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Innovating incumbents and technological complementarities: How recent dynamics in the HVDC industry can inform transition theories

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Abstract

It is a classic theme in the transitions literature that newcomers supporting a novel technology struggle for dominance against incumbent actors and 'their' established technologies. Our study challenges this picture in several aspects with the intention to improve conceptual frameworks in transition studies. We present a case study on high voltage direct current (HVDC) technology - a mature technology for electricity transmission that has remained in a niche for decades but recently gained new momentum in the course of the energy transition. This case highlights i) incumbent actors as key drivers for innovation, ii) coupled dynamics via interaction of multiple technologies, also across industry boundaries, as a central process in transition dynamics, and iii) the increasingly pervasive nature of the energy transition. We interpret our observations from the perspective of two established frameworks, technological innovation systems and the multi-level perspective, and discuss implications for conceptual refinement.

Keywords: Energy transition, Step-changes in mature technology, Technological complementarities, Incumbent actors, High voltage direct current technology

1 Introduction

Transition studies are concerned with fundamental, socio-technical transformations in existing sectors and infrastructures (Markard, Raven, & Truffer, 2012). The ongoing energy transition with a shift from fossil and nuclear energy sources to renewables and from centralized to distributed generation has already received quite some attention in this regard (Kern & Markard, 2016; Strunz, 2014; van den Bergh, 2013). Transition scholars have often focused on the dynamics of novel technologies (e.g. solar, wind, fuel cells, electric vehicles), which are radically different from existing ones and have the potential to substitute established technologies (nuclear power plants, internal combustion engines) and overthrow existing structures. In fact, transitions are typically depicted as a battle between the new and the old, emergence and decline, newcomers and incumbents (Geels, 2005; Kemp, Schot, & Hoogma, 1998). One of the classic examples is the battle of steam ships and sailing ships, in which the latter finally lost (Geels, 2002).

While this picture certainly has its merits, it is also somewhat simplistic. Socio-technical transitions are highly complex and one aspect of this complexity is that there are many technologies (and associated industries) involved at the same time (Markard & Hoffmann, 2016; Sandén & Hillman, 2011; Wirth & Markard, 2011). Both emerging and existing technologies are typically interrelated with other technologies, which leads to coupled dynamics, i.e. changes in one field are associated with changes in another and so on. As a consequence, in a socio-technical transition changes occur simultaneously (as well as time-delayed) in many parts of a larger system.

In a similar vein, also the view on actors, with newcomers being the innovators and incumbents being the ones that resist a transition, does not cover the many different facets of a transition (Berggren, Magnusson, & Sushandoyo, 2015). For example, incumbent actors may well play a key role in the transformation of existing technology (Ansari & Krop, 2012; Bergek, Berggren, Magnusson, & Hobday, 2013; Berggren et al., 2015; Erlinghagen & Markard, 2012; Geels, 2006). Hybrid electric heavy vehicles and combined-cycle gas turbines are two examples of new technologies that were driven by incumbents and had quite a profound transformative impact on the existing industry (Bergek et al., 2013).

In this paper, we further explore both of these issues: technology interaction and the potentially proactive role of incumbents. We present findings from a case study on HVDC, which is a technology for the transmission of electric power that is affected by the ongoing transition of the energy sector (Andersen, 2014). HVDC technology and the associated industry have existed for decades covering very specific applications in the electricity sector. For many years, there were no major changes in the HVDC industry. More recently though, HVDC technology has witnessed major performance improvements and its scope of applications is

expanding rapidly. The latter is particularly true for the subsea segment of the industry which will be our focus. Today, experts expect a five-fold increase in market size over the next 15 years (4C Offshore, 2015; ENTSO-E, 2014). In our study, we identify and analyse key processes associated with the recent performance improvement and expansion of HVDC technology. We build on and extend an earlier study by Andersen (2014), which framed HVDC as a technological innovation system (TIS) embedded in a broader context. Here we take a different approach and mobilize different theoretical frameworks.

We find particular phenomena and dynamics that challenge some of our prevailing assumptions on the role of incumbents in transitions and that bring to the fore the importance of technological complementarities. We use our findings to illustrate limitations of existing dominant frameworks, the TIS approach and the multi-level perspective, with the purpose of nuancing some stylized facts dominant in transition studies. Doing so is an important contribution to the field because transition studies must be able to encompass and analytically grasp the increasingly complex and multi-facetted transition processes currently unfolding. A first step in this regard is to diagnose and acknowledge limitations of current frameworks. Our case study is based on document analyses and interviews[1] with industry experts, HVDC project developers, and service and technology suppliers.

The text is structured as follows. Next, we review how the literature on socio-technical transitions has dealt with the issue of technology interaction and the role of incumbents as drivers of innovation. Then we introduce our methods. In section 4 we present a detailed account of HVDC technology and recent developments including associated industry dynamics. In section 5 we conceptually analyse and discuss our findings from the previous section in the light of two transition study frameworks. Section 6 concludes.

2 State of knowledge in the transitions literature

In the following, we review how technology interaction and the role of incumbents have been addressed in the extensive transitions literature. We draw primarily from articles, which have either applied the multi-level perspective (Geels, 2002; Smith, Voß, & Grin, 2010) or the technological innovation systems framework (Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2008; Markard, Hekkert, & Jacobsson, 2015).

2.1 Technology interaction

Traditionally, transitions have been depicted as technology substitution cycles where a novel technology emerges in a niche, improves and diffuses over time and

[1] That we conducted an encompassing series of interviews for a better in-depth understanding is another difference to the earlier study (Andersen, 2014).

eventually replaces an established technology thereby fundamentally transforming the associated regime (Geels, 2002). This classic and simple picture of two competing technologies, the new (niche) and the old (regime), is the form of technology interaction most often studied in transition studies. It has, however, been criticized and differentiated in recent years in a number of ways.

First, scholars have pointed out that not just one but *multiple regimes* may be involved in the development of novel technologies (Geels, 2007; Konrad, Truffer, & Voß, 2008; Papachristos, Sofianos, & Adamides, 2013; Raven, 2007; Sutherland, Peter, & Zagata, 2015), which means that the relationship between different regimes changes in the course of the transition ('multi-regime interaction'). Multi-regime interaction typically occurs if innovations link into different sectors, or regimes. Biogas technology is an example in this regard (Markard, Wirth, & Truffer, 2016; Sutherland et al., 2015): it is coupled both to the agricultural sector (e.g. farmers operating biogas plants) and to the energy sector (e.g. biogas plants generating heat, electricity and gas). As a consequence of innovations connecting regimes, the nature of regime interaction can change, e.g. from competition to a more symbiotic relationship (Geels, 2007). A related case is about innovations that have grown and matured in one sector and are then applied to another sector, thereby fundamentally changing the second (Dolata, 2009; Papachristos et al., 2013). A good example here are pervasive technologies such as electronics or ICT, which transformed many established industries (e.g. banking, music, industrial production, services).

Second, transition scholars have also examined technology interaction more broadly, pointing to different kinds of relationships in technology hierarchies (Sandén & Hillman, 2011), the various ways in which external niches or regimes may affect a focal innovation (Papachristos et al., 2013) or the relevance of competing vs. complementary innovations (Markard & Truffer, 2008; Wirth & Markard, 2011). Interestingly, different technologies (e.g. hydro, wind, solar, biogas) can even compete and complement each other at the same time (Markard & Hoffmann, 2016; Sandén & Hillman, 2011), e.g. as they benefit from and co-legitimize public support or as they fulfil complementary roles at the sector level. Interactions of technologies are all the more relevant as complementary relationships may change and even break up in the course of transitions, thus either accelerating transitions or creating bottlenecks (Markard & Hoffmann, 2016).

The issue of regime- or technology interaction is important for transition studies. First, it is a necessity to adequately represent the complexity of ongoing transitions (e.g. in energy, in mobility, in ICT), where many different technologies and regimes change simultaneously often influencing each other. Moreover, it is vital to understand systemic and cumulative effects that are characteristic for transitions,

e.g. inter-industry knowledge spill-overs. Finally, in conceptual terms it points to the relevance of how analytical boundaries are chosen (e.g. niche, regime) and how the relationships between the focal object and its wider context(s) are conceptualized (Bergek et al., 2015; Papachristos et al., 2013; Wirth & Markard, 2011).

Although the importance of technology interaction is acknowledged in transition studies, it remains an immature area of research with only few studies addressing it. Our case study further advances our understanding as it illustrates a broad range of interactions (at different levels, across new/established technologies, across fields/regimes) affecting the development of a focal innovation (and its potential impact on the ongoing energy transition).

2.2 Role of incumbents

In recent years, more and more scholars have been studying the role of actors in transitions (Farla, Markard, Raven, & Coenen, 2012), including the strategies different organizations pursue, the resources they deploy towards innovation or institutional change, or the competences they develop or reconfigure in the face of radical change (Berggren et al., 2015; Musiolik, Markard, & Hekkert, 2012; Smink, Hekkert, & Negro, 2015; Wesseling, Farla, Sperling, & Hekkert, 2014). Many studies have found incumbent actors fighting against major technological or institutional changes (Penna & Geels, 2012; Wesseling et al., 2014). To maintain their businesses and their positions, incumbent organizations mobilize various kinds of resources, e.g. as they shape the setting of technology standards (Smink et al., 2015), inform/lobby policy makers and the wider public (Jacobsson & Lauber, 2006; Smink et al., 2015) affect the outcome of ballot initiatives (Hess, 2014) or control market access (Rothaermel, 2001). As a consequence, most transition scholars conceptually view incumbents as conserving regime actors, while newcomers are associated with the development of radical innovation in niches.

This dichotomy is increasingly questioned, however. Berggren et al. (2015) show how incumbent firms in the heavy vehicle industry have targeted the emerging niche on low-emission city buses by hybrid electric vehicles, while at the same time pursuing their established business (regime level). Similarly, Bergek et al. (2013) present cases from heavy electrical engineering (combined cycle gas turbines for power generation) and, again, the automotive industry (hybrid electric vehicles), in which incumbent firms were the ones pushing discontinuous innovation. Taking a sectoral innovation systems perspective, Kishna et al. (2017) present findings from a study on Dutch horticulture, where small incumbent firms are developing and promoting discontinuous innovations. Finally, also incumbents from other, adjacent sectors (e.g. IT, telecommunication or the defence industry) have been

observed as drivers of radical innovation in focal sectors such as the music industry or electricity supply (Dolata, 2009; Erlinghagen & Markard, 2012).

Change in socio-technical systems is ultimately driven by actors. It is therefore important for our understanding of transitions to develop a more comprehensive and nuanced picture of how different actor types engage in transition activities in multiple ways. With our analysis, we add to these lines of research by shedding a different light on incumbent actors as firms that may also drive innovation and potentially accelerate socio-technical transitions.

3 Methodology

3.1 Case selection

Numerous studies on energy transitions have focused on new generation technologies (wind, solar, biogas) or on new technologies related to energy distribution, storage and use (smart grids, smart homes, batteries, demand response). The field of power transmission has received rather little attention (Andersen, 2014) – probably because it has not seen major technological changes in the past. This is changing however.

Power transmission is increasingly affected by the ongoing energy transition. For example, long-distance transmission capacity might have to be expanded to transport e.g. coastal wind energy to demand centres inland. A related issue is to better connect regions with intermittent renewables and those with hydropower, for balancing purposes (OECD/IEA, 2014). A third issue is grid connection of offshore wind parks, for which even offshore 'supergrids' are discussed (Flynn, 2016). We will analyse the relationships between the energy transition and developments in transmission in further detail in sections 4 and 5.

In our study, we focus on subsea high voltage direct current (HVDC) transmission technology.[2] We do so for three reasons. First, the technology is affected by the energy transition and HVDC is experiencing significant technological progress. Second, HVDC consists of several technical components that exhibit interesting interactions. Third, innovation in HVDC is mostly driven by large and mature industry players, which is essential for our intention to study the role of incumbents in transitions. Our case selection is thus primarily based on a logic of theoretical sampling (Eisenhardt, 1989).

[2] The subsea/subterranean segment of HVDC has in recent years advances much more than the segment of overhead line (OHL) transmission in terms of both technology and diffusion. Especially in a European context. For these reasons, we focus on subsea and subterranean installations i.e. cables rather than wires. However, for simplicity we will from this point onwards refer to it as merely HVDC technology.

The regional scope of our analysis, e.g. with regard to market prospects, is Europe. The European Union has clear policy objectives targeting the energy transition (European Commission, 2014), there are ambitious plans to increase offshore wind (EWEA, 2011), and several countries such as Denmark and Germany are quite progressed in the transition towards intermittent renewable energy sources (IEA, 2014). As a consequence, we can expect significant market expansion in Europe. We acknowledge that there are also major markets for transmission technology outside of Europe - e.g. in the US or in emerging economies such as Brazil, China or India but so far, these markets—with the exception of China—are mainly concerned with onshore overhead lines (conventional HVDC technology, see section 4.1).

3.2 Materials

Our primary data source is a series of 11 semi-structured interviews with key stakeholders. To obtain an encompassing impression of recent industry developments, we selected interviewees from different parts of the supply chain including producers of HVDC cables and converter stations, buyers, and industry experts, see appendix for overview. Interviewees were all in senior management and/or engineering positions and had many years of experience with HVDC technology and/or high voltage subsea cables. All interviews were carried out by the first author, with support from an assistant in six of them. They were recorded and lasted 1,5 hours on average. Interview summary reports were prepared immediately after each interview. Four interviews were done in person while seven interviews were conducted via telephone/Skype. Due to the sensible nature of some of the information, interviews are anonymized and ascribed individual codes, see appendix.

We further rely on secondary data in the form of scientific articles, industry reports, engineering magazines, and news items. In addition, we have built a database of HVDC projects in Europe based on publicly available information and data from 4C Offshore (2015). We use it to follow changes in HVDC deployment in terms of volume, technologies, and key actors. Finally, information was collected via attendance at two conferences in 2015. The "InnoGrid2020+ R&D Conference" in Brussels and the "Cigre International Symposium, Across borders – HVDC systems and market integration" in Lund, Sweden.

3.3 Data analysis

Our analysis consists of two parts. First, we describe recent developments in the HVDC industry, including market development, technological development and innovation activities of key industry actors (section 4). In the second part, we explore the reasons for the observed developments. However, motivated by our interest in conceptual developments, we keep empirical analysis and conceptual

interpretation somewhat separate. We split the second part into four steps. First, we identified various processes (in the HVDC industry and its context), which the interview partners considered essential for contributing to the revival of HVDC (our focal technology). In a second step, we inductively grouped these processes into four categories, including context changes, knowledge development in adjacent industries, knowledge development in the focal industry and complementary interactions. In a third step, we interpreted these processes in the light of two conceptual frameworks, the technological innovation systems approach and the multi-level perspective. We use two frameworks instead of one to better identify the general issues arising from our case study. Also, there is not just one way, in which the frameworks can be applied to our case. We make two suggestions for theoretical framing but at the same time contrast the different frameworks. This approach allows for generating complementary insights. Moreover, we draw attention to i) the flexibility analysts have when working with the two frameworks and ii) the implications this has for the results. In a last step of our analysis, we then contemplate how our insights can inform further improvement of the established transition frameworks.

4 Transformation of the HVDC industry

This section gives a more detailed introduction of our focal technology, and depicts the recent changes in the HVDC industry. It covers market development, advances in technological performance and activities of key actors in two major industry segments, converters and cables.

4.1 HVDC technology: overview and developments

There are two fundamentally different technologies for long-distance electricity transmission, high-voltage alternating current (HVAC) and high-voltage direct current (HVDC). HVAC is the dominant technology used in about 97% of the high-voltage grid in Europe. Compared to HVAC, the primary advantage of HVDC is that transmission losses are lower; especially over long distances and subsea / subterranean connections. At the same time, however, HVDC had several limitations. One of these is that it requires converters (from AC to DC and vice versa), which are major cost factor. For decades, HVDC (LCC, conventional) was only used in niche applications, e.g. power supply of islands, ultra-long distance power transmission or connection of separate AC grids. In recent years, however, HVDC has seen major technological progress in some of its key components, especially converters and cables, giving rise to a new generation of HVDC (VSC). In Table 1, we list selected technology characteristics for HVAC, conventional HVDC and new HVDC.

New HVDC uses a novel conversion technology, so-called voltage source converters (VSCs). VSCs appeared in the late 1990s due to technological progress in power

electronics and have significantly improved since then. VSC technology uses IBGT (insulated-gate bipolar transistor) valves for high voltage applications as a substitute for the established LCC converter technology, which is based on thyristors and large-scale, material intensive filters.[3]

Table 1: Overview of transmission technology characteristics

	HVAC (conventional)	LCC based HVDC (conventional)	VSC based HVDC (new)
State of development	Mature	Mature	Emerging
Converter core component	n.a. (no conversion)	Thyristor	IGBT
Energy losses over long distances (transport and switching)	High (compared to HVDC)	Very low	Low
Size and costs of converter stations	n.a. (no conversion)	Large and costly	Smaller and but equally costly
Sensitivity to voltage fluctuations	Low	High	Low
Compatible cable technology	XLPE & MI cables	MI cables	XLPE & MI cables
Power flow reversal	Instantaneous	Non-instantaneous	Instantaneous
Main applications	Short-/long-distance, multi-terminal	Long-distance energy transmission, subsea	Short-/long-distance connections, multi-terminal, offshore wind, oil platforms

VSC technology generates several functional advantages when compared to LCC converters (cf. Table 1). First, it is less sensitive to power instability in adjacent AC grids and even offers black start capability.[4] This makes it suitable for connecting offshore wind farms and for operating in other remote locations with a weak AC grid. Second, converter stations are significantly smaller in size with up to 40% reduction (Sellick & Åkerberg, 2012), which eases offshore installations.[5] Third, VSC enables instantaneous reversal of power flows without reversing the polarity. LCC systems in contrast require polarity reversal of voltage, which takes time and requires back-up support from the adjacent AC grid.

This third characteristic does not only add flexibility and controllability to the DC link but also enables the use of a complementary technological component:

[3] A similar substitution has taken place for low voltage converters used in consumer electronics.

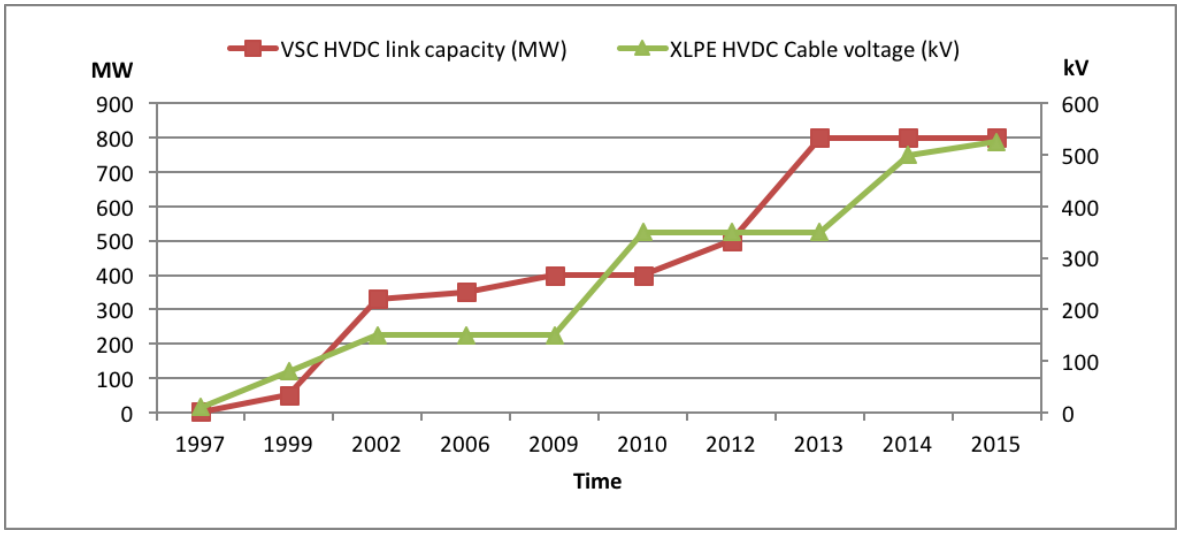
[4] Refers to the ability of the DC link to re-energize after it has been disconnected and de-energized without relying on the external transmission network, and, as a consequence, the ability to re-energize connected AC grids (Hertem, Gomis-bellmunt, & Liang, 2016).

[5] Moreover, the next generation of VSC HVDC is expected to apply gas-insulated switchgear (GIS). This will again reduce the size converters.

extruded XLPE plastic cables.[6] XLPE cables are associated with further important advantages. Compared to conventional, mass-impregnated cables (MI), they are much lighter (eases transport and installation), can be connected with prefabricated joints and are faster to manufacture and install (Chen et al., 2015; Interview 2; Migliavacca, 2013). It is expected that XLPE will soon be the dominant technology for both subsea and underground HVDC (Interview 2; Interview 7; Marelli, 2013; Zaccone, 2014).

Moreover, at the industry level there are more (potential) cable suppliers for XLPE, which means stronger competition and higher overall production capacity for cables which is widely considered a bottleneck for further deployment. As a consequence, the switch to XLPE cables (facilitated by new HVDC) lowers overall cable costs (which often make up the largest chunk of CAPEX for HVDC connections) by cheaper transport and installation, and faster delivery (avoiding costly waiting times). Finally, the insulation capacity of XLPE cables (and thus their transmission capacity) has been improved recently due to technological advances in the chemical industry (production of plastic materials).

Figure 1: New HVDC Learning Curve



Source: Data are obtained from our HVDC database and information about recent technological achievements that have so far not been deployed in commercial projects.

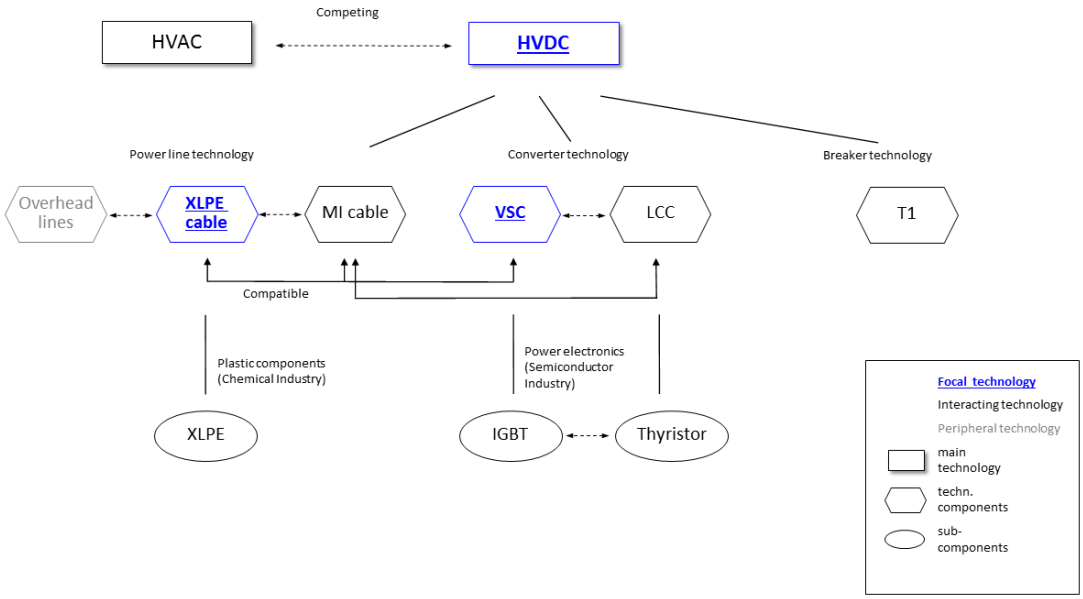
In addition, recent progress in HVDC breaker technology — a long-standing challenge for HVDC — has brought the vision of meshed HVDC grids (rather than point-to-point links) one step closer to realization. Breakers are crucial for any grid to isolate and disconnect faults thus preventing the entire network to crash. The

[6] XLPE is not suited for LCC because space charges in the insulation material can cause damage to the cable when polarity is reversed. And LCC can only support a change in the direction of the energy flow by a change of polarity.

possibility to build HVDC grids would be another important milestone in the competition with HVAC.

The technological advances in new HVDC are reflected in the growth of maximum capacity of in both VSC converter technology (red line) and XLPE cables (green line), see technology learning curves in Figure 1. VSC has not only improved its capacity but also lowered switching losses from above 3% to below 1%. It is expected that from now onwards mainly VSC technology will be installed in Europe (Barker, 2015).[7]

Figure 2: Components of HVDC transmission technology



As a consequence of these recent advances, HVDC can now compete with HVAC already on shorter distances (e.g. connection of wind parks), thus expanding its scope of applications. As a consequence, the technology's market share is growing rapidly and projections place it even above HVAC when it comes to new power transmission lines over the next decade or so (see section 4.2).

From the above we understand that changes in HVDC entails technological dynamics at different levels of the technology hierarchy, see Figure 2 for overview of components and the relationships between them. There is competition with HVAC but also between different HVDC component technologies. At the same time, there are strong complementarities between specific types of converters and cables: the novel VSC converter technology enables the use of plastic cables

[7] There is also policy support in favour of the novel technology: To qualify for the Projects of Common Interest (PCI) initiative — and thus for receiving financial support from the Connecting Europe Facility (CEF) — HVDC projects must use VSC to assure black start capability.

(XLPE), which have several advantages over conventional mass-impregnated (MI) HVDC cables. Furthermore, XLPE cables have benefitted from advances in the chemical industry, while VSC converters have been possible due to innovation in high-voltage semiconductors.

4.2 Market development and prospects

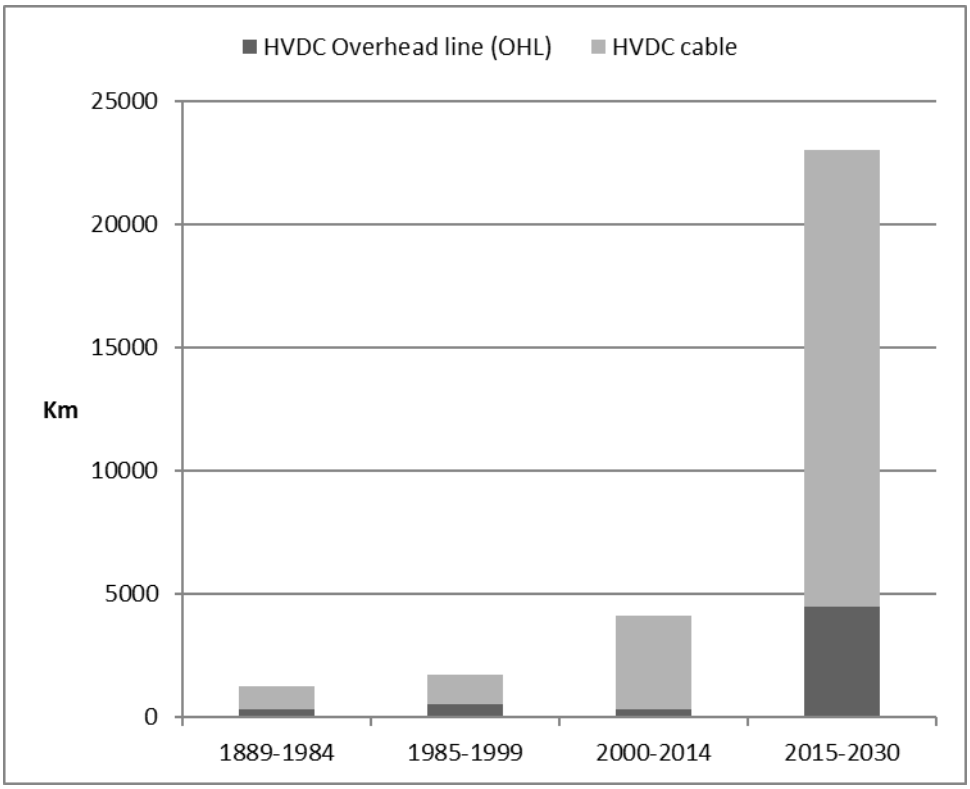
For many years, HVDC was a niche technology in the electricity sector with only a few, irregular projects globally. From 2000 to 2014, however, more than 4'000 km of new HVDC lines have been built in Europe. This is about 2.5 times more than in earlier 15-year periods (Figure 3). Estimations for the future even count another 23'000 km until 2030, which would be a 5-fold increase. These estimates are higher than for HVAC, for which 21'000 km are projected. HVDC is expected to be used primarily for subsea cable applications (75% of the market) (ENTSO-E, 2014).

Four factors have been identified as main drivers of recent and expected market growth. First, adding national as well as pan-European transmission capacity is an important part of advancing the Internal Electricity Market, which is a political objective of the European Union (European Commission, 2013). More interconnection capacity is believed to stimulate energy trade, energy security, and economic growth, and it is considered necessary for achieving the EU's climate goals. A concrete initiative for realising this vision is the 'projects of common interest' (PCI). A PCI project must help mitigate 'strategic bottlenecks' in Europe's transmission grids in return for financial support.

Second, there is additional demand for transmission capacity because rising shares of intermittent renewable energy sources in the course of the energy transition can be complemented e.g. by existing hydropower from large reservoirs. This combination of fluctuating and storable power sources is important for maintaining the stability of the power system. Different kinds of generation are connected across regions or across national grids of countries with different generation mixes and different weather zones (mitigates variability). Examples are the ongoing interconnector projects between Norway and Germany (the NordLink) or Norway and the UK (the North Sea Link). Increasing power system flexibility through additional transmission capacity is both a matter of MW volume and one of timing (when sun isn't shinning and demand is peaking).

Third, some renewable energy sources (wind, hydro) are regionally concentrated within and between countries. Where these sources are far from demand centers, new, so-called electricity highways may be needed to regularly transport large amounts of energy across long distances. An example is Germany's attempt to build HVDC transmission corridors to connect expanding renewable energy in the North with demand centers in the South (Fairley, 2013a, 2013b).

Figure 3: Installed and projected HVDC links in Europe



Source: Own elaboration based on data from ENTSO-E, publicly available internet sources and company websites.

Fourth, more and more far-shore offshore wind parks are built in the course of the energy transition. They need to be connected to the existing grid through subsea interconnections (sometimes even long-distance) and they might also require capacity expansion of the grid onshore. There are estimates that between 2015 and 2022, almost 6'000 km of HVDC subsea cables will be installed to connect offshore wind farms (BVG Associates, 2013).

A last aspect of market development is the electrification of oil and gas platforms in the North Sea as an example of climate policy in oil economies. Although limited in scale more electrification is expected. While these aspects drive the expansion of transmission capacity, there are also ongoing technological developments that reduce the need for new transmission. These particularly include the combined expansion of distributed generation (solar, small scale CHP) and distributed storage (stationary batteries, electric vehicles) or diffusion of demand response technologies, including smart grids.

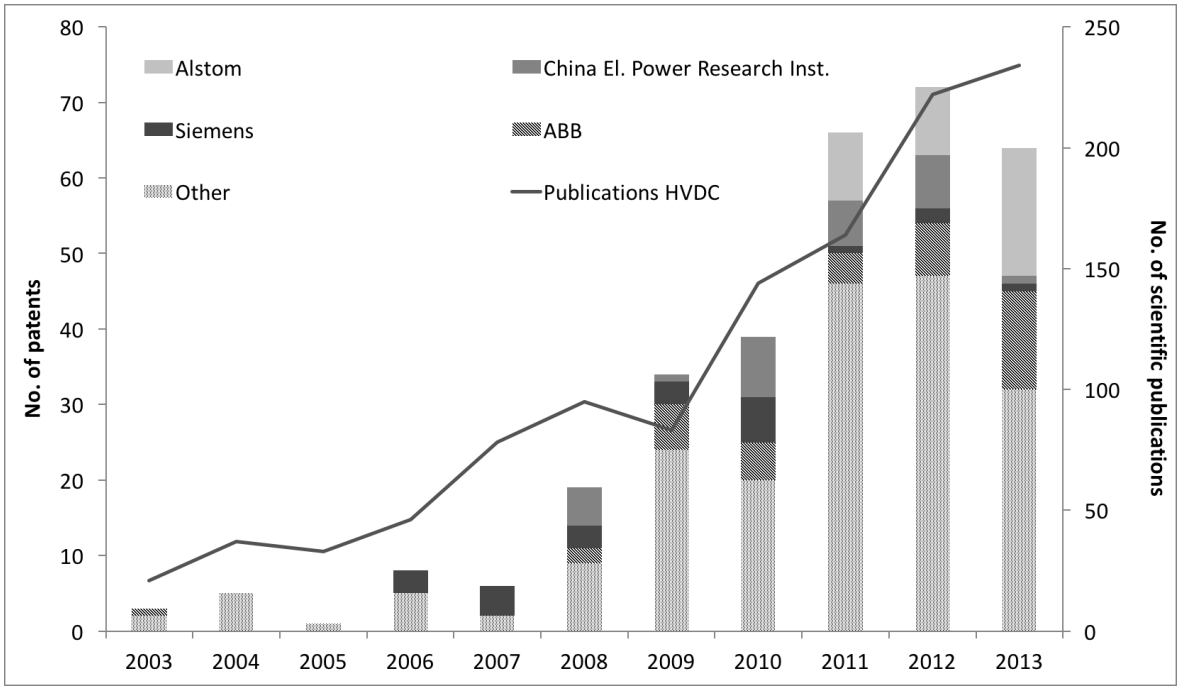
4.3 Major HVDC technology producers and their innovation activity

In this section, we look at the industry actors in HVDC and trace their main innovation activities to better understand the role they play in the changing industry. As converters and cables are largely separate markets we address one after the other.

4.3.1 Converter technology

Currently there are three producers of VSC based converter stations in Europe: ABB, Siemens and Alstom (now General Electric) whose market shares were 67%, 33%, and 0%, respectively, between 2000 and 2014. The first commercial VSC project (50 MW and 80 kV XLPE) was developed by ABB in 1999 on the Swedish island of Gotland. Prior to that ABB set up a prototype and demonstration project in 1997 at Hällsjön, Sweden, (3 MW and 10 kV) (ABB, 2014b). It was thus ABB that first adapted IBGT technology to HVDC and pioneered the new field during the 2000s, referring to its VSC solution as 'HVDC Light'. Its main competitors, Siemens and Alstom, followed later. Siemens introduced its 'HVDC Plus' in 2010 (first commercial project – the Trans Bay cable in the US), and Alstom (now General Electric) introduced its 'MaxSine' converter technology in a pilot project for battery storage in 2013. Despite some attempts, Alstom has not yet delivered a commercial HVDC VSC project (as of 2016).[8] Alstom's first offshore VSC HVDC project in Europe will be the grid connection of the Dolwin3 windpark in the German part of the Baltic Sea (completion expected in 2017). Transmission system operators were relieved that Alstom finally won a project due to the additional competition its presence adds to the market (Beaupuy, 2013).

Figure 4: HVDC transmission technology registered patents and key actors, and number of scientific publications, 2003-2013.



Source: Andersen (2014).

[8] Alstom was awarded a contract for the SydVästlänken in Sweden but the project has been marred by delays. The Swedish TSO blames Alstom for unprofessional conduct.

The analysis of patents demonstrates that ABB and Siemens, more recently also Alstom, are leading actors in knowledge development for HVDC technology, next to the Electric Power Research Institute in China (Figure 4). The three firms hold high shares of total patents in the period (ABB 12%, Alstom 11%, and Siemens 7%). Next to converters, all three are each developing new HVDC breaker technologies albeit following different concept designs (Rajgor, 2013).

We also observe that all three firms have recently invested in additional production and R&D capacity as they anticipate further market growth. ABB's opening of a new HVDC Centre in Sweden (2013) is the culmination of a long expansion period where approximately 1000 HVDC-related new jobs were created (since 2004) and many hundreds more are expected in the near future (Ny Teknik, 2013; Vestmanlands Läns Tidning, 2015). In 2011 Siemens established a global centre of competence for high voltage grids in Manchester, UK, employing around 340, with particular focus on HVDC in the North Sea market (Siemens, 2015; The Engineer, 2011). In 2015 Alstom invested 28 million euros in a new technology centre, again in the UK, for HVDC and automation technology (Alstom, 2015).

4.3.2 Cable technology

In Europe, there were traditionally just three firms – Prysmian, ABB (now NKT)[9], and Nexans – that produce high voltage DC cables, both MI and XLPE. Between 2000 and 2014, their market shares were 45% (ABB), 36% (Nexans), and 18% (Prysmian), respectively. ABB has pioneered the development and deployment of XLPE cables for DC applications in 1999, while its main competitors, in collaboration, commissioned a European project only in 2014 (Skagerak 4 at 500 kV).[10]

The three are also actively improving cable technology, thus pushing the boundaries of maximum voltages. This is exemplified by ABB's recent 525 kV record for XLPE cables (ABB, 2014a) and Prysmian's announcement of a world record with a 600 kV MI cable in 2012 (Prysmian, 2012) – even though the firm has encountered technical problems since then.

All three firms have recently invested in additional production capacity for XLPE cables. Nexans has expanded its main production site for HVDC cables in Norway, first in 2011 and again in 2015 when 35 million euro were invested after winning a contract for the Nordlink project (Nexans, 2011; Reuters, 2015). In a similar vein, Prysmian invested 40 million euros in their Pikkala plant, Finland, for starting up

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[9] ABB announced in September 2016 that is had sold its high-voltage cable system business to Danish firm NKT which until then mainly operated in HVAC cables.

[10] Prysmian did deliver a DC XLPE cable (200 kV) for the Trans Bay Cable in San Francisco in 2010.

HVDC XLPE cable production. Another 50 million euros were invested in the Arco Felice plant, Italy (Prysmian, 2014). And ABB doubled the capacity of its high-voltage cable manufacturing facility in Karlskrona, Sweden (ABB, 2011; BVG Associates, 2013).

The expected boom in XLPE cables for HVDC has also attracted XLPE cable producers that traditionally focused on HVAC technology.[11] XLPE HVAC cables have been used for decades so these companies have accumulated comprehensive competences in the area. Although XLPE for HVDC is more complex than for HVAC—inter alia due to resistivity— for new players it is now much simpler to enter into HVDC though the 'XLPE door'. Earlier MI cables were much more difficult for newcomers to produce as they require tacit knowledge accumulated via experience with custom-made machinery in the manufacturing part (Interview 1). Expected entrants from HVAC include Hellenic (GR), NKT cables (DK), General Cable (US), and others (BVG Associates, 2013; Interview 7).[12]

Finally, the rise of XLPE cables has brought chemical firms into the HVDC industry. Cable producers today collaborate closely with chemical companies such as Bayer, Dow or Borealis to develop new materials and designs. These firms bring competences and equipment to the changing field that cable producers do not command (Interview 2). For example, the development of ABB's recent 525 kV XLPE cable involved close collaboration between the R&D centers of ABB and Borealis to develop new insulation material with novel properties (ABB, 2014a). Indeed, Borealis has announced that it is expanding its production capacity in Sweden to keep up with the subsea cable market (Plastics News, 2014).

4.4 Summary

New HVDC has rapidly expanded in recent years and the prospects for further market expansion are highly promising. Key elements of the technology's progress in terms of performance and costs are recent advances in both converter technology (VSC) and cable technology (XLPE) and the new possibility to combine the two, which creates strong synergies. With regard to industry structure, a few large firms dominate both converter and cable industry. These firms have been in business for decades and are currently investing heavily to keep up with and benefit from the ongoing technological change. While there are no new players in the field of converters, new players from adjacent industries (AC cables) are

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[11] These often also produce HVDC cables at lower voltages. Up to 132kV DC there is a high number of firms in the market, which creates intense competition. Above this threshold there were traditionally only the three aforementioned firms active in Europe (Interview 3).

[12] After completing our interviews, NKT did enter the HVDC cable segment, see previous footnote.

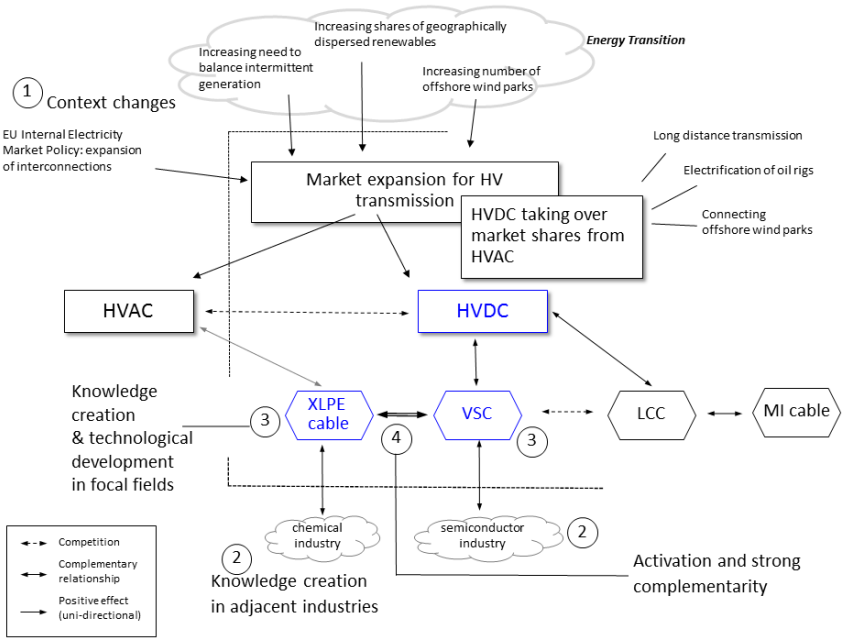
entering the HVDC cable industry and also suppliers of special plastics show an increasing interest in the novel cable technology.

5 Analysis of innovation and industry dynamics

5.1 Key processes

Our analysis revealed four processes that were key for the performance improvement dynamics we currently observe in the HVDC industry. One process is about changes in the wider context of the industry (1), which positively affect the demand for new transmission. Context changes are primarily related to the energy transition but also to European electricity market policy. A second process includes knowledge development and technological progress in adjacent industries (2) such as semiconductors and the chemical industry. A third process is about knowledge development by incumbent firms in both VSC and XLPE cable technology (3). A fourth key process includes the complementary interaction of different components in HVDC (4). This interaction significantly accelerated the observed technological change. Figure 5 provides a schematic overview of how the different developments have influenced or complemented each other. The boundaries of the HVDC industry are indicated by the dotted line.

Figure 5: Processes involved in the recent progress of HVDC technology



5.1.1 Key process (1): Context changes and market expansion

The HVDC industry can be viewed as a part of the broader electricity sector (Andersen, 2014), which means that the ongoing sectoral transformation generates

context changes for HVDC.[13] Interestingly, many of the sectoral changes have contributed to increasing the demand for high-voltage transmission, which affects both HVAC and HVDC. Four factors—increasing intermittency, more dispersed RES, growing offshore wind, and EU energy policy, see section 4.2—have been identified as playing a particularly strong role in this.

5.1.2 Key process (2): Knowledge development in adjacent industries

A second key process is about technological progress in adjacent industries.[14] The observed progress in HVDC would not have been possible without technological advances in semiconductors with IGBTs as a new basic technology that has continuously expanded its scope of applications (e.g. in terms of higher voltages). Moreover, there are ongoing improvements in plastic-based insulation material for HVDC cables, which are achieved by close collaboration between firms from the chemical and the heavy electrical engineering industry. Chemical firms were not involved in HVDC prior to the introduction of the XLPE technology and with the new prospects for HVDC they have directed additional resources into the development of improved insulation materials. Progress here is illustrated by higher kV levels in cables whose constraints are primarily in material development, see Figure 1.

5.1.3 Key process (3): Knowledge development in focal technological fields

Although the basic building blocks for the VSC technology originated outside the HVDC industry, HVDC incumbents have been the key players for technological progress by engaging in research, development, and design to further advance and transform that external knowledge into the needed functional characteristics of electricity transmission. In a similar fashion, even though the interactive learning processes underpinning the development of novel insulation materials for HVDC XLPE depended on inputs from the chemical industry, these were initiated and driven by HVDC incumbents. Hence, knowledge development in our focal technological fields is a pivotal process for recent advances in HVDC and it has been pushed significantly by incumbent firms, cf. Figure 4.

5.1.4 Key process (4): Activation and complementary interaction

Technology interaction played a critical role for the observed developments. First, the emergence of VSC had an 'activation' effect because it enabled the use of XLPE

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[13] We hereby assume that these changes are, at first, independent of what is going on in the HVDC industry, even though HVDC dynamics may feed back into the ongoing changes at some point.

[14] This can also be viewed as a change in context but we took it as a separate entry because of its importance and the different nature of the changes compared to the first process.

cables for HVDC, which had been confined to MI technology for many decades. Second, VSC technology benefitted from its association with XLPE cables due to its superior characteristics (weight, handling, installation, production, competition). These coupled dynamics involved further processes of complementary interaction of technological improvements in VSC technology and XLPE cables.

5.2 Theoretical interpretations

The HVDC case can be conceptually interpreted in different ways. One issue is the level of the technology hierarchy to concentrate on, i.e. whether we concentrate on the component technologies of new HVDC, the competition between new (VSC-XLPE) and old (LCC-MI) HVDC, or at the higher level of transmission technologies (HVDC vs. HVAC). Another issue is the theoretical framing. Below we draw from two established transition frameworks, namely the technological innovation systems (TIS) approach (Bergek et al., 2008; Markard et al., 2015) and the multi-level perspective, MLP (Geels, 2002; Smith et al., 2010). We interpret the processes at the component level from a TIS perspective and apply the MLP at the transmission level. The reason for this selection is that the TIS framework seems better equipped to handle two competing niche technologies, while the MLP better portrays situations where a widely-used and regime technology competes against a growing niche technology. We stick to the four key processes identified above and interpret them the light of the two frameworks. Due to space limitations, this interpretation will remain very cursory.[15] We identify major issues of fit/misfit and make suggestions for conceptual refinement further below.

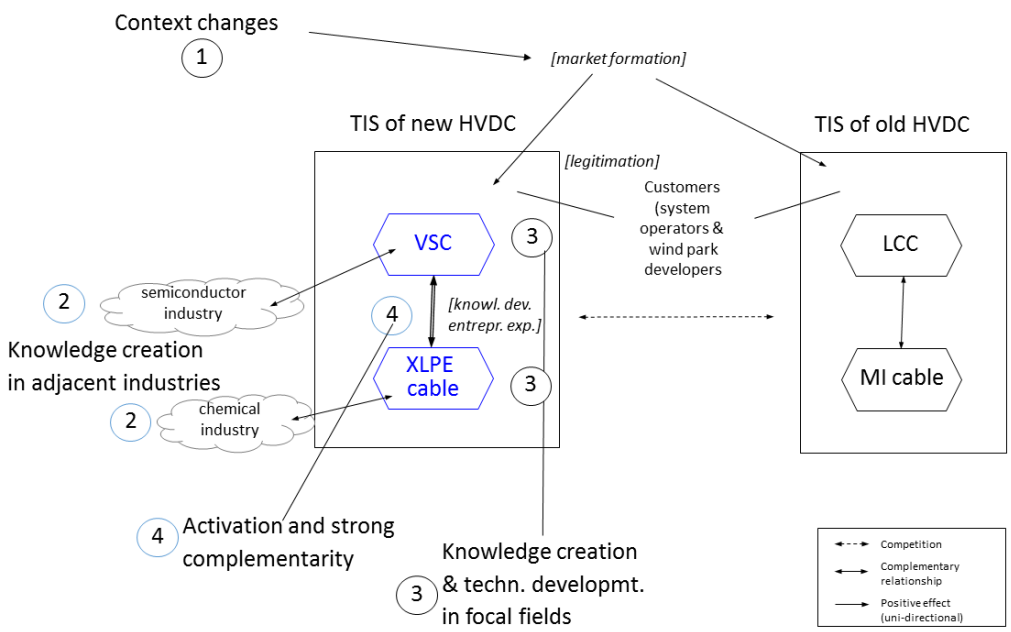
First, at the level of HVDC components, we can interpret the observed development as a 'classic' competition between an emerging (VSC) and an established (LCC) technological innovation system, with the latter being increasingly substituted by the former. Innovation can be associated with the TIS function of market formation (or market expansion) as a result of changes in the TIS context (1) as well as knowledge development and entrepreneurial experimentation within the new TIS (3). Moreover, 'import of new technology' from other industries (2) and complementary technology interaction at the component level of new HVDC (4) play a key role.

This interpretation reveals some deviations from 'typical' TIS dynamics. These deviations include a very strong influence of context developments (1) generating quasi-exogenous market formation (we have not seen TIS actors struggling with that). Another central deviation is a strong influence of complementary technology interaction both in the form of the VSC-XLPE relationship (4) and in form of

[15] See e.g. Andersen (2014) for a more detailed TIS analysis of the HVDC case.

interaction between VSC and XLPE, respectively, and their supplier industries (2). We see a further deviation in that knowledge development and entrepreneurial experimentation were driven exclusively by industry incumbents, apparently, without any dedicated policy support (3). Similarly, we observe relatively minor importance of the functions guidance, resource mobilization, and legitimation.[16] We will discuss the implications for the TIS concept below.

Figure 6: Schematic representation from a TIS perspective (component level)



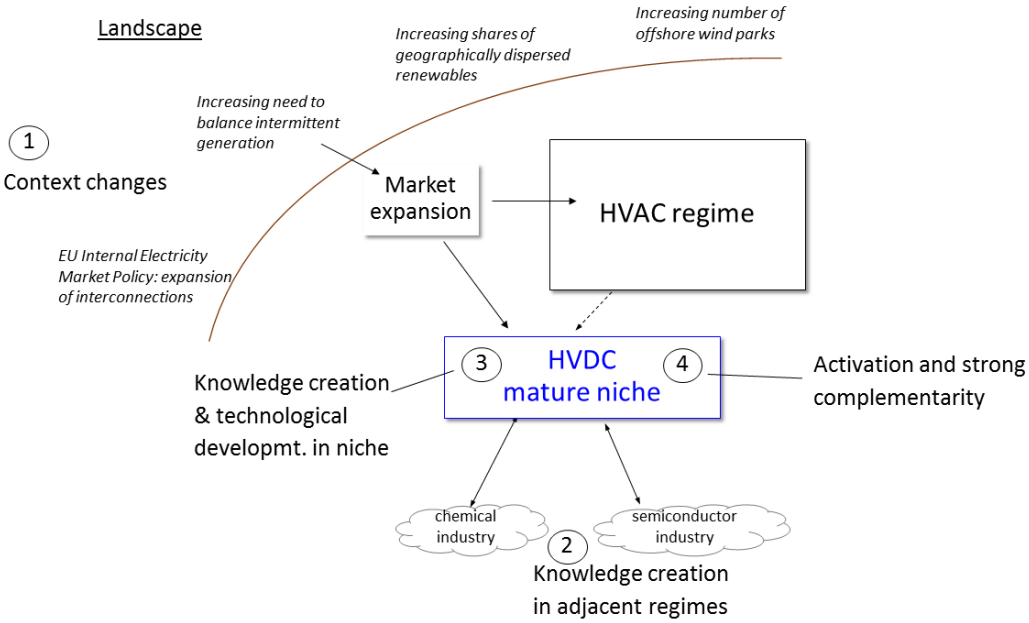
Second, at the level of transmission technologies, we can interpret the case as a struggle between niche and regime. Both technologies have existed for a long time and the roles seemed clear with HVAC being dominant (regime) and HVDC covering niche applications. In fact, conventional HVDC can be interpreted as a *mature niche technology*. Then, as a consequence of landscape developments (1), which primarily include the energy transition, and technological progress (2) in adjacent regimes (semiconductors and chemical industries) the mature niche was roused and niche level processes such as learning (including technological complementarities) were strengthened (3).

Also from this perspective, several aspects do not fit the classic picture. Most importantly, innovation was driven by incumbent actors, in both converter and cable technologies. When faced with the potential of VSC technology and the new demands arising in the course of the energy transition, incumbents engaged proactively and generated major performance improvements from within the

[16] From the interviews, we learned that legitimation of the novel technology is an issue for TSOs (buyers of HVDC). There are even formal and lengthy certification procedures new cables and converter technologies (and their producers) have to pass.

established industry. And in the cable industry, there was even overlap between niche and regime actors, which means that the potential winners and losers of this niche-regime struggle are partly the same. Another particularity is the strong role of complementarities, which have been mentioned in MLP studies (e.g. Raven & Verbong, 2007) but not yet incorporated into the framework. A third issue is about niche protection. Our case shows that in the case of abrupt performance improvements, a niche technology may be able to leap into the regime applications without extra protection.[17]

Figure 7: Schematic representation from an MLP perspective (transmission level)



5.3 *Implications for transition frameworks*

Our case directs attention to several phenomena that can play important roles in transition processes but which currently are not sufficiently appreciated in transition studies frameworks.

First, the issue of mature technologies being involved is relevant for both MLP and TIS. In MLP studies, mature technologies have been viewed mostly from a regime perspective in the sense of rigid structures that pose barriers for innovation. A more differentiated approach both with regard to improvement of mature technologies in transition processes (Berggren et al., 2015) as well as processes of decline (Turnheim & Geels, 2012) is certainly warranted. TIS analysis has rarely considered mature technologies. As a consequence the existing set of TIS functions is less suitable for the analysis of mature technologies and therefore needs to be

[17] We have to acknowledge though that this might also be due to niche and regime actors being the same.

revised to cover a) further major improvements as well as b) processes of decline (Bergek et al., 2008; Kivimaa & Kern, 2015). As indicated above, resource mobilization, legitimation, and policy support may be less important for mature technologies while establishing new linkages to and sourcing new knowledge from other, mature or emerging, technological fields (necessary for performing 'creative accumulation') seems an activity particularly relevant for mature fields (Bergek et al., 2013; Dolata, 2009).

Second, mature technologies are also intrinsically linked with incumbent actors that eventually control critical resources and might thus be crucial for how transitions unfold (Erlinghagen & Markard, 2012; Mäkitie, Andersen, Hanson, Normann, & Thune, 2016). Incumbent actors can assume a variety of strategies (e.g. defensive, proactive, or ambidextrous strategy i.e. supporting both old and new technology), which means that transition scholars may have to pay more attention to conflicts between competing incumbents, incumbents collaborating, or how incumbents pursue organizational continuity while facing technological discontinuity (Bergek & Onufrey, 2013; Farla et al., 2012; Smink et al., 2015). An expansion of studies on incumbent actors is certainly warranted for both the MLP and the TIS literature.

Third, the issue of technological components interacting at different levels is important with regard to the selection of analytical boundaries, which has been a key issue for both TIS and MLP scholars since long (Markard et al., 2015; Sandén & Hillman, 2011). It also points to the conceptualization of contexts: what factors are 'outsourced' (and thus somewhat black-boxed) to the landscape level and what are the implications of that (Bergek et al., 2015)?

Fourth, another key issue is the complementary interaction (of technologies and other components), the dynamics it can create and how this is conceptualized in the frameworks (Markard & Hoffmann, 2016). MLP scholars have discussed niche-niche interaction (Verbong, Geels, & Raven, 2007) and TIS scholars have suggested paying more attention to interacting technologies (Mäkitie et al., 2016; Wirth & Markard, 2011) but interaction has yet to be embedded into the frameworks more explicitly.

Finally, the multi-hot-spot character of transitions might as well be an issue that should receive further attention. It is certainly related to how far a transition has progressed (e.g. early, take-off, late phase) and we are just at the beginning of understanding the implications.

6 Conclusion

We have presented a case study on a mature niche technology that by means of technological complementarities and innovating incumbents has seen major performance improvements in recent years, which may contribute to and further

accelerate the ongoing transformation of the electricity sector. Our findings have implications for the understanding and conceptualization of socio-technical transitions. We conclude with three major lessons.

First and foremost, transitions of large socio-technical systems such as electricity are not just about the substitution of one core technology by another. Instead, they involve major changes in a broad range of different but at the same time interdependent technologies (at different technology hierarchy levels, in different parts of technology supply chains, at different stages of maturity, etc.). Generally speaking, both emerging and existing technologies are typically interrelated with other technologies – next to organizations and institutional structures. This leads to coupled dynamics, i.e. changes in one field are associated with changes in another and so on. It implies that in a socio-technical transition, changes occur simultaneously (as well as time-delayed) in many parts of a larger system. As a consequence, transition frameworks have to explicitly address the interrelated nature of changes in various technical and non-technical components, including the creation and break-up of complementarities (Markard & Hoffmann, 2016). The importance of the coupled dynamics between old and new technologies in large-scale societal transformations is a central tenet in the work of several "classical" scholars associated with an evolutionary perspective on economics (Dahmén, 1950; Hirschman, 1958; Myrdal, 1957; Perroux, 1950). For example, Dahmèn (1989) viewed industrial transformation as driven by 'imbalanced' inter-industry interdependencies that would create bottlenecks and incite firms to make investments. In this perspective, a sustainability transition involves the unfolding of a sequence of interdependencies which by a way of a series of bottlenecks (disequilibria) result in a new balanced situation (equilibrium). Such perspectives may hold new insights about how we can improve conceptualization and analysis of coupled dynamics between interdependent technologies in flux.

Second, incumbent actors may well play a driving role in the transformation of existing industries (Bergek et al., 2013). Transition scholars therefore have to modify established perspectives, which often regard incumbents as opponents or victims of transitions but rarely as winners. A consequence of innovating incumbents is that even mature technologies may see major performance improvements, which can induce shifts in their relative importance and expand their scope of applications. Such dynamics need to be taken into account, among others, when developing lifecycle models of technologies and/or industries in the context of transitions (Penna & Geels, 2012). More generally, our case foregrounds the importance of not conflating actors and technologies. Incumbents can drive new, disruptive technologies, and they can be innovating in both old and new technologies simultaneously (Bergek & Onufrey, 2013). The reason is that even though socio-technical transitions involve discontinuity and 'creative destruction' of technologies (substitution cycles), some incumbent firms seek continuity via

'creative accumulation' (i.e. adapting to transformation pressures and/or seizing opportunities via innovation on basis of existing capabilities). In this regard, we find it of particular interest to explore further under which conditions resourceful incumbents choose to participate in and support rather than subdue transition activities. Management Studies, for example, suggests that the opportunities for redeploying extant resources and capabilities in the new technological field is one important factor (Helfat & Lieberman, 2002) i.e. to what extent change is competence-enhancing or –destroying (Tushman & Anderson, 1986). Such a perspective has not received much attention in a transition context.

Third, as the energy transition advances, it becomes increasingly pervasive in the sense that many different types of industries and technologies increasingly become involved. The latter challenges our currently dominant frameworks for studying transitions that were initially designed to analyse emergence of individual technologies in hostile environments. For example, HVDC is a case in which public support for technology development in the form of R&D programs or deployment subsidies did not play a strong role (e.g. when compared to RES technologies such as wind or solar). As the transition unfolds, we might see more of these kinds of repercussions affecting even those parts of the sector that have remained very stable for decades.

In conclusion, our findings can inform both the multi-level perspective as well as technological innovation systems as the two leading approaches in transition studies. Indeed, a general insight from our analysis is that transition studies, and its dominant theoretical frameworks, is continuously challenged in conceptually mirroring the rising complexities and pace of the ongoing energy transition; something which is required in order to satisfactorily analyse it. In this light, we are confident that the issues for further conceptual development we have identified in this paper will provide fruitful ground for further empirical studies.

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Appendix

Table A: Overview of interviews

No.	Actor type	Position of interviewees	Date
1	HVDC Cable producer	R&D Manager Subsea Cables	09/06/2015
2	HVDC Cable producer	R&D manager, high voltage subsea cables	27/04/2015
3	HVDC Converter manufacturer	Manager power systems	22/09/2014
4	HVDC Converter manufacturer	Head of Global sales and R&D project manager	3/6/2015
5	Potential entrant to XLPE HVDC cable	Director of sales	01/06/2015
6	HVDC Customer	Head of DC interconnector department	04/08/2015
7	HVDC Customer	Principal HV Cable Specialist	14/04/2015
8	HVDC Consultant	Head of section for substation projects	25/06/2015
9	HVDC Consultant	Principal consultant	18/06/2015
10	Industry expert (independent)	Senior consultant on high voltage power electronics	31/03/2015
11	HVDC testing and certifier agency	Vice president	02/06/2015

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