Expert staff? Full scale testing of new technology?
- Is this collaboration in between projects or also during a project? Both?

2. Technological risk

- Some of the people we have spoken to thinks that Tennet has been a TSO pioneer in HVDC by taking onboard new technological solutions (VSC offshore and XLPE DC). What is your reflection on that?

3. **Choice of vendor / technology supplier**

   a. What are the determining factors for deciding:
      i. Price
      ii. Technological edge
      iii. Available capacity
      iv. Company reputation / experience
      v. previous transactions with and trust

   b. Is competition among supplier important? How do you asses current intensity of competition as compared to 10 years ago? (both cables and converters).

4. Which role do technological standards play for your company in technology choice?

- Do you involve 3rd party actor to guarantee compliance with relevant standards?
- Do you participate in the development of standards?
- Does standard compliance have implications for risk assessment?
  - For insurance premium?
  - For cost of capital?
  - Has there been any changes in this over the last 10 years?
- Testing and technology qualification regime
  - Some consultant companies we have spoken to argue that there is a need for a new type of testing and technology qualification regime in HVDC. There is a need for: (i) TSOs can get neutral support in assessing little transparent project offers from technology suppliers, (ii) projects management and designs should be done less ad hoc (i.e. more standardized) which could speed up project executions and minimize mistakes during commissioning, (iii) better neutral

risk assessment with respect to introducing new technology to risk-averse buyers, and so on.

- These consultants argue that change in the way the industry develops new and deploys technology is only possible if TSOs take a more active role in projects. Currently technology suppliers act as "system integrators". TSOs must to a larger extent act as system integrators; they must take the baton. TSOs are not demanding an extension of the test regime and project management. That is the main obstacle to change.

Would you agree with this assessment? Any reflections?

Appendix 3 - HVDC cable projects since 2000 database (screenshot)

X

HVDC cable projects in Europe started and/or finished since 2000 * only above 50kV

									kV	MW	km		Million						
Year compl	**Name**	**Nations**	**Function**	**Customer 1**	**Customer 2**	**Cable company**	**Converters**	**Other com**	**Voltage**	**watt ca**	**Length subm.**	**Length**	**Cabel cost**	**Converter**	**Total cost**	**Type**	**Cable Tech**	**Converter tech**	**Web**
2000	SwePol	Sweden / Poland	Intercon.	Svenska Kraftnät (51%), V	PSE (33%).	ABB	ABB		450		245				$ 250	Submarine	MI	LCC	http
2001	Grita	Italy / Greece	Intercon.	Terna		ABB	ABB		400		200	110				Submarine, land &	MI	LCC	http:
2002	Moyle	Scotland / Northern Ireland	Intercon.	Mutual Energy		Nexans	Siemens		250	500	63,5					Submarine	MI	LCC	http:
2004	Troll	Norway	Offshore oil gass	Statoil		ABB	ABB		60		70				$ 270	Submarine	XLPE	VSC	http:
2006	Estlink	Estonia / Finland	Intercon.	Elering	Fingrid Oyj	ABB	ABB	Global M	150		105		€ 180	€ 100	€ 320	Submarine & land	XLPE	VSC	http
2008	NorNed	Norway /The Netherlands	Intercon.	Statnett (50%)	Tennet (50%	Nexans & ABB	ABB		450		580				€ 600	Submarine	MI	LCC	http:
2009	NordE.ON 1	Germany	OWF	Tennet		ABB	ABB		150		203				$ 400	Submarine	XLPE	VSC	http
2009	Valhall	Norway	Offshore oil gass	BP		Nexans	ABB		150		292		€ 98	$ 50		Submarine	XLPE	VSC	http
2010	BritNed	UK / The Netherlands	Intercon.	National Grid	Tennet	ABB	Siemens		450		245		$ 350		€ 600	Submarine	MI	LCC	http:
2010	StoreBælt	Denmark	Intercon.	Energinet		ABB	Siemens	JD- Contra	400		32	26			NA	Submarine and lan	MI	LCC	http:
2011	Cometa	Spain	Intercon.	Red Eléctrica de España		Nexans / Prysn	Siemens		250		247		€ 267	€ 100		Submarine	MI	LCC	http:
2011	SAPEI	Italy	Intercon.	Terna		Prysmian	ABB		500		435		€ 300	$ 180		Submarine	MI	LCC	http:
2011	Fenno-Skan 2	Sweden / Finland	Intercon.	Fingrid Oyj	Svenska Kra	Nexans	ABB		500		200	103	€ 150	$ 170		Submarine & land	MI	LCC	http:
2012	Borwin1	Germany	OWF	TenneT		ABB	ABB		150	400	125	75			$ 400	Submarine & land	XLPE	VSC	http:
2012	Romulo	Spain	Intercon.	Red Eléctrica de España		Nexans / Prysn	Siemens		250	400	237	7			€ 425	Submarine & land	MI	LCC	http
2012	East–West Intercon	UK / Ireland	Intercon.	EirGrid		ABB	ABB		200		130				€ 600	Submarine	XLPE	VSC	http:
2014	Estlink 2	Estonia / Finland	Intercon.	Elering	Fingrid Oyj	Nexans	Siemens		450		157	14	€ 100	€ 180	€ 320	Submarine, land &	MI	LCC	http:
2014	Skagerrak 4	Norway / Denmark	Intercon.	Statnett	Energinet	Prysmian (DK),	ABB		400	700	244		€ 40 + € 87		€ 400	Submarine & land	XLPE	VSC	http:
2015	BorWin2	Germany	OWF	TenneT		Prysmian	Siemens		300	800	125	75			€ 500	Submarine & land	XLPE	VSC	http:
2015	HelWin1	Germany	OWF	TenneT		Prysmian	Siemens		250	576	85	45				Submarine & land	XLPE	VSC	http:
Confirmed / ongoing projects																			
2015	Åland	Finland	Intercon.	Kraftnät Åland AB		ABB	ABB		110		158				$ 130	Submarine	XLPE	VSC	http:
2015	INELFE	France / Spain	Intercon.	RTE	REE	Prysmian	Siemens		320		64		€ 90			Land	XLPE	VSC	http:
2015	Nordbalt	Sweden / Lithuania	Intercon.	Litgrid	svenska kra	ABB	ABB		300		450				$ 580	Submarine & land	XLPE	VSC	http:
2015	Troll A 3&4	Norway	Offshore oil gass	Statoil		ABB	ABB		66		70				$ 270	Submarine	XLPE	VSC	http:
2015	SylWin1	Germany	OWF	TenneT		Prysmian	Siemens		320	864	160	45	€ 250			Submarine & land	XLPE	VSC	http:
2015	DolWin1	Germany	OWF	TenneT		ABB	ABB		320	800	75	92			$ 700	Submarine & land	XLPE	VSC	http:
2015	DolWin2	Germany	OWF	TenneT		ABB	ABB	Aibel	320	900	135				$ 1000	Submarine & land	XLPE	VSC	http:
2015	HelWin2	Germany	OWF	TenneT		Prysmian	Siemens		320	690	130		€ 200			Submarine & land	XLPE	VSC	http:
2016	Westen HVDC link	Scotland / Wales	Intercon.	National Grid ?		Prysmian	Siemens		600		414		€ 800	€ 350	€ 1 100	Submarine & land	MI	LCC	http
2017	Johan Sverdrup	Norway	Offshore oil gass	Statoil		ABB	ABB				200				NOK 1100		XLPE	VSC	
2017	DolWin3	Germany	OWF	TenneT		Prysmian	Alstom	Nordic Ya	320		160		€ 350		€ 1 000	Submarine & land	XLPE		http:
2017	Italy / Montenegro	Italy / Montenegro	Intercon.	Terna		Nexans	Toshiba		500		393	22				Submarine & land	?		http
2018	Channel Cable	UK / France	Intercon.							1400	130					Submarine & land	XLPE	VSC	http:
2018	caithness moray	UK	Intercon.			ABB	ABB		320	1200	113	48			£ 1118	submarine & land	XLPE	VSC	http:
2018	Shetland	Scotland	Intercon.			N/A			300		345					N/A	N/A		http:
2019	Nemo link	UK / Belgium	Intercon.	National Grid	Elia		Siemens		350	1000	130	10			€ 2 000	Submarine & land			http:
2019	BorWin3	Germany	OWF	TenneT		Prysmian	Siemens		320		200		€ 250			Submarine & land	XLPE		http:
2019	Cobra cable	Netherlands / Denmark	Intercon.	TenneT / Energinet					320	700	300	25			DKK 4700	Submarine & land		VSC	http:
2020	Nordlink	Germany / Norway	Intercon.			Nexans & ABB	ABB		500	1400	500	50	€ 500 + € 500		€ 1,5k - 2k	Submarine & land	MI	VSC	http:
2020	NSN	UK / Norway	Intercon.			N/A			550		700					Submarine	MI		http:
2020	IFA 2	UK / France	Intercon.						400	1000	207	10				Submarine & land			
	Western Isles	UK	Intercon.						150	450.000	80								
2024	Sylwin2	Germany	OWF	TenneT								160				Submarine			