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Mechanisms of Offshore wind growth:

Feasibility of 2030 targets in the North Seas Energy Cooperation

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MESPOM

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ABSTRACT OF THESIS submitted by:

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Offshore wind power has rapidly emerged as a competitive energy technology in proximity to Europe’s North Sea and Baltic Sea. Five frontrunners are driving growth, with the United Kingdom and Germany as lead markets, and Denmark, Belgium, and the Netherlands as smaller competitors. Together, these countries – all members of the North Seas Energy Cooperation (NESC) – are shifting the boundaries of the energy transition from land to sea. The NESC has set a 2030 target of 76GW, up from 22GW; however, the feasibility of reaching this ‘Milestone’ remains underexplored in the literature. To date, few studies have examined the mechanisms that drive offshore wind growth beyond early market formation. To bridge this knowledge gap, this thesis examines past deployment trends to model the parameters of future growth pathways, assessing the potential for exponential, logistic and/or logistic-linear growth in the NESC. Feasibility is assessed by assessing the drivers behind offshore wind growth: techno-economic, socio-technical, and political mechanisms, against the parameters of the model. The study finds that upscaling dynamics play a significant role in driving growth across the NESC, as Offshore Wind Farms (OWFs) cover increasingly larger areas, as they move farther from the shore and into deeper waters. Following newfound energy transition ambitions across the NESC, the study concludes that feasibility is **High** for reaching the current 2030 target, with a possibility of an overshoot should the United Kingdom realise surplus gigawatts of projects in its existing pipeline.

Keywords:

North Seas Energy Cooperation, offshore wind power, Offshore Wind Farms, feasibility, energy transition, upscaling dynamics, growth mechanisms, Technology Innovation System, Milestones and Landmarks.

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List of Abbreviations

European Commission (EC)
European Economic Area (EEA)
European Parliament (EP)
European Union (EU)
First Assessment Report (FAR)
Gigawatt (GW)
Intergovernmental Panel on Climate Change (IPPC)
International Energy Agency Wind Technology Collaboration Programme (IEA Wind TCP)
International Oil Companies (IOCs)
Megawatt (MW)
National Energy and Climate Plans (NECPs)
National Renewable Energy Action Plans (NREAPs)
North Seas Energy Cooperation (NESC)
Offshore Wind Energy (OWE)
Qualitative Comparative Analysis (QCA)
Renewable Energy (RE)
Renewable Energy Road Maps (RERMs)
Renewable Energy Sources (RES)
Renewable Energy Technologies (RETs)
Research, Development, Demonstration and Deployment (RDD&D)
Returns on Invested Capital (ROIC)
Sustainable Development Goal (SDG)
The International Renewable Energy Agency (IRENA)

1 Introduction

1.1 Problem definition and justification

On December 7, 2009, the North Sea Countries Offshore Grid Initiative (NSCOGI) was established by ten countries (Belgium, Denmark, Germany, France, Ireland, Luxembourg, Norway, Netherlands, Sweden and the United Kingdom) together with the European Commission (EC) to promote regional cooperation for facilitating the development of the offshore grid in line with the goals of the European Union's (EU) Third Energy Package[1] (NorthSee 2020; EC 2020a). Subsequently on June 6, 2016, the North Seas Energy Cooperation (NSEC) was signed "in favour of increased cooperation and renewed commitment" towards ensuring "a sustainable, secure and affordable energy supply in the North Seas countries" (EU 2016). Since this political declaration, long-term strategies have been consolidated by leading NSEC Member States including Belgium (BE), Germany (DE), Denmark (DK), the Netherlands (NL) and the United Kingdom (UK), which have consolidated their position as frontrunners in the global offshore wind market (EC 2020).

The move of the NESC has added strength to the European Green Deal, which "emphasises the importance of offshore wind in meeting the EU's 2030 and 2050 climate and energy objectives" (EC 2020b). Notably, at the June 2019 Ministerial meeting in Esbjerg, Denmark, the NSEC agreed on an indicative installed capacity of at least 70GW by 2030, based on national planning of Member States (EC 2020c; Danish Ministry of Climate, Energy and Utilities 2019).[2] The frontrunner group (BE, DE, DK, NL and UK) account for the bulk of this target, at 65.8GW. Following a recent declaration by the German government raising its 2030 target from 15GW to 20GW, the NESC target has increased to 76GW (Knight 2020a, 2020b). Finally, while the 22GW of offshore wind currently installed in the NESC "covers on average 1.5% of Europe's annual electricity demand," the EC has stated that at least 230GW is needed by 2050 and around 450GW would be required to meet 30% of Europe's electricity demand (Freeman *et al.* 20190.[3]

Climate change is a leading motivation for realising a clean energy transition, in which the long-dominant fossil-fuel based energy regime of the industrial world is scaled back in favour of clean energy alternatives such as wind and solar (Jeerts 2017; Pelegry and Basterra 2016). Since the

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[1] The objective set by the EU Energy Union strategy of February 2015 to provide consumers with sustainable, secure, and affordable energy, and the importance it attaches to enhanced regional cooperation (EU 2016).

[2] The UK has since left the NSEC following its departure from the EU on January 31, 2020, but it remains included within the group for the purposes of this study (EC 2020a).

[3] Based on an increase of 50% compared to 2015 levels due to electrification (Freeman *et al.* 2019).

Intergovernmental Panel on Climate Change (IPCC)[4] released their First Assessment Report (FAR) in 1990 – addressing "the question of climate change which might arise as a result of man's activities" (Houghton *et al.* 1990) – the scientific consensus on climate change has strengthened considerably (Maibach *et al.* 2014; Molina *et al.* 2014).[5] Consequently, the need for long-term strategic action on climate change has become a cornerstone of global policymaking (Boran 2018), with mitigation efforts calling for a rapid shift to new modes of production and consumption before biophysical thresholds and socio-economic tipping points are breached (Werners *et al.* 2013; van Ginkel *et al.* 2020). Transformative mitigation is only feasible if countries transition to a new energetic system, since energy alone underpins the global consumption-production nexus and related relationships between trade and resources (Hoff 2011; Schaper 2012). Against this background, climate change is recognized within this thesis as one of the driving forces accelerating the push towards a "sustainable energy transition" (Solomon and Krishna 2011).[6]

International climate change policy aims to limit global temperature increase to "well below 2°C above pre-industrial levels" (Rogelj *et al.* 2016), as set forth in the 2015 Paris Agreement and in alignment to Sustainable Development Goal 7 (SDG7)[7] (UN 2015). This calls for a coherent energy strategy since policy support mechanisms facilitate the potential for sustained diffusion of RETs (Lewis and Wiser 2007). To date, coherence remains either absent or only partial, leaving the energy transition hanging in the balance. To keep global warming within a 1.5°C threshold, policy frameworks such as National Energy and Climate Plans (NECPs)[8] and National Renewable Energy Action Plans (NREAPs) must be stringent, yet ambitious enough to ensure renewable energy sources (RESs) supply a significant proportion of primary energy by 2050 (Rogelj *et al.* 2018).

Even though the European Union (EU) is a global leader in wind power and considered strong on the policy front, it nevertheless remains adrift from meeting its climate change targets (Allen *et al.* 2019). Worryingly, onshore wind power is characterized by increased 'red tape' delays and growing stagnation in European frontrunner markets such as Denmark, Germany and Spain, where

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[4] The IPCC is the UN body for assessing the science related to climate change (IPCC 2020c).

[5] the notion of "climate security" in the so-called 'Age of the Anthropocene'[5] has also escalated (Dalby 2014)

[6] Sustainability is thus strongly embedded in diversifying the energy system towards a decarbonisation pathway (Lacera and Van Bergh 2014) in which modern renewable energy technologies (RETs) provide a counterbalance to fossil-fuel dependency and resultant anthropogenic greenhouse gas (GHG) emissions (Staudt *et al.* 2013).

[7] SDG7 aims to "ensure access to affordable, reliable, sustainable and modern energy for all" (UN 2015).

[8] NECPs are the framework within which EU Member States integrate their climate and energy objectives in submission to the European Commission (EC) (CAN Europe 2020; WindEurope 2020).

most wind turbines are in need of repowering or decommissioning as they approach the end of their planned service life (Ziegler *et al.* 2018).[9] Confronted with the constraints of onshore wind power, governments and energy companies have turned to offshore wind as a secure, clean and competitive energy alternative for decarbonizing European power systems (Dedecca *et al.* 2016):

> Offshore wind has the potential of becoming an important pillar…It can contribute to policy objectives on climate change, energy security, green growth, and social progress (Wiezzorek *et al.* 2013).

The global offshore wind industry is forecast to become a trillion-dollar business in line with a fifteen-fold increase in capacity by 2040 (IEA 2019). Foreseeably, offshore wind power may develop into "the backbone of Europe's green transformation" (Ørsted 2018), generating significant economic value at the national level through supply chain investment and industrial employment (Skoczkowski *et al.* 2019).

Renewable Energy (RE) roadmaps have emerged as a key tool for assessing the feasibility of low-carbon technology deployment pathways, based largely on RESs and energy-efficiency mechanisms (IRENA 2019a; IRENA 2019b). The International Renewable Energy Agency's (IRENA) roadmap – **REmap Case**[10] – provides a key example, calibrated to account for techno-economic, socio-technical and political mechanisms (Cherp *et al.* 2018) representing the main drivers or constraints behind realising a global energy transformation. REmap Case (*2019 edition*) sets an offshore wind target of 78GW capacity for Europe by 2030 – equivalent to approximately 34% of global capacity – compared to a current capacity of 22GW (IRENA 2019b).[11]

Europe is where offshore wind power began in the 1990s and where it will remain most prominent this decade, aside from the ensuing Chinese-led wave of uptake in the Asian Pacific. Europe has set out an ambitious offshore wind plan, targeting an installed capacity of around 76GW by 2030 in line with its NSEC Member States. This uptake will see offshore wind farms (**OWFs**) – multiple wind turbines situated within a defined geographical area that are connect to the electricity grid via the same substation (Borrmann *et al.* 2018) – cover approximately 10% of total electricity generation by 2030 (IEA 2019). However, the feasibility of such targets remains under scrutiny. Furthermore, modelling parameters for offshore wind are underexplored in comparison to onshore wind and solar PV. Moreover, the extent to which anticipated capacity growth will translate into

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[9] ~ 50% of the EU's onshore capacity will reach the end of its operational life by 2030 (Nghiem et al. 2017).

[10] The REmap Case sets a pathway to achieve 86% RESs in the power generation mix by 2050 (IRENA 2019b).

[11] This target coincides with WindEurope's (2017) Central Scenario and High Scenario: 70GW and 99GW.

meeting NECPs and NREAPs, as well as how different Europe countries will ultimately contribute to deployment levels remains subject to uncertainty. Within this context, the feasibility of such targets warrants close attention at the national level and in the wider context of meeting European climate objectives. Findings at the European level may carry strong significance for global offshore wind forecasts, as well as the long-term prospects of RESs in the energy transition.

1.1 Research Goal

Offshore wind power has quickly transitioned from a niche renewable sub-technology – primarily confined to Northern European waters – to a transformative technology that can help mitigate climate change by accelerating the decarbonisation of the electricity sector. To assess the feasibility of future growth potential and related targets, offshore wind should be examined in terms of its past and emerging deployment trends within the wider context of RE roadmaps and the energy transition. Such aspects of feasibility remain underexplored in the literature and to the author's knowledge, a case specific study of offshore wind in Europe – synthesizing historical trends and future projections – has not been undertaken to date. This thesis sets out to cover this knowledge gap by assessing the feasibility of the NSEC meeting its 2030 target of 76GW.

1.2 Research questions and method

The thesis aims to assess the feasibility of installing at least 76GW of offshore wind power in NSEC Member States by 2030. To achieve this aim, it is structured around four research questions:

1. **Which processes ("motors of change") determine the early uptake of offshore wind power?**
2. **What mechanisms drive the growth of offshore wind power?**
3. **Is the current deployment of offshore wind power in the NSEC accelerating, stable or slowing down?**
4. **Is it feasible for NSEC Member States to achieve offshore wind deployment levels compatible with their national targets?**

The research questions (RQs) are addressed within a structured, focused comparison of European frontrunner countries carried out using a mixed-methods approach.

RQ1 focuses on the formative phase of offshore wind development. Key events in each country are assessed through the Technology Innovation Systems (TIS) framework, building an analytical narrative to identify the preconditions influencing the uptake of offshore wind. The TIS framework provides a lens to identify which processes and mechanisms favour early market formation of offshore wind power at the country-level. The focus is on understanding how past events established the landscape for offshore wind to diffuse into the energy system and ‘take-off.’

RQ2 examines how techno-economic, socio-technical, and political mechanisms influence the expansion of offshore wind power in the electricity system; according to changes in the dynamics of electricity generation and installed electricity capacity within the context of national energy transition, The focus is the drivers behind on past and emergent trends in the national energy mix.

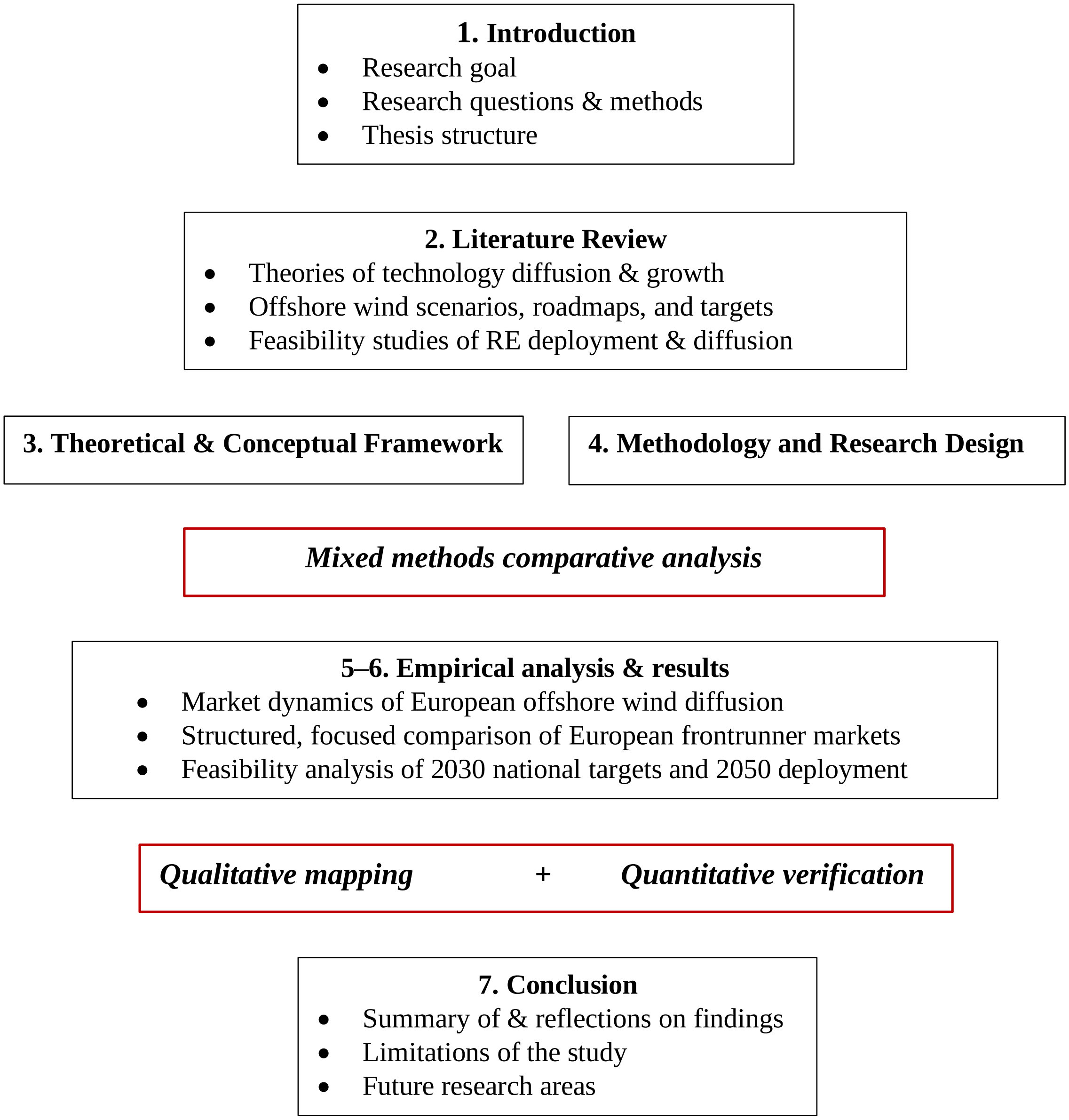
RQ3 is answered by comparing three growth models – exponential, logistic and logistic-linear – to the 2030 targets and their respective deployment timeline. The focus is on illustrating growth pathways to gauge the feasibility parameters of future scenarios.

RQ4 firstly evaluates the feasibility of five national case studies (DK, NL, UK, DE, and BE) against their specific context. The focus is on synthesizing the findings from previous steps to verify the feasibility of meeting 2030 targets in each country. Secondly, the analysis is extended at the aggregate level to assess the feasibility of the NSEC meeting its 2030 target based on results at the national level, in addition to market trends, technological developments and political commitments. Finally, the focus is shifted beyond 2030 to 2050 for further comparison.

1.3 Thesis structure

The structure of this thesis is indicated in Figure 1. **Chapter 1** frames the underlying research interests, introducing the links between climate change and the energy transition with a view to offshore wind power and RE roadmaps. Next, the research goal is stated along with a summary of the proposed research questions and methods. **Chapter 2** presents the literature review section covering the following main areas: theories of innovation and technology diffusion; the evolution of offshore wind in the marine renewable energy (MRE) transition; offshore wind scenarios, roadmaps, and targets for 2030-2050; and finally, feasibility studies of offshore wind deployment. Next, **Chapter 3** presents the conceptual framework of the thesis based on three theoretical pillars derived from the literature review. **Chapter 4** explains the methodology and research design. **Chapter 5** introduces the initial results of the study, reporting on the market dynamics of wind energy and delineating the key phases of offshore diffusion according to the conceptual framework developed in Chapter 3. **Chapter 6** is built around a structured, focused comparison of Europe’s five frontrunner countries. It progresses as follows to tackle *RQs 1–3*: **(1)** analytical diffusion narrative through the lens of the Technology Innovation System (TIS) framework; **(2)** analysis of offshore wind in the context of national energy transitions; and **(3)** feasibility analysis of 2030 national offshore wind targets in the European context. **Chapter 7** concludes with reflections on the key findings, limitations of the study and suggestions for areas of future research.

Figure 1.1. Chapters and breakdown and thesis structure



1. Introduction
- Research goal
- Research questions & methods
- Thesis structure

2. Literature Review
- Theories of technology diffusion & growth
- Offshore wind scenarios, roadmaps, and targets
- Feasibility studies of RE deployment & diffusion

3. Theoretical & Conceptual Framework

4. Methodology and Research Design

Mixed methods comparative analysis

5–6. Empirical analysis & results
- Market dynamics of European offshore wind diffusion
- Structured, focused comparison of European frontrunner markets
- Feasibility analysis of 2030 national targets and 2050 deployment

Qualitative mapping + ***Quantitative verification***

7. Conclusion
- Summary of & reflections on findings
- Limitations of the study
- Future research areas

2 Literature Review

2.1 Introduction

Diffusion of Innovation (DoI) theories and associated models of technology diffusion present a long and rich history, spanning more than half a century and crossing multiple disciplines (e.g. sociology, education, agriculture, medicine, economics, geography, marketing, and communication). Building on this tradition, this thesis is interested in a specific aspect of diffusion, namely how **offshore wind power diffuses through the energy system**, at the national and European level. Offshore wind can be understood as a technological innovation exhibiting unique patterns of development and diffusion, with specific characteristics differentiating it from its onshore counterpart. It competes with other energy sources in a “technology specific innovation system,” which is driven by the interplay between “actors and their competence, networks and institutions” (Jacobsson and Johnson 2000).

This literature review draws on scholarly and professional publications addressing theories of technology diffusion; temporal dynamics of the energy transition; scenarios, roadmaps, and targets for offshore wind; and finally, feasibility studies of offshore wind growth. Sections 2.2 to 2.6 chart the evolution of seminal theories of innovation diffusion with a focus on the S-curve model of technology diffusion. The following areas are examined: Neoclassical theories of technology diffusion as adopted by Griliches in the 1950s (2.2); the Diffusion of Innovation (DoI) framework developed by Rogers in the 1960s (2.3); industry lifecycle frameworks as proposed in the 1970s (2.4); Evolutionary Diffusion (ED) theories of the 1980s (2.5); and finally, the recent departure away from linear models of diffusion, as exemplified by the Technology Innovation Systems (TIS) framework (2.6). Section 2.7 reviews conceptual theories behind the energy transition, the main characteristics of offshore wind power, and barriers to renewable energy diffusion and specifically offshore wind deployment. Section 2.8 presents an overview of scenarios, roadmaps, and targets for offshore wind power. Finally, section 2.9 addresses the feasibility of offshore wind growth, as presented through the lens of techno-economic, socio-technical, and political mechanisms. A summary of key information from the literature review is provided in section 2.10.

2.2 Neoclassical theories of technology diffusion

Complementary as well as competing theories of technology diffusion exist within the literature, with the specific areas of convergence and divergence between approaches remaining a subject of scholarly debate (Sakar 1998). Neoclassical economics provides a starting point for engaging with this debate. The neoclassical theory of technology diffusion begins with “the estimation of a diffusion curve” (Karlsson 1988), which typically represents the proportion of potential adopters who have already adopted the technology, measured as a function of time from the initial adoption (Jensen 1982). The diffusion curve is usually ‘S-shaped’ (initially convex but eventually becoming concave) with the adoption rate increasing as a function of time, before becoming “right-hand skewed” once the “inflection point” of adoption has been reached (Jensen 1982). Neoclassic equilibrium (NE) models conceptualize diffusion “as a continuous, quantitative process,” characterized by “a sequence of shifting static equilibria in which agents are perfectly adjusted at each point in time” (Sakar 1998). While such models retain their own specifications, they share the assumption that adopters of technology are “infinitely rational in their decision making;” capable of exploring pathways for optimal strategy prior to the outset of diffusion (Sakar 1998) while evaluating a given innovation according to the expected economic advantage[12] it may yield (Grichiles 1957; Karlsson 1988).

In his seminal study of study of the spread of hybrid corn across the United States between the 1930s and 1950s, Griliches adopted the NE approach to explain diffusion in terms of “the beginning of the movement, its rate, and its destination,” corresponding to three parameters of a logistic growth curve: “origins, slopes, and ceilings” (1957). The diffusion speed is measured as the slope coefficient of the logistic or the time it takes to move from one level of penetration to another (Van den Bulte 2000). Griliches’ principal interest was in examining profitability across different geographies, “as a function of market density, and innovation and marketing cost” (1957):

> Griliches fitted data to a logistic curve and showed that regional differences in the time of innovation and the rate of adoption could be explained in terms of…profitability of energy into the production of hybrids by seed producers and the profitability of adoption by farmers (Sarkar 1998).

Under the assumptions of NE models, profitability acts as the principle incentive for choosing a business strategy and serves as the main determinant of technology adoption, capital formation and subsequent market growth (Nelson 1995). Diffusion processes are dictated by several interrelated variables making for a complex system; nevertheless, this complexity can be modelled by

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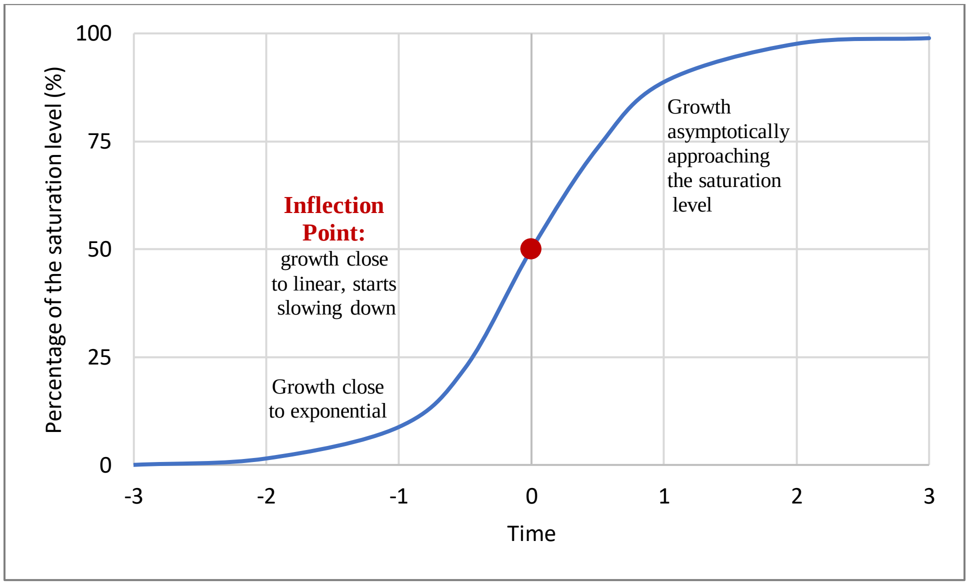
[12] Defined in terms of “the net present value of a future stream of monetary benefits weighted by the probability that these benefits will actually occur” (Karlsson 1988).

simplified or ‘stylized’ mathematical representations that capture the main features of diffusion (Jaakkola 1996) such as a 3-parameter logistic growth function (Wilson 2012):

$$y = \frac{K}{1 + e^{-b(t-t_0)}}$$

K represents the saturation level, b is the growth rate and t_0 is the inflection point of maximum growth (see fig 2.1.). In such models, “…forecasting is based on the best fit of the empirical data to the model formula and trend extrapolation outside the empirical period. The fit gives numeric values to the parameters of the model” (Jaakkola 1996).

Figure 2.1. The components of diffusion models under the Logistic curve



Source: Vinichenko 2018

2.2.1 Diffusion models in the energy literature

S-curves can be observed in terms of different parameters linked to technological growth. For example, when technological performance is plotted against investment and R&D expenditure, diffusion may typically follow a pattern of slow and/or erratic improvement, followed by consistent exponential improvement, before diminishing returns kick in and technological progress stalls (Schilling and Esmundo 2009). While innovation/technology diffusion typically adheres to an S-shaped temporal pattern, there is often significant variance in the “regularity and timing of diffusion processes” (Grübler 1996). Grübler concludes that the generic S-curve pattern holds true for most innovation cases, but also highlights that such a pattern remains subject to variation in terms of its specific breakdown or composition (1996). This rings true since diffusion is a spatiotemporal phenomenon in which technologies diffuse from the 'core' (i.e. the market of first commercial application/the lead market) through to the 'rim' (subsequent markets) and 'periphery' (final markets) at different rates (Wilson 2012; Grübler 1996; Bento *et al.* 2018). Nevertheless, diffusion processes remain far from fluid or inevitable, conforming to clustering, lumping and punctuations under certain conditions such as crises (Grübler 1996). The S-curve therefore serves as "a prescriptive tool" for interpreting technology diffusion (Schilling and Esmundo 2009) since its bounds/limits remain subject to dynamic change and uncertainty.

In a seminal study focused on the role of "innovative clusters" within the industry lifecycle, Audretsch, and Feldman (1996) draw further attention to the importance of geography and spatial proximity to the innovation core, as a key determinants of technology diffusion. Analyzing a range of industries from across the US, the authors make the following key observation:

> …what may serve as an *agglomerating influence* in triggering innovative activity to spatially cluster during the introduction and growth stages of the industry life cycle, may later result in a *congestion effect*, leading to greater dispersion in innovative activity (Audretsch, and Feldman 1996).

This observation has important implications for theories of innovation/technology diffusion, as it highlights the propensity for innovation to cluster around specific geographic niches depending on the stage of the industry life cycle. This holds true for the 'conceptualization' and 'creativity' phases of offshore wind, as markets formed exclusively around Europe's North Sea and Baltic Sea.

Numerous scholarly works have drawn on diffusion models to explain processes of technological diffusion. For example, Schilling and Esmundo (2009) employ a "Technology S-curve approach" to compare the performance trajectories of several prominent RETs to that of fossil fuel technologies. The technology S-curves for (onshore) wind energy (and geothermal energy) in the US show major performance gains as a function of R&D investment over a thirty-year period (1974-2005); nonetheless, government R&D investment remained at about 10% of spending on fossil fuel technologies (Schilling and Esmundo 2009).

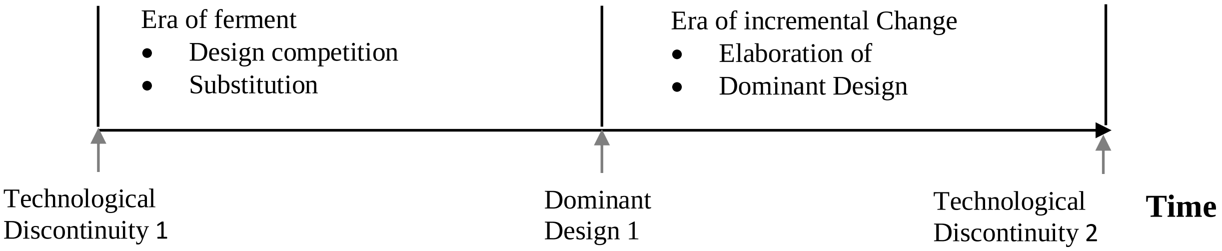
Lund applies logistic curves to investigate rates of market penetration across eleven different technologies including (onshore) wind energy, observing "a decreasing penetration rate with increasing time or market share" (2006). When the market history is short, as in the case of offshore wind, the indication is that "a temporally decreasing functional form for the penetration rate coefficient" can be used to predict "probable behaviour" (2006). Wilson (2012) further examines the historical diffusion of energy technologies in terms of "up-scaling, formative phases, and learning," finding that in the case of onshore wind power in Denmark (1977–2008), the formative phase lasted several decades with "a prolonged period of experimentation with many smaller-scale units" prior to subsequent up-scaling. Economies of scale facilitate synergies for reducing logistical costs, technician hours, the amount of required facilities and inventory levels, which is crucial to lowering the levelized cost of energy (LCOE) for offshore wind (Hanson *et al.* 2019). Meanwhile, countervailing forces of economies of scale and "heterogenous market demand" impact the "rate and timing of up-scaling at the unit level" (Wilson 2012). Helm and Mier (2019) also find an S-Shaped pattern associated with the efficient market diffusion of intermittent RESs as their capacity costs fall over time; highlighting that increasing RE penetration into the electricity market becomes efficient once the levelized cost of electricity has dropped to the same price as fossils.

Bridging together RE deployment scenarios and the dynamics of technology diffusion, Skoczkowski *et al.* (2019) employ logistic S-shape functions to examine the feasibility of pathways for European wind and solar energy deployment to meet energy-climate national targets. Despite observed differences in the target saturation levels of wind and PV technologies, their study predicts stagnation from around 2040 (Skoczkowski *et al.* 2019). In a previous study analysing the global deployment of wind and solar energy systems until 2015, Hansen *et al.* (2017) also identified trends of early stagnation. The study suggested a "pessimistic forecast" for the future of with the logistic model implying saturation levels of approximately 1.6TW, or 1.8TW by 2030 under a more optimistic scenario; in either case falling far short of targets under climate change scenarios (i.e. 1.5°C–2°C thresholds for global warming). However, it is feasible that advances in offshore wind and other emerging technologies may help raise saturation levels. This will remain challenging for the global level if limited to a single RET such as offshore wind. However, as later examined, it is apparent that since the mid-2010s large-scale deployment of OWFs in the North Sea has brought about significant capacity gains to improve the feasibility of reaching European energy goals.

2.2.2 Key stages and processes of the Technological cycle

Throughout each stage of diffusion, competing technologies enter the same sequence as they co-evolve; taking-off and substituting predecessors over the course of another technological cycle (Anderson and Tushman 1990; Utterback and Abernathy 1975), which is characterized by "long periods of incremental change punctuated by technological discontinuities," as shown in Figure 2.2. (Tushman and Anderson 1986). The 'era of ferment' sees design competition and substitution take place leading to the advent of dominant and a new ‘era of incremental change’ before technologies reach saturation levels or obsolescence (Anderson and Tushman 1990). Jacobsson and Johnson (2000) also underline how the innovation process is dictated by incremental gains, since new technologies require extensive “nurturing and diffusion” before achieving a “price-performance ratio” that can enable market stabilization.

Figure 2.2. The technological cycle



Source: Anderson and Tushman 1990

The “destination” towards the end of the technological cycle or what Grichiles (1957) labels as the “ceiling” (i.e. long-run equilibrium use) is only theoretical, as products and services may be rendered redundant in the face of emergent, discontinuous or ‘disruptive’ technologies (Schilling and Esmundo 2009). Such technologies create a rupture in the market by developing an innovative solution founded on alternative knowledge grounds, akin to Schumpeter’s notion of “creative destruction” (1942). As this occurs, incumbent firms may be forced to switch to the new technology or will otherwise rebalance their portfolios, provided the earlier technology is still viable.

Myers and Marquis further describe innovations as “the units of technological change” resulting from “a total process of interrelated subprocesses” (1969). The technological process begins to launch in earnest once technical feasibility and demand opportunities are recognized to warrant the realisation and potential adoption of the innovation (Myers and Marquis 1969).Technological innovation is typically “driven or stimulated” by the emergence of “new market needs and opportunities” (Utterback and Abernathy 1975), while the “stimulus for innovation” increases over time as products develop and mature (Abernathy and Utterback 1978). As firms seek solutions to delivering their innovation, the experimentation or “testing phase” proceeds until a product has been successfully introduced to the marketplace (Myers and Marquis 1969). Thereafter, cost reductions and performance improvements should be achieved quickly to remain competitive.

Finally, “implementation and use” is achieved once the innovation is adopted and begins to scale up, reaching new markets beyond the core (Myers and Marquis 1969).

2.3 The Diffusion of Innovation framework

Departing from the neoclassical framework, Rogers (1962) proposed a conceptual framework of diffusion incorporating rational theories of organizational life drawn together from examples across the social sciences[13] (Valente and Rogers 1995; Sahin 2006). Rogers describes diffusion as “the process by which an innovation is communicated through certain channels over time among the members of a social system” (2010). Throughout his Diffusion of Innovation (DoI) framework, Rogers adheres to distinct diffusion stages, from (pre-) development to take-off, sustained growth, slowdown, and stabilization, confirming the presence of an S-curve:

> There is a typical shape for a diffusion curve…At the outset the adoption rate is low; it then rises gradually and falls again towards the end… it usually takes the shape of an S (Rogers 2010).

Rogers developed adoption categories to reflect the stages in his diffusion model. In addtion to the five main categories, a sixth group can also be incorporated to account for “non-adopters” such as countries that have no available offshore wind resources.[14] Adopters fall in to one of five categories based on the time of adoption: Innovators (2.5% of the population), Early Adopters (13.5%), Early Majority (34%), Late Majority (34%) and Laggards (16%) (Rogers 2010). Rogers’ DoI model was subsequently criticized for being oversimplified or too idealistic based on its bell-shaped demarcation of phases.

2.4 Industry lifecycle frameworks

Harnessing Roger’s framework, scholars have applied the S-curve concept to their respective fields, making “selective use” of his work to examine specific interrelationships between innovation, technology, and the environment (Delaportas 2016). For example, Utterback’s (1974) thesis focused on the impacts of innovation diffusion at the level of the firm, delineating the process of innovation according to three basic phases: generation of an idea, problem-solving or development, implementation, and diffusion. Utterback and Abernathy (1975) later sought an “integrative theory” to account for pluralistic innovation processes at industrial and sectoral levels, identifying systematic differences across the competitive landscape down to the level of the

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[13] Rogers nine major diffusion research tradition are: Anthropology, early sociology, rural sociology, education, public health and medical sociology, communication, marketing, geography, and general sociology.

[14] Countries may also be non-adopters if they have no explicit motivation to adopt a given energy technology.

individual firm. Seen through this specific analytical lens, technology is viewed as "a dynamic and strategic variable" impacting the survivability and success rates of firms within their surrounding environment (Suarez and Utterback 1995). Utterback (1987) highlights how understanding technology diffusion and its impact on national productivity and competitiveness requires an appreciation not only of the linkages between product technologies and the manufacturing process, but also the interplay between structural, organizational and strategic dynamics across firms and industries. The subsequent 1978 A-U-model (Abernathy-Utterback) became a seminal piece in the field of innovation studies for modelling the movements between early-stage incremental product innovation to the advent of dominant design in lead markets (Akiike 2013).

2.4.1 Lead markets and dominant designs

A lead market is ordinarily the first country to achieve the diffusion of a "dominant design" (Utterback 1994). Dominant designs[15] develop as a synthesis of prior technological innovations, which may originate from various sectors or otherwise be product-specific (Suarez and Utterback 1995). Ultimately, these fragmentations are pieced together and subsumed into performance design over time, as commensurability gradually takes shape (Suarez and Utterback 1995).[16] The dominant design concept can also be understood in terms of "the cumulative product of selection among technological variations" (Anderson and Tushman 1990). Beise and Rennings (2005) refine the "lead market-approach" to take stronger account for "the spatial dimension of technology diffusion," noting how, for example, the benefits of certain off-grid technology innovations are best matched to large, industrialized nations with low population densities such as in Scandinavia (Beise and Rennings 2005). Beise and Rennings (2005) observe that "penetration rates" of technological innovation tend to remain higher in the lead market for an extended period, usually several years as "learning mechanisms" take effect; enabling knowledge diffusion and positive feedback loops to accelerate the experience curve (Junginger et al. 2010; Weiss et al. 2010).[17]

As affordability improves, the benefits of consolidating a "lead market position" start to spillover across borders, highlighting "the importance of spatial conditions to the international diffusion" of

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[15] These terms are used interchangeably to account for the presence of different offshore wind technologies and the potential co-existence of dominant designs (i.e. monopiles and the emergence of floating designs).

[16] Dominant designs tend to amalgamate existing technological features that correspond optimally to market demands, as opposed to optimizing performance on individual aspects of a given technology or striving for innovative breakthroughs (Anderson and Tushman 1990; Schilling and Esmundo 2009; Miller and Sawers 1970).

[17] Weiss *et al.* describe the experience curve approach as "an empirical concept that models production costs of technologies as a power–law function of cumulative experience, i.e., cumulative production" (2010).

RETs and indicating how a "diversity of local characteristics" may come to shape global development (Lacerda and Van den Bergh 2014).[18] Additionally, studies of global diffusion patterns have shown that innovative breakthroughs tend to become successful at the international level following a period of initial adoption and development in a single country (Beise and Rennings 2005). According to Beise (2001), lead markets are likely to present a mix of the following strategic advantages: price advantage, demand advantage, transfer advantage, export advantage and market structure advantage.

2.5 Evolutionary theories of technological diffusion

The 1980s marked a definitive departure from neoclassical theories of technological diffusion, which had repressed the notion that technological advancements are largely 'blind' (Nelson 2002). Evolutionary economics engages with "questions of dynamics and changes" focused on multiple processes and patterns including innovation, entrepreneurship and other economic phenomena, alongside institutional factors (Hodgson 1998; Nelson 1995).[19] From this rich discipline, Evolutionary Diffusion (ED) theories adhere to key characteristics of the evolutionary process, viewing the technological diffusion system as inherently non-linear and unstable (Sakar 1998).[20]

Departing from the static view of technological diffusion, (ED) models see the industrial landscape as shaped by dynamic competition between alternative technological regimes (Anderson 1996; Wilkins and Swatman 2006). Technologies enter the market through a "multiplicity of selection environments," which have an impact on subsequent growth and survival rates (Dosi and Nelson 1994). In turn, it is no longer the economy or society that acts as the de facto 'selector' between competing technologies (Dosi and Nelson 1994). Additionally, the timing of events in technology adoption determines not only the 'innovation journey' but also "the ultimate market structure itself" (Gort and Klepper 1982). For example, Arthur (1988, 1989) proposes a "density-dependent" evolutionary model, in which "an individual adopter's payoff from a given technological option is assumed to depend positively on the number choosing the option" (Sakar 1998). Diffusion becomes

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[18] For example, Lacerda and Van den Bergh (2014) examine lead markets in the context of onshore wind power, investigating the formation of frontrunner markets for wind power technologies in China, Germany and the US; analyzing the relationship between policy support for RE innovation and price competitiveness. The study demonstrates that as diffusion takes off the "cost gap" between RESs and conventional fuel sources narrows, making RE investment more attractive in countries where it was previously too costly.

[19] Witt (2016) provides a review of the particularities of evolutionary economics and its wider history.

[20] While neoclassic theories are analogous with Newtonian mechanics, evolutionary theories are analogous with evolutionary biology (Sakar 1998).

subject to the interdependencies shared between decision-makers (i.e. adopters) (Arthur 1988, 1989), resulting in opportunities for increasing returns or the possibility of 'lock-in,' as "path-dependency, hysteresis and sensitivity to initial conditions" come to characterize diffusion processes (Sakar 1998). In effect, ED theories emphasize the ways in which diffusion patterns are impacted by the "initial configuration and small changes in parameter values" (Sakar 1998).

2.6 Departure from linear models of diffusion

Scholars have increasingly pointed to the flaws in linear models of technology diffusion, highlighting the dynamic nature of innovation and the complexities inherent to diffusion patterns (Utterback 1987). In turn, diffusion has come to be understood as a dynamic process dependent upon co-evolving factors in an interconnected system, composed of multiple actors and cross-country particularities. The system remains in a state of change, with the technological frontier shifting as newcomers extend the distance between the core and the periphery until saturation.

2.6.1 Redefining technological systems

Hughes' (1983) seminal study on the electrification of western society during the formative period (1880-1930) provides a useful starting point for understanding the evolution of scholarship on technological systems. In his preface, Hughes acknowledges that the study of complex systems – the unit of his study – although in progress for more than a decade had advanced little in providing "a [structured] model for the evolution of electric power systems" (Hughes 1983). Dissatisfied with the 'internalist's approach'[21] to studying the history of technology and building upon the newly established field of Science, Technology and Society (STS)[22] Studies (Pannabecker 1995; Cutcliffe 2002), Hughes set out to comprehend "the economy, efficiency, and system imposed by inventors, engineers, managers, and entrepreneurs of technological change," recognizing early on that "*causal links* are no respecter of political boundaries" (emphasis added) (1983). His work remains important today, not least because it helped pave the way for new approaches to the study of technology and innovation; critical of the shortcomings of earlier modes of thought rooted in neoclassical economics and linear models (Jacobsson and Johnson 2000).

Following in the tradition of Hughes, Karlsson (1988) describes the conditions for a new technology architecture as emerging from the shared scientific, technical, and economic

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[21] Focusing on the 'artifact,' as opposed to its relations to the social context (Pannabecker (1995).

[22] Formalized in the United States during the 1960s.

dimensions of innovative breakthroughs. Carlsson and Stankiewicz further define a technological system in terms of “competence flows” – as opposed to “flows or ordinary goods and services” – embedded in [competence] networks; where agents interact and knowledge disseminates “under a particular institutional infrastructure to generate, diffuse, and utilize technology” (1991). Networks and institutions play a fundamental role in the evolution of the technological system, accelerating or halting diffusion rates alongside market forces (Jacobsson and Johnson 2000). “Prime movers” are regarded as particularly important to the system, as these actors may yield sufficient technical, financial, and/or political power to directly shape the development and diffusion pathway of a new technology (Jacobsson and Johnson 2000). As witnessed in the context of climate change, the global energy regime remains deeply intertwined in the current economic system, creating problems of inertia and ‘lock-in’ (Hughes 1983) that slow the diffusion of RETs while prolonging the problem of anthropogenic GHG emissions.

2.6.2 Multi-phase patterns of development and diffusion

In the context of innovation breakthroughs in communication technologies, Ortt and Schoormans (2004) understand the S-curve and embedded trends of erratic growth that typically occur prior to the ‘take-off’ or “market stabilization phase,” as a single “multi-phase pattern of development and diffusion” (Dedecca *et al.* 2016). Each phase presents specific differences in terms of duration, markets actors, market mechanisms and other key factors. This conceptualization departs from the classical S-curve model proposed by Rogers and other early pioneers of DoI studies by incorporating two distinct phases prior to the configuration of a “smooth diffusion curve” (Dedecca *et al.* 2016). Diffusion is defined as “the gradual adoption of an innovation in a market segment” and delineated through a three-phase process, which begins with the “innovation phase,” transitions to the “market adaptation phase” and culminates in the “market stabilization phase” (Ortt and Schoormans 2004).

Dedecca *et al.* (2016) apply the three-phase framework to identify the main barriers to the development of offshore wind power technology, which in turn influence the market strategies of private developers and subsequent diffusion patterns (Dedecca *et al*. 2016). Under this framework, the innovation, market adaptation and market stabilization phases are demarcated respectively as 1990-2001, 2002-2008 and 2009-present, with the 1980s regarded as the invention or ‘pre-innovation’ phase (Dedecca *et al.* 2016). During its development and diffusion, offshore wind moved beyond experimentation to reach a dominant design (Dedecca *et al.* 2016). The market adaptation phase began with the launch of large OWFs with a commercial purpose, while the market stabilization phase took shape once larger OWFs became grid-connected "using the dominant design of monopile foundations with permanent magnet generators (PMG)" (Dedecca *et al.* 2016). The development and diffusion of offshore wind has largely mimicked that of onshore wind, but with three main differences: **(1)** policy support mechanisms are a prerequisite for offshore wind diffusion; **(2)** offshore wind has more clearly defined target market; and **(3)** a higher market concentration than onshore wind (Dedecca *et al.* 2016).

Analysing the development of Offshore Wind Projects (OWPs) in the North Sea, Rodrigues et al. (2015) also demonstrate how activities moved from the "proof of concept" phase located in shallow, near-shore waters with few turbines to larger scale commercial projects located further offshore.[23] Finally, synthesizing an Evolutionary Economic Geography (EEG) perspective with a Global Production Networks (GPN) approach, MacKinnon *et al.* (2019) examine the development and diffusion of offshore wind in Germany, the UK and Norway. The study highlights the ability of national states in shaping "the strategic coupling of regional and national assets" to specific mechanisms of path creation (MacKinnon *et al.* 2019). Interestingly, Germany presents the most integrated path to date, as characterized by leadership in both deployment and manufacturing, whereas the UK and Norway have followed less holistic pathways (MacKinnon *et al.* (2019).

2.6.3 Technology Innovation Systems

Drawing on both the neoclassical the NE theory of diffusion and the DoI framework while also building on ED theories and more recent Innovation Systems (IS) literature,[24] the Technology Innovation Systems (TIS) framework has become a standard tool for examining diffusion processes, especially for RETs. In accordance to DoI theory: "…the diffusion curve of a technology describes the extent of diffusion on international level of the technology and has the shape of an S-curve" (Hekkert *et al.* 2011). The TIS framework is composed of interdependent actors, networks and institutions,[25] with its specific structure shaped by dynamic interactions between seven key functions: entrepreneurial activities (F1); knowledge development (F2); knowledge diffusion (F3);

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[23] In addition to having higher installed capacities, these projects are more complex and capital intensive, covering larger seabed areas and requiring a greater number of turbines (Rodrigues *et al.* 2015)

[24] Edquist and Lundval define the national innovation system "as constituted by the institutions and economic structures that affect both rate and direction of technological change in society" (1993).

[25] Technology can be integrated as a 4th structural process, defined as "accumulation of knowledge (i.e. drawings or patents, engineers and scientists) and artefacts in the whole value chain (Jacobsson and Karltrop 2013).

guidance of the search (F4); market formation (F5); resource mobilsation (F6); and legitimacy/counteract resistance to change (F7) (Hekkert *et al.* 2007). TIS functions examine the performance of the innovation system and its interrelations (Bergek *et al.* 2008; Wieczorek *et al.* 2013), so the development of a specific technology can be determined according to "the structures and processes that support or hamper it" (Wiezzorek 2014).

The TIS framework understands innovation and technology diffusion as intrinsically embedded in an interactive environment populated by socio-technical configurations (Geels 2004; Negro *et al.* 2012); shaped by the complementarities between knowledge, entrepreneurship, social acceptance, resources, public support and markets (Delaportas 2016). Bergek *et al.* view the TIS model as "a socio-technical system focused on the development, diffusion, and use of a particular technology" (2008), with innovation viewed as "a collective activity that takes place within the context of an innovation system (IS)" (Wieczorek *et al.* 2013). This theoretical perspective sees the market as "a knowledge coordinating dynamic system" driven by entrepreneurially focused, "non-optimizing adaptive agents," as opposed to rational decision-makers (Bleda and Del Rio 2013). Attesting to the "complex evolutionary character of innovation," adaptive agents strive to create new knowledge networks; confronting market uncertainties and technical imperfections through processes of experimentation and 'learning by doing' (Bleda and Del Rio 2013).[26]

2.6.4 Technology Innovation Systems in the wind energy literature

Wieczorek *et al.* (2013) apply the TIS framework in a 'function by function' **(F1–F7)** approach to identify systemic weaknesses hindering the development of offshore wind innovation in Europe. From the innovation perspective, offshore wind remains an emerging and dynamic system "driven by the engineering knowledge developed by in-house R&D centers of the industry;" however, market formation (F5), resource mobilsation (F6) and legitimacy creation (F7) are lacking (Wieczorek *et al.* 2013). These functions are needed to support policy intervention for addressing "institutional, actor-related, infrastructural and issues concerning connectivity within the system" (Wieczorek *et al.* 2013). Adopting a similar approach, Jacobsson and Karltrop (2013) examine blocking mechanisms in the European offshore wind innovation system, focusing on three lead markets (Denmark, Germany and the UK) and two passive countries with significant market potential (Netherlands and Sweden). The study builds out a qualitative assessment of the seven

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[26] Quitzow (2013) examines the "co-evolutionary process" of TIS developments and growth for silicon-based solar PV technologies between 2004 to 2010 in relation to the "dynamic inter-linkages" between Germany and China.

functional components of the TIS framework, pinpointing the weakest functions (F5–F7) in line with the findings of Wieczorek *et al.* (2013) and presenting subsequent policy challenges (see (Jacobsson and Karltrop 2013).

2.7 Offshore wind powering the Marine renewable energy transition

2.7.1 Theoretical dynamics of the renewable energy transition

The onset of climate change has intensified the debate on the nature of technology diffusion, with Technological Transition (TT) and energy scholars seeking to better understand diffusion patterns of RETs. Grübler (1996) advanced the scholarly literature on the temporal dynamics of technological innovation through a comprehensive study of key diffusion patterns over the last two centuries. His work considered the wider implications of these historical trends to the future of the built environment and social practices. Implicit throughout Grübler's historiography is the notion of energy transitions, which should be considered "non-deterministic," since future pathways are determined by specific actors, networks, and institutions (Fouquet 2016). At its core, the emerging energy transition underlines a diminishing dependence on the long-dominant, fossil fuel-based energy regime of the industrial world, in favor of clean energy alternatives such as wind and solar (Jeerts 2017; Pelegry and Basterra 2016). Subsumed under the Grüblerian framework, wind energy can be considered as a contributory innovation to the energy transition.

National energy transitions are typically longer, multi-decadal processes reflecting a "change in the state of an energy system" (Grübler *et al.* 2016). For example, an effective transition to 'green' hydrogen for potentially revolutionary "[sector] coupling between electricity and buildings, transport and industry" (IRENA 2018b; Wouters 2020) may prove a timely process due to "the multiplicity of forward and backward linkages" across technological, physical and organizational infrastructures (Grübler 1996). By contrast, Sovacool (2016) showcases examples of individual energy technologies that have experienced relatively fast rates of uptake. For Bridge *et al.* (2013), the energy transition is driven by geographical processes involving the reconfiguration of "spatial patterns of economic and social activity," while Fouquet (2016) stresses that all transformative technologies originate as niche products before they come to dominate the market or energy system. Accordingly, TT theorists understand the energy transition through the lens of a socio-technical paradigm, which sees multi-level processes play out across the niche, regime, and landscape (Geels and Schot 2007).

Complex system dynamics is part and parcel of the energy transition, making it a far from smooth process that is steeped in relative unpredictability and subject to potentially erratic growth rates. Given the complexity, RETs are typically deployed more effectively in countries employing "multi-dimensional decarbonisation mechanisms" (de Leon Barido *et al.* 2020), as decarbonisation rates are largely determined by "the complex interaction between enabling environments, inherent characteristics, and motivations" (de Leon Barido *et al.* 2020). Notwithstanding, the contemporary debate on "the temporality of energy transitions" highlights the inherent difficulty in predicting rates of technology diffusion (Sovacool 2016),[27] since RETs evolve as "a complex phenomenon" without a single universal pattern of diffusion (Rao and Kishore 2010). Alongside historical forces, an array of techno-economic, socio-technical and political factors shape the evolution of energy transitions (Cherp *et al.* 2018), which can also be viewed "as catalysts for certain economic, social and political transformations" (Fouquet 2016).

2.7.2 The emergence of Marine Renewable Energy

The drive towards a low-carbon energy transition has been accompanied by increased state and commercial interest in Marine Renewable Energies (MREs), with offshore wind energy being the main player in this emerging niche (Multon 2013). The European Commission (EC) has recognized that a "proactive policy" is fundamental to seizing the vast potential of offshore wind power (EC 2008), incentivizing governments to rally behind the technology by implementing supportive polices to enable its deployment (EC 2008). Several high-profile multinational energy corporations have also followed suit with multimillion-dollar investments into the offshore wind sector.[28] Critically, International Oil Companies (IOCs) are diversifying their portfolios through investments in MREs (Pickl 2019). This move presents a viable strategy for minimizing against the potential impact of 'stranded assets,' (Mace 2019) under conditions of rapidly changing global energy market dynamics (McKinsey 2019).

Separating the offshore wind construction into four main industrial segments,[29] van der Loos *et al.* find that each segment is dominated by a handful of heavy industry incumbents; seeking diversification strategies away from "oil and gas, shipping, maritime, dredging and/or cable

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[27] See *Energy Research and Social Science 22* (2016) for a further review of this debate.
[28] Equinor (formerly Statoil) is a case in point for successful diversification of its portfolio (equinor.com 2015).
[29] Offshore wind turbines; foundations (mostly monopiles); cables (inter-array and sub-station to grid); construction and installation, including key vessels (particularly jack-up and heavy-lift vessels) (van der Loos *et al.* 2020)

industries” (2020), as exemplified in the Norwegian case (Mäkitie *et al.* 2018; Mäkitie *et al.* 2019). In addition to the market pressures, socio-political unrest is impacting the energy industry landscape, with the fossil fuel divestment campaign gaining traction (Ansar *et al.* 2013; Andreasson 2019) and bolstering climate change activism across parts of the Western world (Extinction Rebellion 2019). Against this turbulent backdrop, offshore wind power is attracting corporate investment and government support, as it rapidly approaches technological maturity as the potential “variable baseload technology of the future” (IEA 2019).

2.7.3 Advantages of offshore wind power

Offshore wind has distinct characteristics that set it apart from its onshore counterpart. Firstly, OWFs typically present fewer social and environmental problems, being less susceptible to NIMBY (‘Not-in-my-backyard’) syndromes than wind farms located on land. Most commonly, onshore wind farms have been associated with problems of visual blight, noise pollution and shadow flicker (Keller 2010; Bosch *et al.* 2018). There is generally less opposition to OWFs on environmental grounds, as ecological impacts are less visible compared to onshore impacts. For example, the public intuitively understand that onshore wind turbines may pose a heightened danger to “volant species such as birds and bats” and these effects have been well-documented by ecologists and environmentalists alike (Thaxter *et al.* 2017). In contrast, the potential impacts of OWFs to the marine environment are less understood, partly because cumulative impact assessment (CIA) methods vary significantly in terms of “transparency, efficiency and complexity” (Bailey *et al.* 2014).[30] Due in part to these differences, investments have flowed more readily to offshore wind sites in recent years, particularly in countries such as the UK where NIMBY-based opposition has been fierce. According to an interview conducted with the CEO of DONG, the decision to head offshore was strongly influenced by public perceptions of the wind industry: “We’re going offshore, offshore is invisible…we don’t bother any of the inhabitants, we don’t change the landscape onshore” (Kern *et al.* 2014).

Onshore wind also faces distinct drawbacks due to spatial limitations and distance from urban hubs (Kaynia *et al.* 2019). In contrast, offshore resources compete less directly with alternative land uses (Bosch *et al.* 2018) and can be deployed in closer proximity to densely populated coastal cities

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[30] Willsteed *et al.* (2018) find that environmental statements for OWFs in the UK may neglect important interactions between environmental receptors; Pezy *et al.* (2018) concur that limited resources are dedicated to interpreting “ecosystem structure and functioning” in regard to French OWFs.

(AGI 2020). Keivanpour *et al.* also recognize that increasing electricity demand in densely populated coastal regions is one of the main enabling factors of offshore wind deployment, alongside stronger wind resources and reduced social and geographical constraints (2017). Offshore wind is a better-quality energy resource that is more abundant, stronger and consistent (Madariaga *et al.* 2012), as the smoother surface of the sea results in less frictional resistance, yielding faster, steadier winds (Kaynia 2019; Markard and Petersen 2009; González *et al.* 2018; Owens 2019). For example, a turbine operating in 15-mph wind speed can generate double the energy of the same turbine in conditions of 12-mph wind speed (AGI 2020). It follows that offshore wind turbines can and must be designed much larger than their onshore counterparts to reap the benefits of superior capacity factors. At sea, capacity factors over 50% are already common (Bosch *et al.* 2018; IEA 2019), situating offshore wind far ahead of both onshore wind and solar PV in this regard , and in stronger competition with non-renewable energy sources (EIA 2020). Other benefits accrue from the "ever-increasing size of turbines" and OWFs, as described by Hüffmeier and Goldberg:

> ...there are less resources required per MW for installation and operations, requiring fewer Balance of Plant (BoP) components…and incurring less maintenance trips per MW (2019).

It is evident that the superior design features of OWFs can help to secure efficiency, longevity, and profitability for the sector; however, robust maritime plans must also be in place to account for a wide range of other key maritime economic sectors that compete for finite space resources (Dedecca *et al.* 2016; Borrmann *et al.* 2018).[31]

2.7.4 Barriers to renewable energy diffusion

Deeply rooted in seminal work on welfare economics (e.g. Arrow 1962; Coase 1960; and Pigou 1929), the neoclassical paradigm explains the misallocation of resources in terms of market failure; whereby prices fail to account correctly for (technological) externalities, in turn breaching "the efficiency of decentralized market calculation" (Bator 1958). Under this framework, government intervention is seen as the solution for correcting market failures and economic inefficiencies (Sutherland 1991). Since energy is a basic commodity, price levels may prove to be the strongest influence on the market, as opposed to innovative features or other factors (Lund 2006).

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[31] In the UK context, Toke (2011) lists economic and environmental maritime factors as: landscape and tourism, fishing, defence and aviation, birds and wildlife, Natura 2000 sites, oil and gas installations, dredging, shipping, yachting and recreational boating; highlighting the diversity of competing offshore interests.

Energy developers strategize their efforts to maximize activities most likely to yield increasing returns on technological investment (Schilling and Esmundo 2009). In the case of offshore wind and similar RETs, demand is a derivative of electricity consumption levels, with offshore wind power feeding into the national grid and adding to the energy supply. The market landscape evolves partially from competition for increased returns on invested capital (ROIC), which may depend on a number of factors including supply chain mechanisms and scalability, and the manufacturing costs of specific inputs; especially those directly impacting the optimization of turbine design (e.g. blades, rotors and tower sizes) and consequently generation capacity (Lacerda and Van den Bergh 2014; Zhang 2012). At the global level, the "first mover" in RET innovation typically becomes well-positioned to stimulate exports to early adopter markets, increasing its profit margins as international diffusion gets underway (Lacerda and Van den Bergh 2014). Technology diffusion proves critical to the performance and survival of RETs because over time it reduced costs gaps between RESs and conventional fuel sources (Lacerda and Van den Bergh 2014). As costs fall, renewables become more competitive, scalability increases and a greater level of positive externalities can reach society and the environment (i.e. lower GHG emissions, better air quality and greater access to clean energy) (Lacerda and Van den Bergh 2014).

Various studies have discussed the impact of market failure on RE diffusion, examining the external costs of energy consumption and production as market barriers to investments in energy efficient, renewable-based services (e.g. Sutherland 1991; Levine *et al.* 1995; Owen 2006). For example, Neij (1997) examines the evolution of wind and solar in relation to experience curves, arguing that the main determinant of diffusion rates is the relationship between how fast costs fall (i.e. the cost of generating electricity) compared to the costs of conventional electricity producers (i.e. fossil fuels or nuclear etc.) (Delaportas 2016). Nakicenovic (2002) argues that although it may be more costly to invest in RETs initially, the favorable "learning by doing" aspects of RET adoption and diffusion enable a relatively fast rate of ROIC, promoting additional market uptake. Nevertheless, even when a winning business formula is implemented and proves successful over extended time-periods, profitability levels will eventually plateau as subject to the law of diminishing returns (Schilling and Esmundo 2009). Thus, in the marketplace, it is timing of decision-making that influences the survival rates of firms and their products, with profitability remaining a key indicator of the technological lifecycle.

Negro *et al.* (2012) present a comprehensive review of why the development and diffusion of RETs may be stalled, problematic or lackluster, citing a range of "systemic problems" stemming from unfavorable market dynamics (e.g. the strength of incumbents in the energy regime, infrastructural deficiencies and institutional constraints – 'hard' and 'soft' – among other barriers) (see Table 2.1.) (Kemp 1994; Klithou *et al.* 2015). Incumbent actors are more willing to adopt and lobby for technologies that conform with their existing product or service, such as in the case of Dutch biomass gasification which saw energy companies withdrew their support for the technology, following the implementation of the EU Electricity Directive and subsequent liberalization of the energy market in 2004 (Negro and Hekkert 2012; Van Damme 2005). This example highlights how incumbent actors can slow down the diffusion of renewables and even collapse an innovation system (Negro and Hekkert 2012; Negro *et al.* (2012).

Table 2.1. Innovation Systems perspective of barriers to RE technology diffusion

TIS component	Types of barriers
Actors and Markets	Established technology characterized by increasing returns; market control by incumbents; local search processes; poorly articulated demand
Networks	Poor connectivity; wrong guidance with respect to future markets
Institutions	Legislative failures; failures in the educational system; skewed capital market; underdeveloped organizational and political power of new entrants

Source: Jacobsson, S., and Johnson, A. 2000

'Hard' institutional barriers are a common blocking mechanism, arising when legislation inhibits the uptake of a technology or otherwise promotes an incumbent technology at the expense or RETs, as documented by Johnson and Jacobsoon (2001). In the case of Swedish renewables, it was the passing of a "bias" electricity tax legislation that deterred the investments in combined heat and power (CHP) generation plants (Jacobsson and Johnson 2000). Focusing specifically on onshore wind in Europe, Negro *et al.* (2012) show that in the absence of stringent policy instruments, large R&D budgets may prove ineffective in delivering their goals. Without policy support measures in place, RETs may struggle to bypass the 'valley of death' between the R&D phase and market introduction, since the odds of successful early market formation improve when governments provide an extended period for experimentation and pilot projects (Verbong *et al.* 2008).

‘Soft’ institutional problems arise when resistance forms around RETs. This may take shape through lobbying, public resistance, or media backlash. For example, Dutch utility companies have historically opposed the deployment of wind turbines, citing their comparatively low level of electricity generation as an argument against the rationale for energy diversification (Negro *et al.* 2012; Luteijn 2016). At the same time, building permit issues and a lack of cohesion between authorities – central, provincial, and local – acted as a major barrier to the development of wind energy in the Netherlands (Bergek and Jacobsson 2003). While in the UK, ‘NIMBY’ discourses have been prevalent in the public debate on wind energy siting, leading to a downturn in project approval for OWFs (Burningham 2015). ‘Nimbysim’ has also recently gained increased traction in Germany and Denmark (Naumann and Rudolph 2018) and consequently offshore wind projects have become a more attractive proposition to investors.

2.7.5 Barriers to offshore wind deployment

Despite its promise, offshore wind power is not without difficulties and limitations which weaken its innovation system (Dedecca *et al.* 2016). The maritime environment is especially harsh, making installation expensive and extremely challenging even by today’s engineering standards, while maintenance requirements must be minimized to secure affordability and long-term profitability (Sathyajith 2006). Sovacool and Enevoldsen (2015) outline the associated technical and business challenges of OWFs as harsh operational conditions, difficulties in reducing capital intensity and securing economies of scale, and finally, propensity for production bottlenecks given the need for specialized labor skills sourced primarily from frontrunner markets. Dedecca *et al.* likewise conclude that the offshore wind sector is susceptible to “shortages of skilled labour,” while prone to high capital costs and liquidity risks, which together inhibit the scope for technological innovation (2016). Moreover, ‘multidisciplinarity’ is inherent to the sector (Dedecca *et al.* 2016), as OWFs fuse multiple engineering and computing disciplines with fields such as meteorology and logistics, which calls for both “deep” and “integrative” competences throughout the project lifecycle (Jacobsson and Karltorp 2012). Consequently, offshore wind is a technologically demanding and capital-intensive sector requiring specific organizational resources and considerable investment (Markard and Petersen 2009).

Unlike onshore wind, OWFs usually require costly integration into the electrical grid, as extreme distances must be connected by expensive underwater cables requiring special licenses (Markard and Petersen 2009). Furthermore, onshore coastal grids may need expansion to ensure electricity can be effectively distributed to areas of high energy consumption (Bilgili *et al.* 2011). The need for renewed grid infrastructure (Dedecca *et al.* 2016) and integrated planning of power systems (Caglayan *et al.* 2019; Syranidis *et al.* 2018) remains both a technical and institutional barrier (Dedecca *et al.* 2016; Dedecca *et al.*, 2017). Additionally, a range of "onsite installation variables" can potentially limit deployment, as "specific sectoral singularities" including water depth and distance to the coastline present important considerations in planning decisions and OWF performance (Varela-Vázquez *et al.* 2019).

Although the offshore grid exists as "a multilevel, multi-actor system," it currently operates without a proven model of governance (Dedecca *et al.*, 2018). European projects designed to promote the expansion of offshore grid governance suffer from inertia, with revision of the Energy Union framework currently delayed until 2026 (Dedecca *et al.* (2019).[32] Luo *et al.* emphasize the importance of developing "a uniform grid strategy" alongside "a pan-European electricity code" (2012). In addition to policy progress, Bosch *et al.* (2018) and Dedecca *et al.* (2018) demonstrate that identifying prime OWF locations – compatible with the characteristics outlined above – calls for finer spatiotemporal resolutions in GIS-based studies and related planning assessments. Hong and Möller (2011) similarly recognize that GIS-based tools provide "the resource, economic and policy basis" for planning the development of OWFs within China's EEZ. Such an approach will prove critical to future developments, since historically most early OWFs were confined to shallow waters, but "logistics, geology and public pushback" have since forced operations away from coastlines and into deeper waters (Powers *et al.* 2019).[33]

Onshore and offshore wind evolve in tandem as "technology clusters," exhibiting rapid efficiency gains through higher capacity factors and other technical improvements, boosting RE productivity levels over time (Grübler 1996). Nevertheless, the shift towards securing greater capacity factors for OWFs may be stalled by counteracting "social and political arrangements" in the existing energy regime (Tsoutsos and Stamboulis 2005). These arrangements block developments from across the engineering, computing, and business disciplines, inhibiting the realisation of technical,

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[32] In 2010, the North Seas Energy Cooperation identified four key areas for development: (1) maritime spatial planning; (2) development and regulation of offshore networks and other offshore infrastructure; (3) mechanisms to support and finance offshore wind projects; and (4) technical standards and rules in the offshore wind sector (EC 2018a). Nevertheless, offshore grid governance remains in its infancy.

[33] For example, in 2009 the Dutch government forbid the construction of wind farms within 22 km of the shore (i.e. within Territorial Waters) (Loeff 2015). The UK government's strategic environmental assessment also expresses a strong preference for building sites beyond territorial waters (DECC 2009).

digital, and managerial advancements in promotion of RETs.[34] Thus, socio-political forces can block the formation of a new system in preservation of the old regime. This undesirable state of path-dependence occurs when "management and power structures, technical disciplines and divisions, and regulatory capture" 'lock-in' the old regime (Tsoutsos and Stamboulis 2005).

Under conditions of social and political instability, it becomes even more challenging to reliably predict diffusion pathways for RETs (Utterback and Brown 1972). Furthermore, policy reversals may transpire or intense competition between energy sources may otherwise stall or altogether halt RET growth. For example, the UK have more than flirted with a switch from wind and/or solar support to nuclear energy and shale gas fracking, following a distinct "policy apparatus for [deep] incumbency" in the mid-2010s (Johnstone *et al.* 2017). Half-hearted political commitment or even 'U-turn-style' decisions regarding phase-outs or associated moratoriums for fossil fuels or nuclear energy are not uncommon, especially when political power undergoes a shift or is otherwise unstable. Social and political instability reinforce the non-deterministic nature of energy transitions and the potential pitfalls of probabilistic assumptions.

2.8 Offshore wind scenarios, roadmaps, and targets

Following a notable shift in the "Narratives of climate change" (Daniels and Endfield 2009), Renewable Energy (RE) roadmaps have become a prominent part of global energy policymaking (Zervos *et al.* 2011; El-Katiri 2014; IRENA 2018a; Jacobson *et al.* 2017; Gielen *et al.* 2018). Veum *et al.* (2011) define a roadmap as "dynamic and responsive plan" comprised of "a starting point, a destination and a route description," which is usually motivated by the need to carve a better pathway for the future. RE roadmaps have grown in importance following the growing call to heed scientific recommendations and enact timely updates, as stressed by the European Parliament (EP) in response to criticism of its *Energy roadmap 2050, a future with energy*:

> [The EP] Regrets that the Commission did not implement the recommendations of its peer-reviewed Advisory Group on the Energy Roadmap 2050; calls on the Commission to issue an updated version of the Energy Roadmap, taking these recommendations into account (EP 2013).

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[34] As the offshore industry matures, innovation led by startups and established actors are underway across a range of areas: "specialized vessels, quieter pile-driving hammers, wave motion-compensated equipment, innovative foundations, new installation techniques, radical turbines and numerous digital solutions" (van der Loos *et al.* 2020)

The EP also affirmed its belief that meeting the 2050 goals would rest heavily on the EU taking an active and responsible role in facilitating the energy transition, "especially for huge projections such as the construction of off-shore wind farms in the North Sea" (EP 2013). Nevertheless, marine renewable energy-specific roadmaps remain relatively scarce in the policy or academic literature. Most notably, offshore wind is usually subsumed under onshore wind power or appears within RE roadmaps in less explicit than onshore wind (e.g. Ushiyama *et al.* 2010).

In 2014 the European Commission (EC) proposed that "the share of renewable energy in the European Union (EU) final energy consumption reaches at least 27% by 2030" (EC 2014), which became a legally binding target under the '2030 climate and energy framework' (EC 2016). However, in 2018 the original target was increased to 32% "including a review clause by 2023 for an upward revision" (EC 2020) (see Table 2.2.). Given the unpredictable nature of RET diffusion, RE targets may appear to bring a greater sense of transparency and structure to proceedings, yet the political environment may prove equally unpredictable at times.

Therefore, RE roadmaps must respond dynamically to account for the ever-changing intricacies of technological diffusion (Grübler 1996) while staying relevant to the revisions in NREAPs and related targets. Skoczkowski *et al.* (2019) suggest that future analysis of the dynamics of technology diffusion in RE roadmaps scenarios should include a focus on "a consistent multifactor analysis of the main parameters of the dynamics" (i.e. pace of diffusion and extent of diffusion in specific markets). Thus, developing RE roadmaps is a dynamic task subject to high degrees of uncertainty, especially when emergent energy sources such as offshore wind are added to the mix.

Table 2.2. Overview of the EU's energy targets, 2030–2050

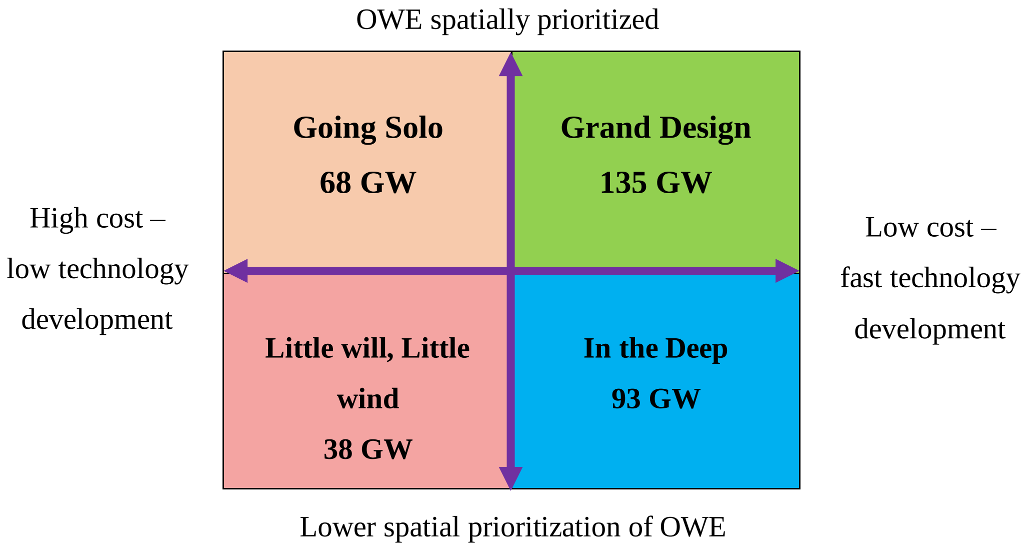
	Year and Target (%)		
Target parameter	**2020**	**2030**	**2050**
Greenhouse Gas Emissions	20%	40%	80–95%
Renewable Energy Consumption	20%	32%	~ 66%
Energy Efficiency	20%	32.5%	41%

Source: European Parliament 2019, Hüffmeier and Goldberg 2019

Given the growing importance of offshore wind power especially in the European context, there is justification for developing Offshore Wind Energy (OWE) Roadmaps under strict criteria to meet climate change targets. Some early progress has been made in this direction to date. In 2011, the

EU-funded *Offshore Renewable Energy Conversion* platforms – Coordination Action (ORECCA) Project (Jeffrey and Sedgwick 2011) was launched to "create a framework for knowledge sharing and to develop a research roadmap for activities in the context of offshore renewable energy" (CORDIS 2020). Veum *et al.* (2011) analyse deployment pathways in the Central and Southern North Sea under four district scenarios (see fig. 2.4), with a wind range of potential growth.

Figure 2.3. Estimated offshore wind capacities under WINDSPEED 2030 scenarios



Source: Veum et al. 2011

Hüffmeier and Goldberg (2019) also review energy scenarios in the Baltic Sea under low, central, and high deployment scenarios.[35] Low scenarios reflect "a stagnation or recession in economic development and/or geopolitical instability," where sustainable energy policy is deprioritized and targets are less ambitious (Veum *et al.* 2011). In contrast, high scenarios see RE growth promoted in support of climate change mitigation targets. Findings confirm the long-term dominance of the North Sea as the major offshore wind hub, although Baltic-based activities are showing potential growth with the addition of newcomers such as Poland (Hüffmeier and Goldberg (2019).

WindEurope (formerly EWEA) also analyse wind energy scenarios (both onshore and offshore) for 2030 using the conventional approach of low, central and high deployment scenarios, stating 70GW and 99GW for their central and high scenarios, respectively (see fig. 2.4). The REmap Case forecast for European offshore wind energy falls within this range, stated as 78GW for 2030 and growing to 215GW by 2050. Remarkably, under the same scenario the global offshore wind

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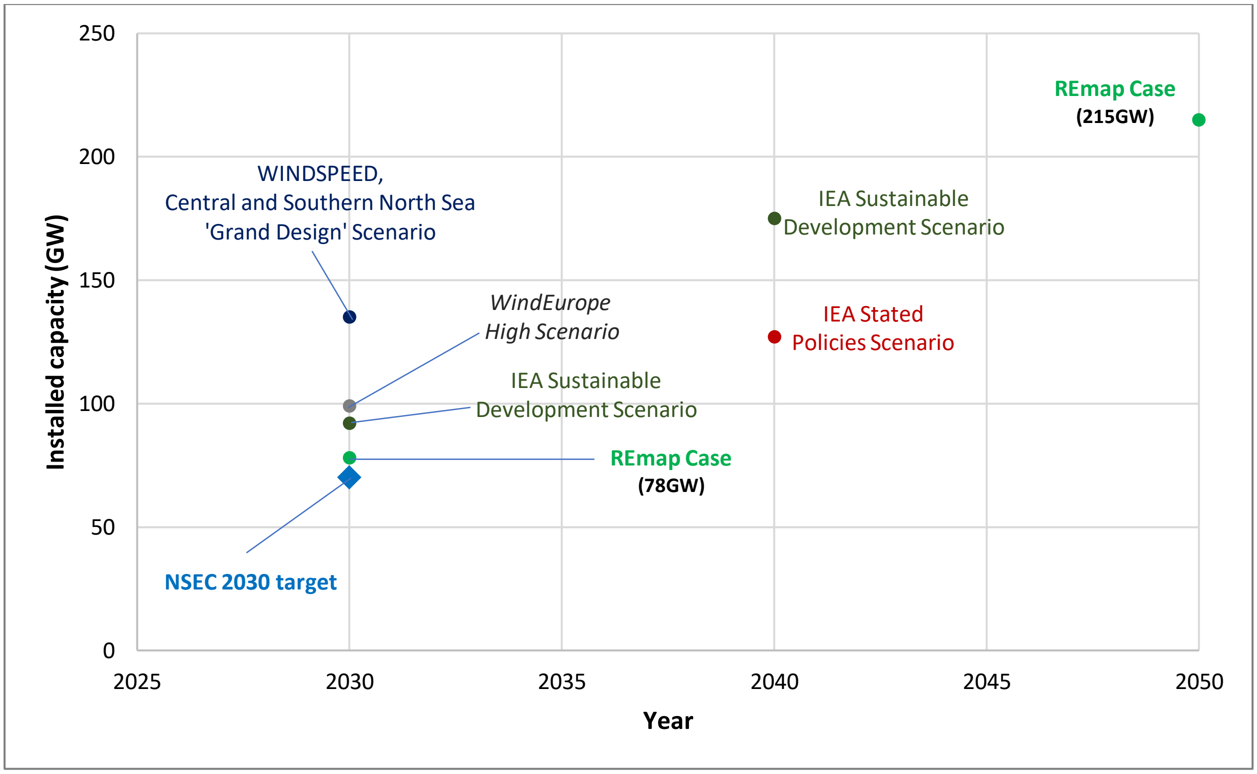
[35] Low scenarios are excluded as central and high scenarios are of interest to in this study.

projection reaches 1000GW, having been just 521GW in the previous forecast (2018 edition); whereas onshore wind yields much more stable projections at both the European and global level (IRENA 2018a, 2019b).

Figure 2.4. 2030-2050 European offshore wind energy targets under Roadmap scenarios



Source: Veum *et al.* 2011; WindEurope 2017; IRENA 2018a, 2019b; IEA 2019

The gap between IRENA’s recent projections confirms that onshore wind has already achieved relative global success in scaling up; giving it a more stable deployment pathway as it approaches saturation levels faster than offshore wind. Early RE roadmaps have at times suggested a dramatic divergence between interrelated RETs, while in some cases 2030 targets conform quite closely across different roadmap scenarios. According to the Global Wind Energy Council, global offshore wind capacity has the potential to reach around 200GW by 2030 (GWEC 2019a) while the REmap Case scenario forecasts around 230GW of installed global capacity by 2030 (IRENA 2019b). National energy transitions should be understood as a dynamics process dictated by a range of interacting mechanisms, which at times constrain the growth of RESs or block deployment altogether. Given this reality, RE roadmaps have emerged as an important tool for assisting policymakers to reach smoother planning decisions and more comprehensive objectives and timelines for fulfilling national targets or meeting international laws.

2.9 Feasibility studies of offshore wind diffusion

Roadmaps and various scenario pathways put forward what is desirable or necessitated given a context-specific setting such as climate change mitigation in line with a 1.5°C threshold or renewable energy deployment above a target percentage; however, the feasibility of achieving such desirable outcomes inevitably remains an area of uncertainty. This uncertainty is amplified since technology diffusion is subject to dynamic conditions, case-specific pathways and underlying variance, resulting in unpredictable results across different geographies, even when considering the same technology within a short timeframe. The sensitive and often volatile nature of the global economic environment further exacerbates uncertainty and unpredictability.

Feasibility studies of RE diffusion attempt to narrow down such grey areas by quantifying the impact of the underlying dynamic mechanisms that drive a specific technology diffusion pathway. Such studies are often framed in terms of 'drivers' or 'enablers,' and 'blocking mechanisms,'[36] 'barriers,' or 'constraints,' which may be used somewhat interchangeably to evaluate what fosters or hampers diffusion. Casual mechanisms of RE uptake reside in the techno-economic, socio-technical, and political factors shaping the energy system, which can be viewed alternatively as a set of interdependent variables that are changing over time. In his discussion of evolutionary economics, Nelson (1995) highlights what lies at the core of understanding dynamic change:

> The focus of attention is on a variable …that is changing over time and…for an understanding of the dynamic process behind the observed change; a special case would be a quest for understanding of the current state of a variable or a system in terms of how it got there (1995).

Accordingly, feasibility studies in the energy literature evaluate relevant variables to assess their significance as drivers/enablers of diffusion and the ways in which mechanisms may change over time. The remainder of this section presents a range of offshore wind energy studies, which focus on underlying feasibility dimensions for realising desirable deployment targets.

Taking a holistic approach, Keivanpour *et al.* (2017) investigate the "feasibility, sustainability, and flexibility" of global offshore wind capacity through a systematic literature review focused on the period 2000–2016, summarizing various methods for assessing offshore wind capacity, market

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[36] The TIS framework uses 'inducement' and 'blocking' mechanisms in relation to its functions (Bergek *et al.* 2007).

deployment and other key parameters The authors identify eight broader categories (technical, geographical, economic, social, environmental, market, policy, and technology evolution) encompassing respective techno-economic, socio-technical and policy factors in order to conduct a feasibility assessment (Keivanpour *et al.* 2017).

Honing in on techno-economic factors, Rodrigues *et al*. identify trends in European Offshore Wind Projects (OWPs) in relation to the following key characteristics: "installed capacity, number of turbines, water depth, project area, distance to shore, transmission technology and investment cost" (2015). The study confirms that both the average distance to shore and the water depth have been increasing over time; however, project area has not increased at the same rate as installed capacity, since higher-rated capacity turbines enable additional nameplate capacity without the need for new turbines (Rodrigues *et al*. 2015). The authors also examine potential drivers for establishing multi-terminal direct current (MTdc) networks in the North Sea, exploring the synergies between different energy carriers and markets (e.g. wind and ocean energy, and oil and gas markets) (Rodrigues *et al.* 2015). In addition to the relative price of energy sources (i.e. techno-economic factors), "institutional, behavioural and social factors" may slow the pace of RETs and if political action is delayed such factors are likely to have a greater impact on the feasibility of reaching climate mitigation targets (Iver *et al.* 2015). Iver *et al.* (2015) also highlight that constraints on the expansion of RETs (as well as carbon capture storage (CCS)) are more impactful than for older technologies with larger capacity baselines such as nuclear and bioenergy.

Akbari *et al.* (2019)[37] use the number of turbines, cost, distance to shore, and area of OWFs as input variables, and connectivity to population centres, electricity production and water depth as output variables to carry out "a cross-European efficiency assessment" (Belgium, Denmark, Germany, the Netherlands, and the UK). While Borrmann et al. (2018) analyse capacity densities for OWFs in Europe's lead markets (Belgium, Denmark, Germany, the Netherlands, and the UK), identifying differences between projects located in the North Sea and the Baltic Sea regions. Differences in capacity densities can be partly explained by respective regulatory frameworks as defined by national authorities, highlighting how "capacity density choice is not a purely *techno-economical* decision" (emphasis added) (Borrmann *et al.* 2018). OWFs in Belgium and Germany are shown to have the highest capacity densities while "turbine spacing shows to be the dominant

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[37] Applying the Data Envelopment Analysis (DEA) Method.

driver of capacity density" in the Baltic Sea (Borrmann *et al.* 2018). Additionally, Hong and Möller (2011) emphasize the importance of "technical, spatial and economic constraints" using a GIS-based approach to evaluate offshore wind resources in the Chinese EEZ.

The International Energy Agency's Wind Technology Collaboration Programme (IEA Wind TCP) recently conducted an international comparative analysis of the offshore wind sector, assessing "the physical site characteristics, technology choices, and regulatory context driving levelized cost of energy" in seven key markets[38] (Noonan *et. al* 2018; MacKinnon *et al.* 2019). LCOE is a key indicator for calculating offshore wind costs throughout a project's lifecycle, equivalent to the discounted lifetime cost divided by discounted lifetime generation (i.e. total cost of developing and operating an OWF divided by total electricity generation, properly discounted) (IRENA 2012). The study finds that falling trends in the LCOE are linked to the following aspects of "innovation and market maturity:" larger turbines, higher capacity factors, longer life of assets, autonomous inspective and predictive maintenance, several large owner/operators competing for market dominance[39] and lower Weighted Average Cost of Capital (WACC) (Noonan *et. al* 2018).

Sovacool and Enevoldsen (2015) pivot away from the national level to analyse offshore wind energy innovation from the corporate perspective through the lens of Vestas and Siemens Wind Power (SWP); seeing the intrafirm level as woven together by 'seamless' interconnections across "technical, social, political, institutional, and economic" dimensions of the socio-technical system. The study places a focus on the cultural dynamics of innovation at the corporate level, dissecting the respective technological management strategies of each firm in the context of turbine development (Sovacool and Enevoldsen 2015). Finally, the INNOPATHS project[40] (2019) examines "historical dynamics of technology diffusion" across a range of sectors including the renewable energy sector. The chapter on wind (and solar) energy involves fitting data to logistic curves to gauge insights into the feasibility of future deployment scenarios (INNOPATHS 2019). When comparing wind energy technologies, the authors find that offshore wind diffuses faster than onshore wind, while also speculating on two conceivable possibilities: (1) offshore wind may saturate at a lower level; or (2) it may possibly surpass onshore wind, depending on how fast OWFs scale-up and increase in size over the next decades (INNOPATHS 2019).

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[38] Belgium, Denmark, Germany, Japan, the Netherlands, the United Kingdom, and the United States.

[39] With increased interest in 'wind farm clusters' and 'multi-wind farm offshore bases' (Noonan *et. al* 2018).

[40] Innovation pathways, strategies, and policies for the Low-carbon Transition in Europe.

2.10 Summary

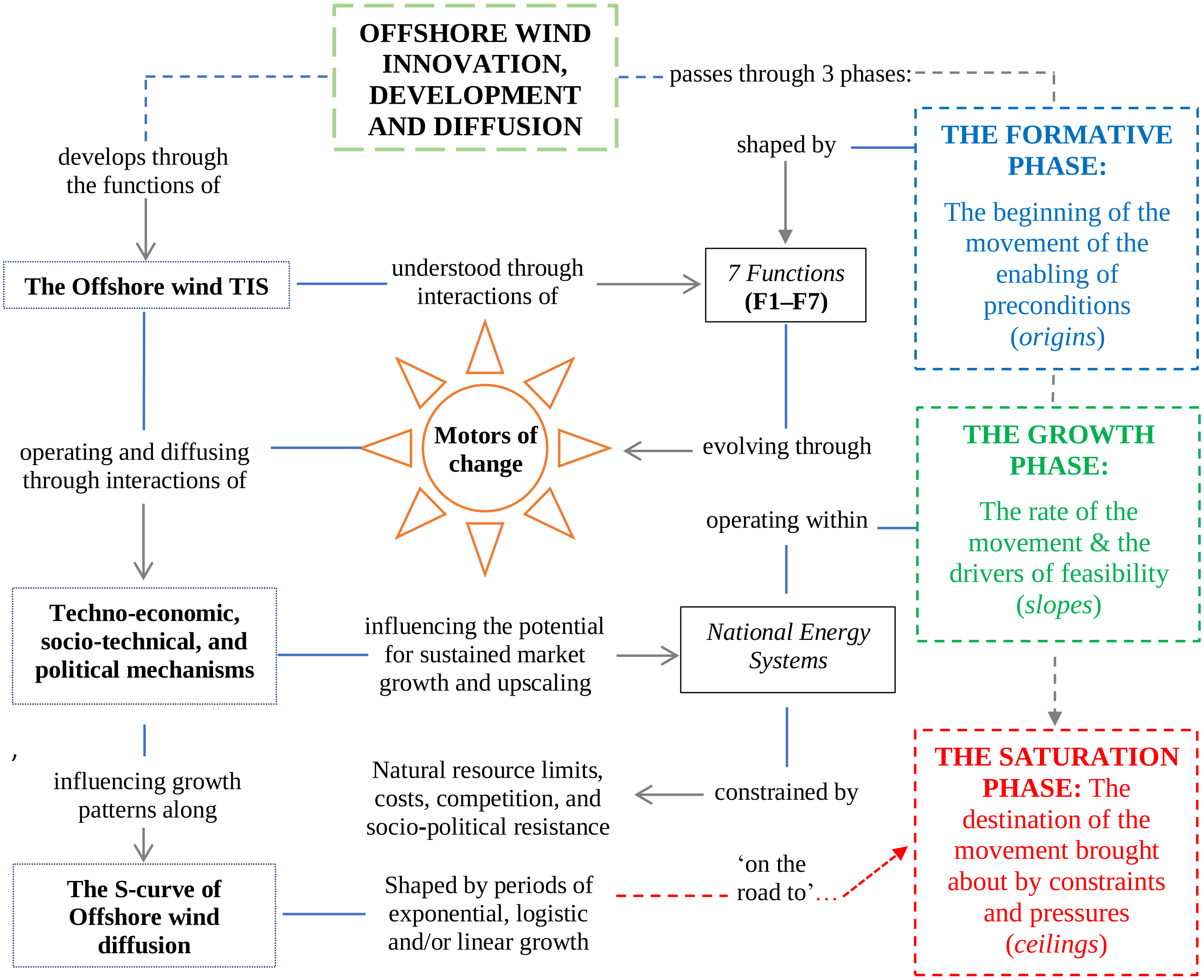
The literature review has chartered major developments in technology and innovation theory, highlighting key the emergence of the Technology Innovation System (TIS) as a leading framework that departs from linear models of diffusion. Additionally, it has been shown that offshore wind diffusion remains underexamined in the literature, as roadmaps typically subsume offshore wind into the renewable energy or wind energy discussion, leaving the parameters of is growth potential unverified. To this end, feasibility studies are required, but first roadmaps and targets must be firmly in place for assessing. Figure 2.4 provides a starting point for situating offshore wind energy within its target range, which can be compared to the ambitions of the North Seas Energy Cooperation (NESC). It has been demonstrated that offshore wind power is driven by political commitments, techno-economic characteristics, and technology clusters that shape around its socio-technical system. To evaluate the feasibility of offshore wind growth, in addition to disseminating these driving mechanisms, growth parameters can be modelled to assess if the technology is growing exponentially or closer to reaching its ceiling along the S-curve of technology diffusion (i.e. logistic growth). Finally, the literature review draws attention to the barriers that may block the development of offshore wind power, flagging constraints and pressures that will need to be resolved if the technology is to diffuse at scale

3 Theoretical and Conceptual Framework

3.1 Introduction

This chapter develops a conceptual framework based on three theoretical pillars, which provide the toolkit for engaging with the research problem. The theoretical framework rests on “the (…) principles, constructs, concept, and tenants of a theory,” serving as a ‘blueprint’ for the research objectives (Osanloo and Grant 2016). The conceptual framework (see Figure 3.1.) houses an integrative approach (Adom *et al.* 2016; Liehr and Smith 1999), which synthesises the theoretical pillars that represent the key variables and presumed relationships at hand, while reflecting the logical steps behind the research process (Miles and Huberman 1994; Ravitch and Carl 2019).

Figure 3.1. The conceptual framework of Offshore wind diffusion



Source: Author’s illustration based on Hekkert *et al.* 2007; Cherp *et al.* 2018; Griliches 1957

3.2 Theoretical pillars

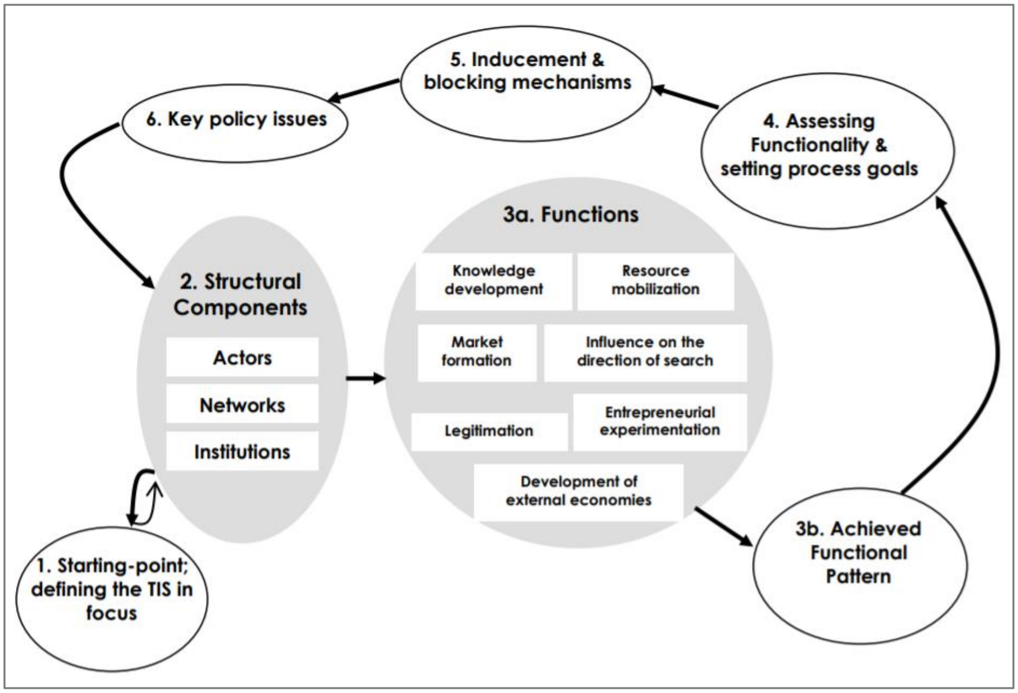
3.2.1 Pillar 1: The Technology Innovation Systems framework

Scholars have come to reject one-dimensional theories of innovation and technology diffusion rooted in neoclassical economics, in turn embracing dynamic, non-linear models to better comprehend "processes underlying innovation, industrial transformation and economic growth" (Bergek *et al.* 2008). The technology innovation system (TIS) framework has risen to prominence to help systematically map such processes, as justified by Hekkert *et al:*

> …technological change is a dynamic process requiring a transformation of the innovation system…a dynamic innovation system approach is needed to understand and…guide its direction (2007).

Actors, networks, and institutions constitute the structural components of the TIS (Bergek *et al.* 2008). Beyond the structural core of the TIS lie specific functions or processes, which relay the operational patterns of the system (Bergek *et al.* 2008). These processes are assessed normatively to identify the respective mechanisms driving or constraining technology diffusion. Policy measures can then be formulated to address constraints or to further enhance drivers (Bergek *et al.* 2008). While the TIS is subject to dynamic relations, operating through the interactions of its various components, the links in the chain can be simplified sequentially as shown in **Error! Reference source not found.**.

Figure 3.2. Key steps in the Technology Innovation Systems framework



Source: Bergek *et al.* 2008

The TIS method "can be characterized as a non-linear process analysis or history event analysis" used to explain innovation diffusion and technological development in interaction with the surrounding political, economic, and social environment (Hekkert *et al.* 2007). Activities contributing to innovation and technology diffusion and are categorized as 'functions' within the TIS framework (see Table 3.1). (Hekkert *et al*. 2007

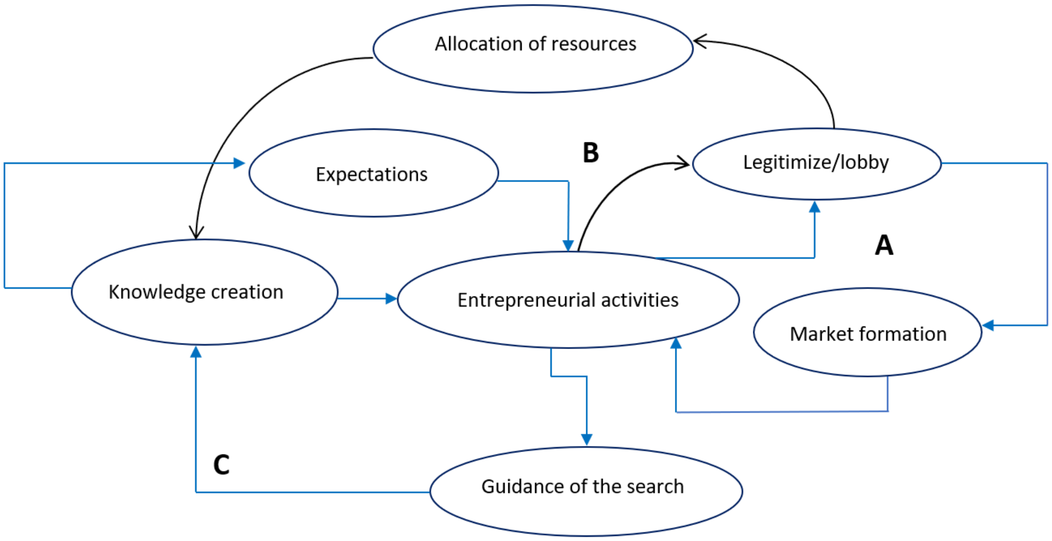
Table 3.1 The seven functions of the Offshore wind TIS framework

Function type	Application
F1 **Entrepreneurial activities**	Entrepreneurial activities involve company engagements in projects, high technology level readiness level product testing, diversification into new industries, new entrants, and commercial activity. Entrepreneurs seek to convert the potential of new knowledge, networks, and markets into actionable market opportunities.
F2 **Knowledge development**	Knowledge development occurs in private in-house R&D departments or in publicly funded research institutes or universities. The focus is on basic research and low-technology readiness levels.
F3 **Knowledge diffusion**	Diffusion through exchange of information via networks, partnerships, and shared project experience/collaboration, helping to foster learning-processes.
F4 **Guidance of the search**	Those processes that establish a clear development pathway and long-term objectives for the new technology based on technological expectations, articulated user demand and social discourses. The search originates from both the government in the form of discourse and policy visions/targets, and company/private sectors visions to guide the distribution of key resources.
F5 **Market formation**	The creation of viable markets for the new technology set by government market policy, tax exemptions, market regulations and consumer and private sector demand. Formation may begin with a small niche market but later requires market expansion to secure cost reductions and incentives for investment and further entrepreneurship.
F6 **Resource mobilisation**	The financial, human, and physical resources for scaling up technology and industry, including government funds supplied for R&D and market subsidies, as well as private investments in human and financial resources.
F7 **Legitimacy/counteract resistance to change**	Legitimacy is driven and supported by the government, consumer acceptance and private lobbying activities. A certain level of legitimacy is required for actors to commit to the new technology, execute investments and take adoption decisions.

Source: Wieczorek *et al.* 2013; Reichardt *et al.* 2016; van der Loos *et al.* 2020

The seven TIS functions are inherently interrelated with specific functions acting as levers or "motors of change" within the system (Hekkert *et al.* 2007). Hekkert *et al.* 2007 illustrate three initial patterns triggering a "virtuous cycle" for technology diffusion (see fig. 3.3). Entrepreneurs can seek political backing to increase R&D funding during the early formative phase (**Motor B**), or lobby for stronger support and better conditions in favour of market formation, in turn counteracting resistance to change (**Motor A**). The guidance of the search (F4) helps to mobilse additional resources, in turn boosting knowledge development and the potential for market formation (**Motor C**). Alternatively, Other positive feedback loops are possible, bearing in mind that knowledge creation (F2) is a prerequisite for creating "new market needs and opportunities" en route to establishing legitimacy (Utterback and Abernathy 1975).

Figure 3.3. Motors of change in the Technology Innovation System



Source: Hekkert *et al.* 2007

3.2.2 Pillar 2: The 'three perspectives framework'

Following the "three perspectives framework on energy transitions" presented by Cherp *et. al* (2018), there are three types of co-evolving systems in which national energy transitions take shape: techno-economic systems; socio-technical systems; and systems of political actions and institutions (Cherp *et al.* 2018). In turn, the interplay between respective mechanisms within each system also shapes individual branches of the energy transition such as the uptake of offshore wind power. Taking an individual RET as a microcosm of the energy transition, offshore wind deployment and diffusion can be viewed through the lens of the three perspectives framework:

(1) Techno-economic mechanisms linked to energy flows: originating with the harnessing of offshore wind resources, subsequent conversion into electricity production, and final end-user consumption, as coordinated by energy markets.

(2) Socio-technical mechanisms linked to R&D, innovation, and industrial performance: established through knowledge, practices and networks associated with the offshore wind supply chain and complementary technologies.

(3) Political mechanisms linked to the institutional environment and the regulatory setting: influencing offshore wind-related planning decisions, policies, and targets in the wider context of National Energy Climate Plans (NECPs) and National Renewable Energy Action Plans (NREAPs).

It can be surmised vis-à-vis Cherp *et al.* (2018) that flows of offshore wind power (production and consumption) are determined by mechanisms influencing technological change and transformation, the coordination of electricity markets, and the subsequent distribution of offshore wind power to consumers; as governed by respective policies regulating the underlying socio-political fabric of the national energy system.

Techno-economic mechanisms set the stage for the uptake of RETs such as offshore wind, shaped by (energy) resources, services, demand, infrastructure, and prices (Cherp *et al.* 2018). In turn, policy-dependent and policy independent factors influence the diffusion of offshore wind power. For example, wind speed represents a policy independent factor since it is a natural characteristic that is uncontrolled for,[41] influencing internal factors such as efficiency (capacity factors) and costs. Furthermore, electricity demand is dependent on a combination of dynamic factors, determined by “the functioning of the system and values,” shaped by the simultaneous interaction of techno-economic, socio-technical, and political mechanisms (Shalabh 2020).

3.2.3 Pillar 3: The S-curve theory of technology diffusion

The S-curve theory of technology diffusion is represented by a logistic curve, defined by an extended period of slow growth as the technology enters the market as a new commercial

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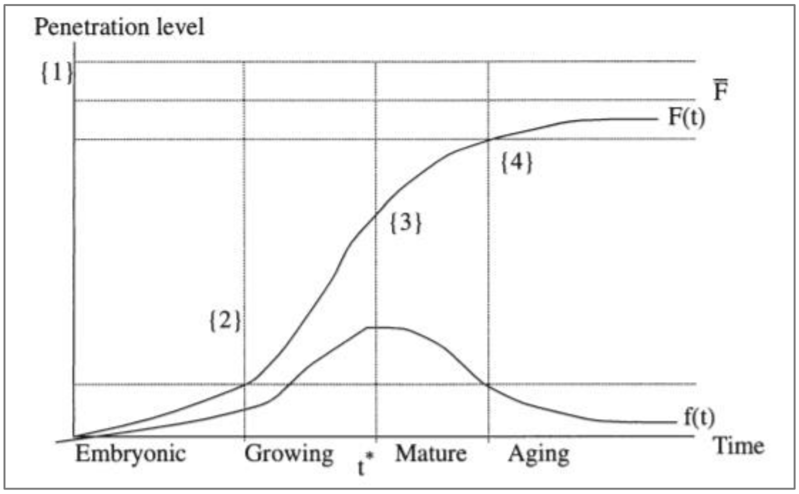
[41] It is only indirectly influenced by external factors (i.e. human interference) in the sense that wind farm developers choose optimal zones for situating turbines; however, they have no direct means to ensure desired wind speeds.

application, followed by phases of exponential acceleration, slowdown and saturation (Grübler *et al.* 1999).

Figure 3.3 presents the main components of standard diffusion models.

Figure 3.3. The components of diffusion models under the Logistic curve



Source: Jaakkola 1996

The model parameters can be explained as follows, according to Jaakkola (1996):

f(t)=non-cumulative adoption function; *diffusion function*

F(t)=cumulative adoption function; *adopter (distribution)* function

$\widetilde{\mathbf{F}}$=potential adopter population (most of the models presuppose a fixed potential of adopters during the adoption period)

(1) *the whole population* in which the potential adopter population is a subset.

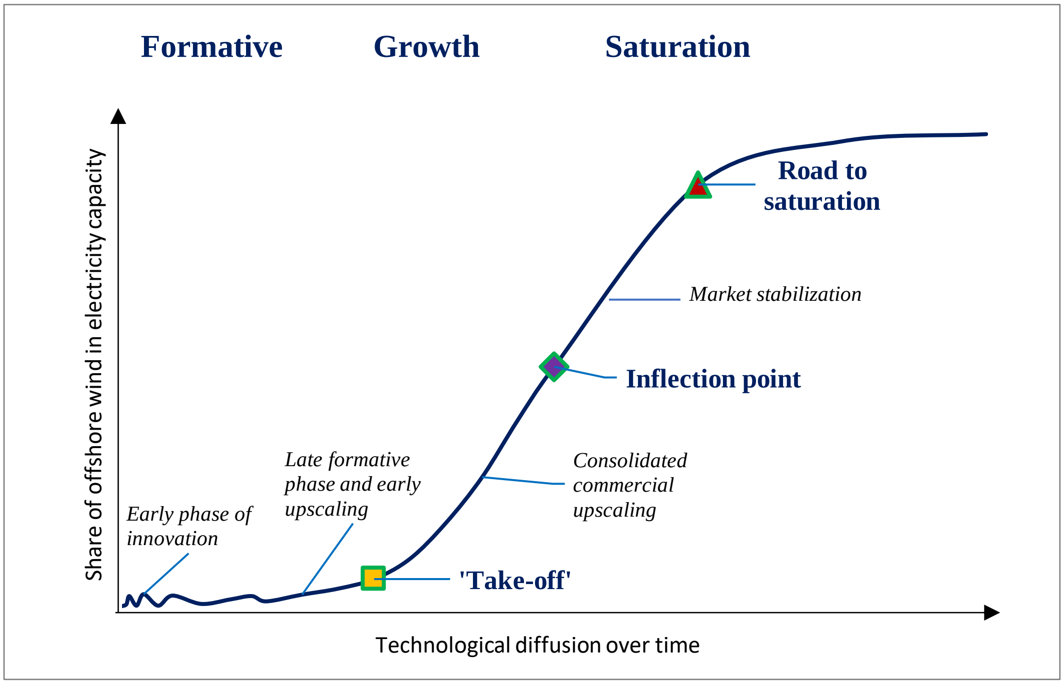
(2) the *lower threshold level* of penetration; if a substitution has progressed to this level it will proceed to its completion; practically, the threshold level is 10% of the potential, and the behavior of the diffusion process before this point is irregular (Fisher and Pry 1972).

(3) *on the inflection point* t=t*, f(t) has its maximum value and the first-degree derivative of F(t) will change from positive to negative.

(4) the upper threshold level, *maturation level*; after reaching this level of penetration, the process is practically finished and the behavior of the rest of the population is not regular and exactly modellable (Jaakkola 1996).

Jaakola (1996) presents the logistic curve according to the "embryonic, growing, maturing and aging" stages. The diffusion rate is measured as the slope coefficient of the logistic or the time it takes to move from one level of penetration to another (Van den Bulte 2000). The slow growth witnessed in the embryonic stage corresponds to the formative phase of technology diffusion; leading to the growth phase as characterized by fast uptake and subsequent stabilization and finally, saturation ('aging') as the technology reaches maturation. The three phases of the technology cycle for offshore wind power – formative, growth and saturation (see Figure 3.4) – can be demarcated according to what Griliches categorized as "origins, slopes, and ceiling," corresponding to "the beginning of the movement, its rate, and its destination" (1957).

Figure 3.4. The three phases of the Offshore wind technology cycle



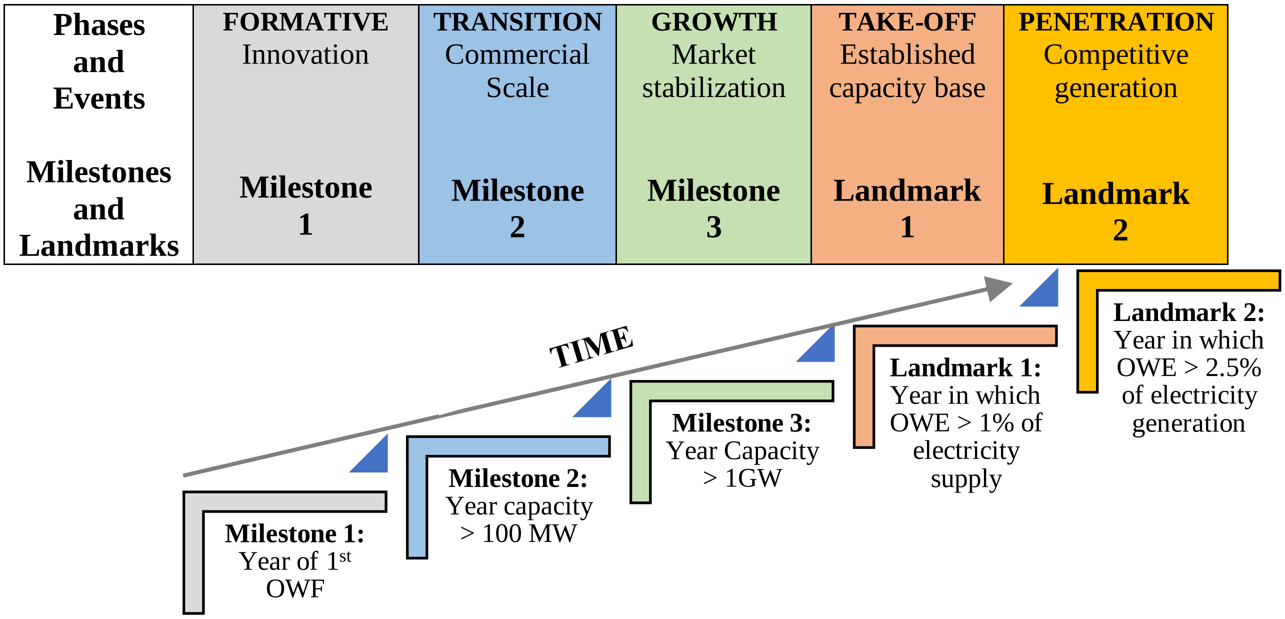
Source: Author's illustration based on Vinichneko *et al.* 2020

Following Vinichenko *et al.* (2020), the formative phase is defined by learning and experimentation with the backing of R&D policy support. This phase is inhibited by extreme levels of uncertainty and high costs, which constrain the potential for early upscaling and market formation. Thereafter, the growth phase gathers momentums as increasing returns kick in, leading to economic profitability and political legitimacy for continued growth and further upscaling. As offshore wind moves beyond its early niche, it may encounter resistance from incumbent actors representing the interests of conventional energy sources. However, once offshore wind growth passes the inflection point – where the maximum growth rate is reached – the regime stabilizes and locks-in. Growth levels are constrained by techno-economic factors such as grid integration and resource limits. Socio-political pressures such as environmental concerns or regressive pricing policies may also bring about saturation and resistance, accelerating ‘the road to saturation.’

3.3 Conceptualizing the development and diffusion of offshore wind energy

The formative phase, also commonly referred to as the innovation or development phase, begins in earnest when a country connects its first offshore wind turbine to the electricity grid. Under the *Milestones and Landmarks Framework* (see Figure 3.5.), this event is labelled as **Milestone 1**. Prior to this milestone, countries typically pass through a ‘pre-development’ phase in which extensive R&D and experimentation lays the stage for moving from the ‘test lab’ to the real world. The pre-development stage typically shortens as diffusion takes place, since new adopters no longer need to dedicate extensive resources and time to achieving innovative breakthroughs. The same principle generally holds true for the formative phase, as dominant designs are established making technological uptake more readily accessible and achievable beyond the core.

Figure 3.5. The Milestones and Landmarks Framework for Offshore wind diffusion



Phases and Events	**FORMATIVE** Innovation	**TRANSITION** Commercial Scale	**GROWTH** Market stabilization	**TAKE-OFF** Established capacity base	**PENETRATION** Competitive generation
Milestones and Landmarks	**Milestone 1**	**Milestone 2**	**Milestone 3**	**Landmark 1**	**Landmark 2**

The formative phase is typically characterized by extended trends of erratic growth, although smoother and quicker growth patterns are also possible. Next, a country reaches **Milestone 2** once it passes the 100MW of installed capacity level, signalling the transition towards commercial-scale deployment. Thereafter, **Milestone 3** corresponds to breaking the 1GW threshold, acting as a marker for measuring levels of early upscaling. This milestone will typically be reached quicker by larger countries such as the UK and Germany than smaller market players such as the Netherlands or Belgium. Alongside three specific milestones, countries should achieve two distinct landmarks as their offshore wind market grows towards a meaningful level on the national scale.[42] **Landmark 1** occurs when a country reaches 1% share of offshore wind in its electricity capacity, marking the 'take-off' for offshore wind diffusion and the end of the formative phase. This event is closely correlated to achieving **Landmark 2**, which corresponds to reaching a 2.5% share of national electricity generation from offshore wind. As such, Landmarks 1 and 2 provide a relative measure of how offshore wind performs at the level of the national energy system, whereas Milestones 1–3 are closer to absolute markers of deployed capacity (scaling up ten-fold). The timing of achieving Landmarks is directly determined by national characteristics.

3.4 Summary

This chapter has presented a conceptual framework for explaining the **parameters** (i.e. the beginning of the movement, its rate, and its destination), **processes** (TIS functions 1–7), **mechanisms** (techno-economic, socio-technical and political), **phases** (formative, growth and saturation) and **key events** (i.e. Milestone and Landmarks) of offshore wind deployment and diffusion. In the beginning of the movement – the formative phase – offshore wind is developed and deployed according to the interactions between functional components of its Technology Innovation System (TIS); as the 'guidance of the search' for market formation takes grip, leading to 'take-off' under favourable conditions. Subsequent deployment potential is a result of co-evolving techno-economic, socio-technical, and political mechanisms, which together dictate the rate of growth and the scope for upscaling. The rate of the movement along the S-curve conforms to patterns of exponential, logistic and/or logistic-linear growth; culminating in the saturation phase when growth ceases due to techno-economic and socio-political constraints. In the case of offshore wind, saturation pressures remain in the (distant) future for the most part, whereas onshore wind has already faced prolonged stagnation episodes across leading European markets (see section 5.2).

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[42] Other milestones can be added such as 5GW and 10GW capacity etc. as the offshore market grows. Similarly, different milestones may prove appropriate depending upon the size of the country's electricity capacity etc.

4 Methods and Research Design

4.1 Introduction

The research design applied in Chapters 5 and 6 can be simplified into two respective stages. The first stage consists of analysing past trends of offshore wind power to identify the driving factors (TIS functions) behind the processes of early market formation, and the causal mechanisms influencing the rate and scale of deployment, as represented by observed diffusion patterns. The second stage assess the feasibility of national offshore wind targets. Feasibility is examined through national case studies within a Structured, focused comparison of Europe's frontrunner countries. Each country's deployment timeline for 2030 is tested against pathways of exponential, logistic and linear growth. Testing the parameters of growth potential at the national level provides the basis for gauging the feasibility of the NESC 2030 target of 76GW. The implications of achieving 2030 targets for future growth pathways through to 2050 is also considered. A mixed-methods study design is adopted. The methodology is further discussed in this chapter.

4.2 Overview of research design and methods

Results are derived from three main sections which link to the theoretical pillars in Chapter 3:

1. Identification of the factors driving the early uptake of offshore wind; informed by analysis of wind energy markets and the dynamics of market formation, supported by linking **TIS functions** to key offshore wind **Milestone and Landmarks** (conceptual framework).
2. Analysis of the main causal mechanisms (techno-economic, socio-technical, and political) determining the growth of offshore wind offshore wind in the electricity system, within the context of national energy transitions, vis-à-vis the '**three perspectives framework**.'
3. Feasibility assessment of 2030 national targets and indications for Europe's cumulative offshore wind targets, as well as implications for 2050; determined by past and emerging growth patterns, country-level characteristics, and interactions across Northern Europe's offshore wind hub, examined through the **S-curve theory of technology diffusion**.

Chapter 5 contextualises the study at the broader level beyond events in Europe's frontrunner markets (Belgium, Germany, Denmark, the Netherlands, and the UK). In addition to disseminating key events surrounding the early market formation of offshore wind, developments in onshore wind are reviewed to provide an additional comparative perspective. The relationship between onshore and offshore wind is a thematic element of the study, crucial for analysing emerging trends in electricity supply and demand, and the interactions between energy sources. Chapter 5 provides the building blocks for conducting a structured, focused comparison of Europe's frontrunner markets. The "method and logic of *structured, focused comparison*" is essentially eponymous: the method must be *structured* to each case, asking the same questions in line with the research objective and theoretical focus to enable "systematic comparison and cumulation" of the results; and *focused* in that it carefully selects the most relevant aspects of the case history (George and Bennett 2005). Chapter 6 is constructed according to which country deployed offshore wind earlier: DK, NL, UK, DE, and BE. This approach adds to the narrative structure of the chapter, which sets out to relay key diffusion processes and mechanisms of growth, before assessing the feasibility of 2030 national and European targets.

Methods for market analysis

Market analysis in regard to key wind energy trends was carried through a literature review of a range of key sources: The International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), WindEurope, MarketsandMarkets™ and supporting reports and databases. The aim in this section was to chart the shift from land to sea, as onshore wind stagnates in key markets while offshore wind booms across Northern Europe. In additon to the European picture, the global persepctive is provided, reported mostly in the Appendices. The principle here it to contextualise European wind in the global market and to evaluate respective growth trends over the last decade. An emphasis is placed on highlighting the territorial diffusion patterns of offshore wind and the corresponding market shares, as well as shares in electricity generation for a comparative overview.

Methods for Milestones and Landmarks Framework

The Milestones and Landmarks Framework constitutes a novel conceptual contribution of the thesis. To the author's knowledge, no such approach has been applied to the offshore wind sector and this terminology/classification is not found within the energy literature.[43] The framework is built upon the fundamental truth that all growth involves key events and phases, which can be categorised respectively. The choice between using 'milestones and landmarks' or the reverse order is of little significance here; critically the merging of the two terms into one unit of conceptual

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[43] It is recognised that similar approaches may exist elsewhere in the literature, but these have not been observed by the author at the time of writing.

analysis provides a means to demarcate moments (i.e. readily captured spatiotemporal events) that signify a change to the narrative.[44]

Milestones require no further method than reference to energy databases to confirm the year in which a country connects its first offshore wind turbine to the electricity grid, transitions to 100MW of installed capacity and scales up to 1GW. Other milestones can be conceptualised depending on the case; thus, the method is malleable and additional milestones can be incorporated to match the scale of analysis. Landmark 1 requires a straightforward calculation for any given year:

$$\frac{Installed\ offshore\ wind\ capacity\ (GW)}{Total\ installed\ electricity\ capacity\ (GW)} \times \frac{100}{1} = Capacity\ share\ of\ offshore\ wind\ (\%)$$

Landmark 2 follows the same logic:

$$\frac{Generation\ of\ electricity\ from\ offshore\ wind\ (TWh)}{Total\ \ electricity\ generation\ (TWh)} \times \frac{100}{1} = \ Generation\ share\ of\ offshore\ wind\ (\%)$$

Methods for Technology Innovation System narrative

The starting point for each country case study is an analytical narrative examining offshore wind diffusion through the lens of its Technology Innovation System (TIS). The aim is to provide a ‘story’ behind of the key events behind the early development and uptake of offshore wind through the interaction of TIS functions, especially those that act as ‘motors of change’ toward early market formation. More broadly, the TIS approach identifies what processes determined the *duration of the transition* – from the innovation phase to take-off – vis-à-vis the political landscape and market conditions during the formative phase; examining the role of the government, investment mechanisms, socio-technical networks and other key functions. Within each country case, the focus is on using **process-tracing** to identify the preconditions that determine the early uptake of offshore wind power (**RQ1**). The primary focus is on how the ‘guidance for the search’ to move from small-scale OWPs (niche level) to large-scale OWFs (commercialisation) was achieved in each country and how this evolution shaped emerging developments and targets.

The process tracing method strives to “identify the intervening causal process – the causal chain and causal mechanism – between an independent variable (or variables) and the outcome of the dependent variable” (George and Bennet 2005). In this thesis, the dependent variable is represented by offshore wind growth as a percentage of installed electricity capacity, in addition to recording

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[44] This kind of thinking is espoused in narrative theory, striking a chord across other disciplines (i.e. philosophy).

absolute installed capacity over an annual timeframe. National cases are then examined in relation to respective techno-economic, socio-technical, and political mechanisms, which serve as proxies for independent variables. Process tracing is committed to "taking temporality seriously" (Büthe 2002), internalizing 'time' as a contributory factor to "causal pathways and feedback processes" (Trampusch and Palier 2016); offering "a fundamental tool" for conducting qualitative analysis (Collier 2010) by testing theories using observations within individual cases (Van Evera 2015; Hall 2008).[45] Accordingly, the TIS narrative lens focuses on "systematic and rigorous qualitative analysis" to decipher the links between "causal factors, events, sequences and outcomes," across the offshore wind chain, thereby "unpacking causal and temporal mechanisms" behind observed phenomena (Trampusch and Palier 2016).

Scholars have further sub-divided process tracing into specific branches. Falleti defines the method of theory-guided process tracing (TGPT) as "the temporal and causal analysis of the sequences of events that constitute the process of interest" (2016). Successful application of the TGPT method requires in-depth insight into socio-political phenomena to identify "feasible causal mechanisms" capable of explaining "complex causal relationships" involving "multiple causality, feedback loops, path dependencies, tipping points, and complex interaction effects" (Falleti 2006). This description is a direct fit to the subject matter of this thesis.

When applied to the case of a structured, focused comparison (**Chapter 6**), the TGPT approach enables hypotheses and theories to be formally tested (Falleti 2006). Blatter and Haverland describe the 'causal-process tracing' (CPT) method as an approach for revealing "the sequential and situational interplay between causal conditions and mechanisms in order to show in detail how these causal factors generate the outcome of interest" (2014). As such, the CPT method is centered on answering the 'why' and 'how' behind observed phenomena, serving as 'a within-case' method of analysis linking "processes and/or mechanisms" to "the causes and the effects within specific cases" (Blatter and Haverland 2014). Waldner (2015) comments how the within-in case approach allows the process tracing method to elevate "internal validity over external validity," allowing for the generation of robust, in-depth explanations (Waldner 2015).

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[45] Waldner (2015) further comments how a 'longitudinal research design' based on data derived from sequential events can be "represented by non-standardized observations drawn from a single unit of analysis."

When dealing with a small-N study, the CPT approach strives to provide a “comprehensive storyline,” presenting relevant causal mechanisms in a ‘narrative style’ that differentiates key events (i.e. **Milestones and Landmarks**) to identify critical junctures that shape subsequent outcomes (Blatter and Haverland 2014). Analytical narratives play a key part in understanding dynamic processes and testing causal arguments (Büthe 2002) and prove especially valuable for examining “explanations for historical processes with an important temporal dimension;” providing the means to integrate “nuanced detail and sensitivity to unique events” (Büthe 2002). Furthermore, multiple narratives strengthen the validity of the approach by improving the likelihood that dynamic processes are legitimately captured, in line with “a scientific causal explanation of historical processes” (Büthe 2002). This final point is critical because while the analysis centers on different countries as well as their combined impact – taking Northern Europe’s offshore hub as a singular socio-technical system – it likewise compares events across different time periods according to the three phases of the offshore wind technology cycle (Figure 3.4).

Methods for national energy transitions analysis

To situate wind energy in its proper context, two levels of analysis were specifically chosen to illustrate the evolution of offshore wind power in the electricity system and as part of national energy transitions: **(1)** dynamics of electricity generation; and **(2)** dynamics of electricity capacity. The former serves to make explicit the share of offshore wind in the electricity system (% of TWh) and how this has changed over a ten-year period (2008–2018), while the latter performs the same function at the level of electricity capacity (% of GW), as this is the unit by which growth targets are measured within this study in line with national policy. However, in part 2 the focus is specifically on comparing levels of onshore and offshore wind capacity to gauge the relationship between the two. The first measure is represented by Landmark 2, while the second measure is represented by Landmark 1. The reverse order is justified here since wind energy must ordinarily climb to 1% of electricity capacity before it can reach 2.5% of electricity generation. Methodologically, it is more fitting to examine the wider context of electricity generation before comparing onshore and offshore wind capacity.

In part 1, the following energy sources were calculated for each country: nuclear (except DK), coal, natural gas, onshore wind, offshore wind, solar PV, biofuels, and ‘other’ sources.[46] The calculations

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[46] Other energy sources include oil, waste, hydro (including generation from pumped-hydro power stations), geothermal, solar thermal and chemical heat. Coal also include peat and oil shale (IEA 2020).

require three basic steps: **(Step 1)** retrieve data on the total size of national electricity generation per year, measured in TWh (retrieved from BP 2019); **(Step 2)** retrieve data on the annual contribution of each energy source (extracted from IRENA Renewable Energy Statistics 2019, IEA Data and Statistics and national databases); **(Step 3)** divide each data point in step 2 by the step 1 (i.e. each energy source by the total to find its share, as performed in '**Methods for Milestones and Landmarks Framework**.' In part 2, the same kind of process was repeated to examine the following parameters: onshore share of electricity (%), offshore share of electricity (%), and offshore share of total wind capacity (%). Each measure was calculated by taking the respective installed capacity for onshore and offshore wind and dividing by total installed electricity capacity. The variables were plotted on primary and secondary axes accordingly (e.g. Figure 6.3.). The same databases were consulted for extracting annual figures.[47] The data results from parts 1 and 2 were then analysed in terms of their underlying trends, with qualitative research vis-à-vis the three perspectives framework used to explain the key findings. Thereafter, techno-economic, socio-technical, and political drivers of offshore wind were further reviewed to support the feasibility of national targets within the national energy transition context.

Methods for fitting growth functions

Fitting growth functions to assess the parameters of future offshore wind deployment pathways stands at the heart of this study, providing the boundaries within which a discussion of feasibility can be pursued and formalized. To perform the feasibility analysis, logistic, logistic-linear and exponential functions were fitted to historical data for offshore wind power in Europe's five frontrunner markets: Belgium, Germany, Denmark, the Netherlands, and the UK

In addition to fitting the empirical data for each country up to 2019 to assess the feasibility of 2030 targets, models were also produced based on the fulfilment of 2030 targets (mapped according to provisional national deployment schedules) to provide a comparative picture for 2050. In total, ten models were produced, two for each country. The first set attests to *time-period 1* (**2030**), and the second set attests to *time-period two* (**2050**). Finally, having tackled the national level, the feasibility of Europe's 2030 target is systematically assessed based on the cumulative growth trends of its five frontrunners projected to 2050. For enhancement, a final growth fit is produced based on data for DE, DK, NL, and UK. Belgium is removed from this final exercise as it has a relatively

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[47] All calculations were performed in Excel and charts were also generated in Excel.

low ceiling for offshore wind expansion (i.e. six times lower than the next frontrunner). This last step (*2 aggregate models*) extends the comparative analysis at the European level by indicating which growth pathway is most feasible and moreover, quantifying the extent to which meeting 2030 targets may impact the parameters of growth potential.

The *nls* function from R programming environment was used to fit growth functions (Bates and Chambers 2017). This implements the Gauss-Newton algorithm to apply least squares fitting to non-linear functions, and the *nlsLM* from *minpack.lm* package was used to implement the more robust Levenberg-Marquardt algorithm (Bates and Watts 1988). This method has been adopted by Vinichenko *et al.* to assess “the worldwide uptake of wind and solar power as a function of distinct causal mechanisms involved in specific technology uptake phases” (2020).

Following Vinichenko *et al.* (2020), data is fitted for the specific purpose of assessing European 2030 offshore wind targets, parametising growth into three tangible pathways, Thus, this method serves as a tool for diagnosing current growth trends against short and long-term targets put forward by policymakers, providing clear indications for 2030 and early insights into diffusion patterns up to 2050. In sum, past events (i.e. annual growth patterns) inform the feasibility of delivering on (future) policy goals (i.e. meeting capacity targets). Three growth functions were fitted to help realise this aim: (S-curve) Logistic function (LOG, **S**); Logistic-linear function (LOG-LIN, **L**); and Exponential growth (EXP, **E**). Together, these growth functions provide a means for approximating the potential growth of offshore wind. The remainder of this section explains the components of each function, its relationship to the model and how to interpret the quality of the fit.

Logistic function

The three-parameter logistic growth function is the standard approach for assessing the growth of RETs (see 2.2 and Figure 2.1). These parameters characterize ‘the beginning of the movement, its rate, and its destination’ vis-à-vis Griliches study of hybrid corn (1957):

$$f(t) = \frac{L}{1 + e^{-k(t-t_0)}}$$

Here L is the saturation level (i.e. the asymptote), k is the growth constant and t_0 is the ‘inflection point.’ At t_0, offshore wind deployment reaches half of the saturation level ($L/2$) and growth becomes close to linear before slowing down (i.e. ‘saturating’).

Logistic-linear function

While the three-parameter logistic growth function is a highly valuable modelling tool, it fails to capture more realistic growth patterns that deviate away from the idealized (i.e. symmetrical) S-curve. In most instances, real-world technology diffusion – as witnessed here in the case of offshore wind power – fails to adhere to an exact S-curve, instead abiding by the two 'laws of energy-technology deployment' (Kramer and Heigh 2009). Kramer and Heigh (2009) show that new energy technologies initially grow at an exponential rate until reaching 'materiality,' (**Law 1**) corresponding to approx. 1% of primary global energy consumption. Thereafter, the growth switches to linear until the technology captures its final market share (**Law 2**). Under such conditions, the inflection point will no longer correspond to half (½) of the eventual saturation level. This is typically observable in emerging markets where expansion is pronounced, wherein linear growth reached at the inflection point may continue without plateauing. In this scenario, growth can be represented by a *logistic-linear* function; whereby initially logistic growth switches to near linear growth after reaching its maximum value at the inflection point,[48] thereafter continuing at the same (linear) rate until an indefinite time in the future:

$$f(t) = \begin{cases} \dfrac{L}{1+e^{-k(t-t_0)}}, & t < t_0 \\ \dfrac{L}{2} + Lk(t-t_0)/4, & t \geq t_0 \end{cases}$$

L/2 corresponds to the level achieved at the point where logistic growth switches to linear growth. At *L*/2, the peak growth rate for both the logistic and the logistic-linear function is achieved and calculated as follows: $G = kL/4$. When $t < t_0$ there is an immediate slowdown in the growth rate; however, if $t \geq t_0$ growth is sustained beyond the inflection point. Accordingly, there is no saturation level in this growth model.

Exponential growth

When a technology grows at an exponential rate, there is essentially no 'ceiling' and growth is infinite. There is no saturation level and likewise no observed inflection point or maximum growth rate to report. Here t_0 is selected arbitrarily (e.g. 2019) and *L* corresponds to the level at t_0:

$$f(t) = L * e^{k(t-t_0)}$$

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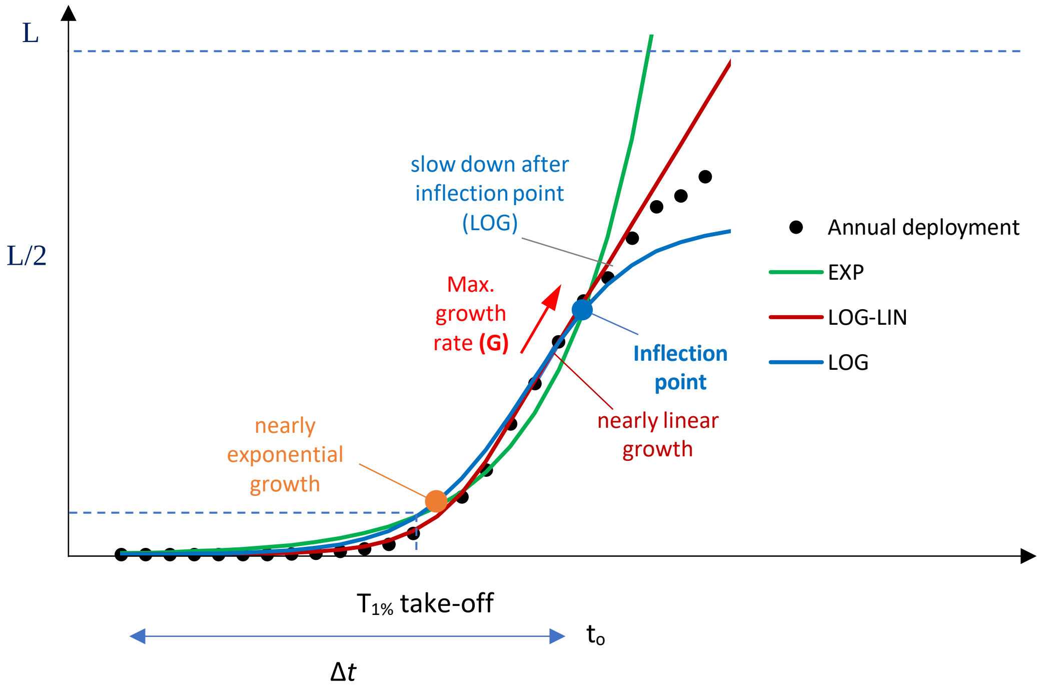
[48] Logistic growth is always higher than for the logistic-liner model.

Figure 4.1. illustrates "the mathematical formalization of the S-curve" of technology diffusion through the three growth functions (Vinichenko *et al.* 2020), where **black dots** represent empirically observed levels of offshore wind deployment. The logistic function (LOG) is fitted to these points and the alternative growth models, logistic-linear (LOG-LIN) and exponential (EXP) are also plotted. Logistic and logistic-linear models can be described by the following markers: '$T_{1\%}$ take-off' which is when offshore wind reaches 1% of national electricity capacity; and 'maximum growth rate, G' which occurs prior to the inflection point (**blue dot**), achieved at time t_0. The inflection point (L/2) corresponds to one-half of 'the destination' for a symmetrical S-curve (Griliches 1957). Δ*t* (delta t) – the time it takes for offshore wind to grow from 0.01L to the inflection point, t_o (i.e. 'the duration of the transition') – serves as an alternative growth metric.[49]

Figure 4.1. Mathematical formalisation of the S-curve according to growth functions



Source: Illustration based on Vinichenko *et al.* 2020

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[49] Δt is useful for comparing divergent "historical technological transitions" to emerging clean energy transitions; it typically corresponds to the time between 10% and 90% of the asymptote. (Wilson et al. 2013). It is less helpful here as the saturation level of offshore wind remains indeterminable and is likely to be decades away.

Application of method

For each frontrunner country, past annual deployment levels were recorded (i.e. black dots) and the year in which offshore wind power reaches 1% of electricity capacity is calculated (i.e. a proxy for 'take-off' at the national level). Categorizing empirical data in this way allows for a clearer separation between the formative phase and the subsequent early growth phase. The time between deployment of the first OWF (or grid-connected turbine) and reaching 1% share of electricity capacity from offshore wind power corresponds to the move from **Milestone 1 to Landmark 1**. This demarcation provides one option for measuring growth rates (i.e. the number of years of the 'transition'). The rate of offshore wind growth is otherwise determined by calculating the annual growth rate at the inflection point. Next, 2030 targets are mapped according to annual deployment plans (i.e. tenders and sub-targets ahead of 2030), and these data points are plotted (**purple dots**) for each country against the three growth curves derived from the empirical capacity data.

Empirical data was recovered from the year in which each country launches its first grid-connected turbine until the most recent year of deployment (2019). However, for methodological purposes, the year in which capacity becomes notable (relative to its subsequent growth trend) was instead taken as the starting point. The rationale behind this adjustment is to minimize the impact of erratic or prolonged episodes of incremental growth during the formative phase, which also includes periods of stagnation in some cases (i.e. Denmark and Netherlands). Implementing this approach provides "an analytical language" and theoretical framework for characterizing dynamic, cross-national differences of offshore wind uptake. In addition to analysing growth levels at the national scale for 2030 and 2050, the method can be extended to evaluate growth potential at the European level. To gauge the feasibility of 2050 growth parameters – as put forward by the European Commission (EC)[50] and other authorities (e.g. IRENA) – the cumulative growth potential of the European frontrunner group was tested against 2030 targets, extending the analysis to 2050 based on the two scenarios previously outlined.

Interpreting the quality of fit

The residual sum of squares (RSS) was used to measure the quality of fit. RSS can be compared for the three functions being fitted to the same set of datapoints, allowing for comparative analysis between different growth curves for the same country; however, RSS is not used as a measure for

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[50] These targets were recently assessed in a feasibility study by WindEurope (Freeman *et al.* 2019).

comparing results between different countries. Only significant differences between RSS should be considered relevant to the results (i.e. tens of percent). For example, if the RSS for two functions is 8500 and 8200 respectively, they fit the data equally well. In this study, the RSS for the three functions was reported in normalized form for each country case: the smallest possible value 1 represents the best value (0 would be a perfect fit), while other values are normalised proportionally, rendering values greater than 1 where applicable (sometimes marginally so and in other instances several-fold). Thus, larger numbers indicate progressively worse growth fits for the empirical data. The range of RSS values across the three functions thereby provides a measure of the quality of fit, however, in some case there is no range since all values may be equivalent to 1.

There are several key variants defined by the relative values of RSS for the three functions, LOG (**S**) LOG-LIN (**L**), and EXP (**E**):

- Cases in which the RSS for S, L and E are close to one another in terms of fit correlates to exponential growth. This includes instances where E is the best fit while S and L also have good fits due to close to exponential growth during the formative phase; or alternatively S and L can be marginally better fits than E.[51]
- If S and L present a similar goodness of fit, but E is significantly worse, then growth is accelerating slower than the exponent. Nevertheless, growth is still accelerating or moving closer to linear growth, however, there is no slowdown at this stage. In cases where S and L have the inflection point in the future, they are essentially the same function at the empirically observed range and will only differ after the inflection point.
- In cases where S in significantly lower (i.e. better) than L, there is pronounced growth slowdown; whereas if L is significantly better than S then linear growth continues far into the future beyond the inflection point, which is where the S-curve would ordinarily start to plateau towards eventual saturation, reaching the ceiling following technology ‘lock-in.’

4.3 Limitations

The modelling component of this study has limitations that may skew results. One key drawback is that the model is sensitive to latter data points with high levels and can even be skewed by a

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[51] However, it is critical to note that if the growth proves to be close to exponential, the estimates of the inflection point and maximum growth rates for S and L are typically far into the future and unreliable.

single last datapoint (i.e. for 2019 in this case). The model deals solely with current deployment patterns and cannot disassociate between OWPs that were deployed in phases or those that have been decommissioned. The former is a significant issue because OWPs are often deployed in waves, which may be restricted to just one or two large-scale projects every few years in small countries, or those with a small EEZ). The model makes no adjustment to episodes of stagnation but rather subsumes all data points on equal grounds. The latter issue makes little significance to the current results as few projects have been decommissioned to date, and only small ones at that, but this should be noted for special cases and more so for future research (see Chapter 7). Special cases of offshore wind deployment may also include pilot projects.

4.4 Summary

The selected methods and the research design are summarized in Table 4.1

Table 4.1. Research design and methods

CHAPTER (Section)	**CHAPTER 5** (5.2 – 5.3) Market dynamics of wind energy	**CHAPTER 6** (5.4) Dynamics of offshore wind diffusion	**CHAPTER 6** Structured, focused comparison of Euro. frontrunners
Qualitative **MIXED METHODS** *Quantitative*	Key events and developments in wind energy markets Annual growth trends, capacity shares and breakdown of market share and position	Key milestones and landmarks of European offshore wind diffusion Duration of the formative phase, timing of ‘take off’ and early growth patterns	Narratives of offshore wind diffusion (TIS framework) Dynamics of national energy transitions; feasibility assessment of 2030 targets based on parameters of logistic, logistic-linear and exponential growth
TASKS AND OBJECTIVES	Define spatial & temporal diffusion patterns of wind energy; define the European offshore wind landscape according to market share & respective country categories; establish the context of the comparative case study at the European level	Delineate phases of offshore wind diffusion (Milestones & Landmarks Framework); illustrate findings at the European level; categorize countries according to their position on the technology frontier (core, rim, periphery)	Identify the main factors and causal mechanisms behind offshore wind growth; situate the role of offshore shore wind in national energy transitions; assess the feasibility of national and European 2030 targets and their implications for 2050

5 Results

5.1 Introduction

Chapter 5 presents the first part of thesis results. Section 5.1 reviews: (1) the core market dynamics of wind energy; (2) the shift from the formative phase to the early growth phase of offshore wind; and (3) respective milestones and landmarks across Europe's frontrunner markets including how these achievements have dictated the growth patterns beyond the national scale. Section 5.2 introduces the general dynamics of wind energy, highlighting the shift from onshore projects to OWFs within the North Sea cluster and around the Baltic Sea. Section 5.3 presents a synopsis of events during the formative phase and early growth phase through the **Milestones and Landmarks Framework**. Having gauged the context of national diffusion pathways and the interactions between Europe's frontrunners, section 5.4 focuses more specifically on the market dynamics of offshore wind and patterns of territorial diffusion. This chapter concludes with an overview of diffusion phases at the European level and a summary of the key findings.

5.2 Market dynamics of wind energy

Offshore wind diffusion has played out in the wider context of shifting dynamics related to global energy markets, renewable energy technologies (RETs) and more specifically onshore wind power in Europe. Behind hydropower[52] and biomass-based forms of power such as cogeneration (i.e. CHP), onshore wind power remains the dominant 'modern' RE technology at the global level, followed by solar PV (Ritchie and Roser 2020; Gosens *et al.* 2017). Onshore wind technologies emerged meaningfully between the 1960s and late 1980s. Niche markets were established in the early 1990s, with dominant turbine designs consolidated between the mid-1990s to early 2000s, as a result of Danish and German innovation (Lema *et al.* 2014). Widespread commercialization and global uptake followed in the mid to late-2000s (Dedecca *et al.* 2016; Vinichenko 2018).

The success of onshore wind has proven crucial to the development of the RE sector at large; strengthening the role of intermittent RESs in the electricity grid while creating new markets based on alternative models of electricity consumption (i.e. 'prosumers')[53] (Holmes and Papay 2011; Schleicher-Tappeser 2012). In the EU, total wind energy met 11.6% (336 TWh) of power demand

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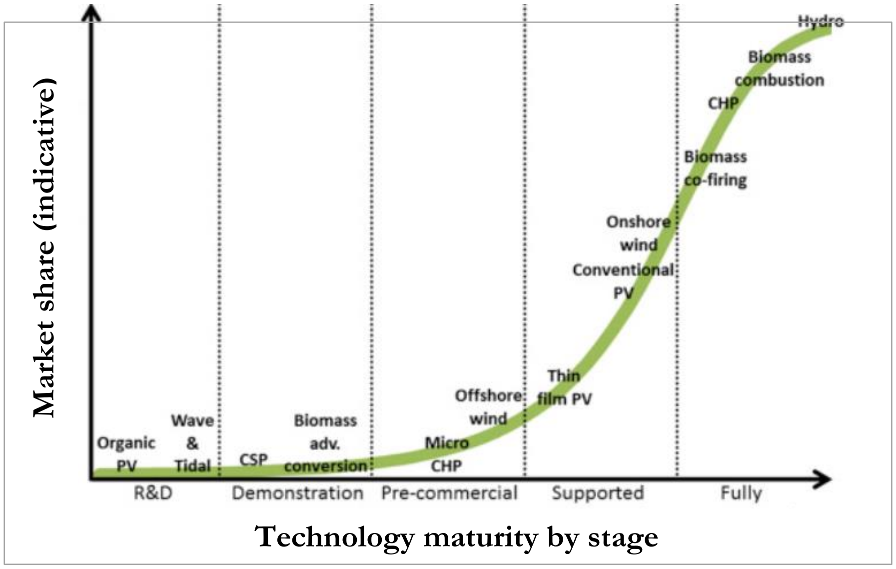
[52] Developed as an economical source of electricity during the late 19th and early 20th century (Deudney 1981).

[53] Prosumers both consumer and produce electricity such as residential owners of solar PV rooftop panels (EP 2016).

in 2017, ranking as "the most competitive source of new power generation" (Hüffmeier and Goldberg 2019). While onshore wind is a mature technology well ahead of most modern renewables on the growth curve, offshore wind has emerged as a rapidly maturing sub-technology that is gaining on competing energy sources (see fig. 5.1.). In retrospect, the technical feasibility of offshore wind power emerged as a spin-off from the onshore sector, which in turn attracted R&D and investment for realising commercialization; principally in high-income European countries with established onshore wind fleets such as Denmark, the Netherlands, the UK and Germany.

Figure 5.1. Market development of maturing RE technologies



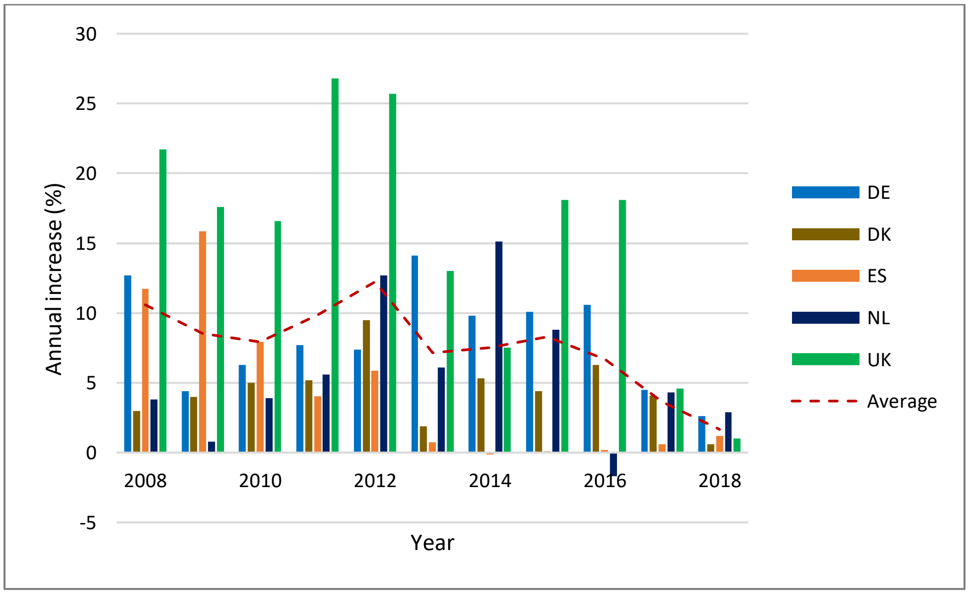
Source: Gosens *et al.* 2017 (based on Foxon *et al.* 2005 and Marigo *et al.* 2007)

5.2.1 Saturation pressures in European onshore wind markets

Onshore wind energy potentials remain vast in many regions around the world including a potential 'untapped' nameplate capacity of 52.5TW in Europe alone (Enevoldsen *et al.* 2019). Between 2010 and 2018, installed onshore global wind capacity grew from 178GW to 540GW, with Europe more than doubling its capacity from 84GW to 179GW (IRENA 2019b). Despite this achievement, onshore wind growth is declining across key European markets (see fig 5.2.) Under current market and regulatory conditions, pioneering countries such as Denmark and Germany are approaching saturation point (Reinhold *et al.* 2016). While Denmark is a relatively small contributor to overall capacity, Germany is Europe's lead market and well ahead of its next competitor Spain.

In some instances, total stagnation has been reached following the enforcement of virtual moratoriums. Most notably, the Spanish wind industry – having once stood as a "global wind power" (López 2018) – came to an abrupt halt in the mid-2010s.[54] The halting of onshore deployment in Spain between 2013–2018 had a significant impact on the competitive landscape of the global wind industry, rupturing supply chains while sending shockwaves to energy companies and policymakers (Backwell 2017). Furthermore, stricter regulatory measures (i.e. planning and approval processes) and public opposition have forced premium sites within permittable zones into short supply (Hay 2005; Sell 2015). As a result, onshore wind is characterized by 'red tape' delays and increased stagnation in European frontrunner markets such as Germany, Spain, Denmark and the UK where most wind turbines are in need of repowering or decommissioning, as they approach the end of their planned service life (Ziegler *et al.* 2018).[55] In the face of global competition, the European share of onshore wind has gradually dwindled towards 30% .[56]

Figure 5.2. Annual increase onshore wind power capacity, 2008–2018



Source: Author's calculations based on IRENA 2019d, 2019e; IEA 2020

5.2.2 From onshore stagnation to offshore maturation

With some of the best offshore wind resources available worldwide – primarily in the North Seas which covers the Baltic Sea and the Atlantic Ocean around France, Ireland and the UK, as well as the North Sea itself – Europe single-handedly built up the offshore wind industry during the 2000s

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[54] In the aftermath of the 2008 global financial crisis, economic instability and a series of policy failures saw capacity additions to the onshore fleet cease altogether (Backwell 2017; IRENA 2019b).

[55] ~ 50% of the EU'S current onshore capacity will reach the end of its operational life by 2030 (Nghiem *et al.* 2017)

[56] The European share fell dramatically as China, the United States and India deployed at scale, with a combined installation of nearly 230GW between 2010 and 2018 (IRENA 2019b).

and early to mid-2010s (Ørsted 2018; Krohn *et al.* 2009).[57] Since launching its first pilot projects during the 1990s, Europe has dominated the offshore wind sector, with "highly concentrated industrial clusters" across the North Sea and Baltic Sea accounting for virtually all deployment up until 2016 (van der Loos *et al.* 2020). Success is perhaps best exemplified by large-scale deployment across the shores of the UK (Whitmarsh *et al.*, 2019). Alongside the UK, Germany has recently become a rival market leader, while Denmark, Belgium and the Netherlands have a combined market share of 20%. The expanding geographic scope of offshore wind illustrates the distinctive "pan-European nature" and the move towards global expansion (Fichaux *et al.* 2009):

> …the different institutional conditions amongst European counties, including differing energy polices, subsidy systems, R&D mechanisms, environmental regulations, and local content restrictions demonstrate that this is truly an international market (van der Loos *et al.* 2020).

The decline in European onshore wind has been partly offset by the growth of its offshore sector. Moreover, the prospect of increased cross-border project activities offers new opportunities for regional cooperation and coordinated policy efforts (i.e. pan-European governance) in accordance to the principles of the EU's Third Energy Package ((Dedecca *et al.*, 2019; Barysch 2011).

5.3 Crossing the formative phase: Time of take-off in Euro frontrunner markets

The Milestones and Landmarks Framework demarcates the key phases and events embedded in offshore wind diffusion and how these respective stages or turning points can be categorized and defined, as outlined in Chapter 3 (see Table 5.1). **Milestone 1** marks the year in which the first offshore wind turbine becomes grid-connected. **Milestone 2** marks the year when capacity reaches 100MW+, while **Milestone 3** marks the year in which capacity exceeds 1GW (i.e. 1000MW). Alongside these three early milestones (e.g. Milestone 4 would correspond to 10GW of installed capacity), two key landmarks should be met to secure offshore wind growth in the electricity system. **Landmark 1** corresponds to the year in which offshore wind reaches a 1% share of installed electricity capacity, while **Landmark 2** corresponds to the year when offshore wind reaches a 2.5% share of electricity generation. The former sees offshore wind 'take-off' in the electricity mix, while the latter corresponds to a subsequent time when offshore wind has achieved a level of 'competitive generation' (see Table 5.1).

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[57] China has become a significant player in the global offshore market, shifting expansion beyond Europe.

Table 5.1. Milestones and Landmarks framework for offshore wind diffusion

Phases and Events **Milestones and Landmarks**	**FORMATIVE** Innovation **Milestone 1**	**TRANSITION** Commercial Scale **Milestone 2**	**GROWTH** Market stabilization **Milestone 3**	**TAKE-OFF** Established capacity base **Landmark 1**	**PENETRATION** Competitive generation **Landmark 2**
Event/ definition	*Year of 1st OWF*	*Year capacity > 100MW*	*Year capacity > 1000MW*	*Year OWE > 1% share*	*Year OWE > 2.5% share*
BE	2009	2010	2018	2012	2014
DE	2004	2011	2014	2015	2017
DK	1991	2002	2013	2002	2005
NL	1994	2006	2017	2015	2017
UK	2000	2004	2010	2009	2013
Range (yrs.)	**17**	**8**	**8**	**13**	**9**
Mean year	**1999.6**	**2006.6**	**2014.4**	**2010.6**	**2013.2**

Source: Author's calculations based on BP 2019; IRENA 2019d, 2019e; IEA 2020

Offshore wind was launched in 1991 at the Vindeby OWF, giving Denmark the mantle of the first country to deploy a commercial OWF (**Milestone 1**). Denmark acted as first mover and lead market at the core of offshore development. In 2002, Denmark became the first country to achieve Milestone 2 while reaching Landmark 1 in the same year with 200MW of installed capacity. By 2005, Denmark was generating 2.5% of its electricity from offshore wind energy (**Landmark 2**), following a doubling of capacity to over 400MW. Meanwhile the UK completed the transition to commercial-scale wind farms in 2004 (**Milestone 2**), while in the same year Germany deployed its first offshore wind turbine at Ems Emden, marking the arrival of Europe's onshore wind giant. While Denmark was the first country to achieve Milestones 1 and 2 (1991 and 2002), as well as Landmarks 1 and 2 (2002 and 2005), the UK became the first country to reach 1GW of installed capacity in 2010 (**Milestone 3**). This milestone will typically be reached quicker by larger countries such as the UK and Germany than smaller market players like the Netherlands or Belgium Denmark followed suit behind the UK in 2013 while Germany hit the 1GW mark in 2014.[58]

In respect to achieving Landmark 1, there was a seven-year gap between first mover Denmark at the heart of the core and the next take-off country, the UK in 2009. In 2012, Belgium joined these

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[58] Germany had an installed capacity of 994MW in 2014, which qualifies as reaching the 1GW threshold (Milestone 3). This is appropriate since Germany then scaled up capacity to over 3GW in 2015, setting it apart from Denmark and on a closer par with the UK, as the second lead market.

two lead markets, as it reached nearly 400MW of installed capacity, comparable to Denmark in 2003. Following Belgian take-off, the next wave of uptake activity at the rim occurred in 2015 with take-off in both Germany and the Netherlands. In all cases, Landmarks 2 is hit two years after Landmark 1, except for the UK which took three years. Consequently, the average year for completing Landmark 1 across the frontrunner group was 2010.6, while Landmark 2 averaged 2013.2. This is a significant finding since it relays a predictive metric for measuring growth at the level of electricity generation for offshore wind power in relation to its installed capacity.

The length of the formative phase – *the time to move from Milestone 1 to Landmark 1* – averaged eleven years across Europe's frontrunner markets. Denmark, the UK, and Germany all had similar lengths for the formative phase, even though they deployed their first offshore wind turbine(s) in 1991, 2000 and 2004, respectively. The Netherlands has been the clear lag market across the group, whereas Belgium secured the quickest take-off. By 2015, the formative phase at the European level ended, signalling the prospect for global diffusion to China and other non-European adopters. Consequently, rim markets have started to form beyond the core of Northern Europe, while operations also continue to intensify within the North Sea cluster.

5.4 Market dynamics of offshore wind

During the formative period, OWFs were generally constructed on the continental shelf, 10 km away from the shore and about 10 m deep (Hay 2005). The late 2000s to early 2010s marked a shift from small-scale projects to commercial projects built further away from shore exceeding 100MW. Consequently, by 2010 European installed capacity reached 3GW, growing to 11GW by 2015 (approx. 95% of global installations).[59] In 2015, Germany became the second lead market behind the UK, growing its capacity from 1GW just over 3GW in just a year. As a result, the UK and Germany made up three-quarters of the European market in 2015 (46% and 30% respectively, followed by Denmark (11.5%) and Belgium (6.5%). The UK and Germany have since maintained their dominance as market leaders, while Denmark Belgium and the Netherlands remain on a similar par to one another, alternating as more modest European frontrunners.

European offshore wind is characterized by a strong aspect of territorial deployment, which has in turn determined its diffusion patterns. The North Sea, the Irish Sea, the Baltic Sea, and the Atlantic Ocean currently make up 77%, 13%, 10% and 1% of European offshore wind capacity, respectively

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[59] Belgium, Finland, and Norway entered the market but only Belgium has proven to be a significant market player.

(WindEurope 2019).[60] By the end of 2019, 5047 offshore wind turbines were connected to the European grid across twelve countries, with its frontrunner markets accounting for 99% of total capacity: the UK (45%); Germany (34%); Denmark (8%); Belgium (7%); and the Netherlands (5%) (WindEurope 2019). Ireland and Finland, along with Sweden, Norway, France, Spain, and Portugal remain at the opposite end of the spectrum – the 'outer rim' and 'periphery' – stuck in the formative phase with limited capacity gains to date. In 2019, Europe's share of global capacity stood at a less dominant but still impressive 80%, following recent large-scale deployment in China

5.5 Summary

Offshore wind has rapidly become more than a niche sub-technology, as it nears 5% of globally installed wind capacity, having been below the 1% mark only a decade ago. Overall, the share of wind energy in total global electricity generation has climbed from 1.7% in 2010 to around 6%; nevertheless, offshore wind contributes just a small fraction to this total (approx. 0.3%), eclipsed nearly twenty-fold by its onshore counterpart (approx. 5.7%) (IRENA 2019b). Given that resource potential is estimated to be close to twenty times present day global electricity demand – equal to a generation capacity of 400,000 TWh/yr – offshore wind power is primed to become "the variable baseload technology of the future" (IEA 2019). The market dynamics described in this section are set to become more prominent in the future, as offshore wind contends for the position of Europe's chief electricity source (IEA 2019). Growth is set to be driven by breakthroughs in transmission and turbine technologies alongside stronger regional governance frameworks (Dedecca *et al.* 2018, 2019), as the offshore grid promises large-scale integration through the expansion of inter-country and island connections (MarketsandMarkets™).

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[60] In 2018, the North Sea accounted for approximately 62% of annual installations in 2018, while the Irish Sea, the Baltic Sea and the Atlantic Ocean made up 15%, 14% and 9%, respectively (Ramirez et al. 2019).

6 Structured, focused comparison of NESC frontrunner countries

6.1 Introduction

This Chapter reports the main results of thesis. It is structured around five country case studies covering the NESC frontrunner group – Denmark, the Netherlands, the United Kingdom, Germany, and the UK – presented according to order of deployment year in line with the narrative texture of the Chapter. The case studies thus form the ‘Structured, focused comparison’ component of the thesis. They are systematically designed to follow a similar flow and logic, entailing the same sections and corresponding selection of figures and tables.

Each country case composes of three key parts. Part 1 describes the early uptake of wind energy through the Technology Innovation System (TIS) lens, fulfilling the main objectives of building an analytical narrative of offshore wind energy diffusion through process-tracing. Part 2 reviews offshore wind at the level of national electricity generation and installed electricity supply, contextualising, and quantifying changes in wind power (primarily offshore) in the wider discussion of national energy transitions. Part 3 assesses the feasibility of 2030 targets by firstly examining techno-economic drivers (distance from the shore, area, and depth of OWPs), alongside political and socio-technical mechanisms behind offshore wind growth. Thereafter, feasibility is assessed in terms of growth parameters according to the modelling method described in Chapter 4. To close each case study, the ‘quest’ to reach 2030 targets is examined and finally, implications for 2050 deployment levels – contingent on the attainment of 2030 targets – are also considered.

Armed with findings at the national context, a comparative analysis is carried out to address each of the research questions (**RQ1 to RQ4**). A separate discussion is developed to flesh out the following areas: **(1)** TIS functions and ‘motors of change’ in the context of early market uptake; **(2)** causal mechanisms of offshore wind growth within the context of national energy transitions; **(3)** current growth rates and deployment patterns across the NESC frontrunner group; and **(4) the feasibility of 2030 targets** and growth prospects for 2050.

6.2 Denmark

6.2.1 Early uptake of wind Danish offshore wind through the TIS lens

Introduction

Denmark is credited as the pioneer of both onshore and offshore wind energy. In 1989, it became the first country to generate 1% of its electricity from wind power (Vinichenko 2018); repeating this feat for offshore wind in 2003 (eight years ahead of the UK). Denmark's success as the first innovator for both technologies is linked to its long history of entrepreneurship and experimentation **(F1)** with wind energy (Vinichenko 2018; Beise and Rennings 2005).[61] In the 1970s, entrepreneurial activities started to facilitate the socio-technical environment for onshore wind uptake (Gipe 1995). As onshore wind made early strides by securing 'technical feasibility' (Myers and Marquis 1969), demand opportunities flowed from high levels of energy import dependence. Energy security pressures motivated the search towards a clean energy transition, with wind power becoming a coup for economic security in the face of the 1973 oil crisis (Gipe 1995).

Building on its onshore success, Denmark became the outright "first mover" in offshore wind (State of Green 2020), launching the worlds' first commercial OWF at Vindeby in 1991; constructed in shallow waters (2.5–5 metres) (EWEA 2011; Ewing 2019). Domestically manufactured 450kW Bonus turbines[62] operated at Vindeby, meeting the annual electricity consumption of 2,200 households (Gottlieb *et al.* 2019) and demonstrating the potential for offshore technologies. Moreover, Vindeby's success contributed to fine-tuning Denmark's offshore wind Research, Development, Demonstration and Deployment (RDD&D) activities **(F1)**, acting as a motor of change for facilitating knowledge development and diffusion **(F2 and F3)**. These processes stimulated the necessary conditions for key learning mechanisms and feedback loops (Metz *et al.* 2007). Consequently, novel offshore wind technologies soon filled a technological niche, as the early stages of market formation took shape **(F5),** ahead of subsequent upscaling (Smith 2004). Furthermore, offshore wind grew from strength to strength following the implementation of a combined "science-technology push" and "market-pull" strategy **(F4)** (van der Loos *et al.* 2020), which acted as a motor of change in support of offshore deployment (van der Loos *et al.* 2020).

Denmark's success is reflected by the fact that it brought online nearly half (6 of 13) of the world's OWFs between 1995 and 2003.[63] In 2001, Middelgrunden (40MW) became the first "utility-scale" OWF (EWEA 2011), commissioned at a cost of EUR 54 million and constructed at twice the size of the world's second largest OWF located in the Netherlands at Irene Vorrink (EWEA 2011; Bilgili *et al.* 2015). Historically, the Danish population has rallied behind the offshore wind

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[61] Since the time of the First World War, 120 Danish energy utilities were providing 3% of national electricity production, operating small windmills of 20 to 35 kW (Beise and Rennings 2005).

[62] Bonus began operations in DK in 1983 but was later acquired by Siemens (DE) in 2004 (The Wind Power 2020a).

[63] Tunø Knob (5MW; 1995); Samsø (23MW) and Frederikshavn (10.6MW; 2003) (Bilgili *et al.* 2015).

industry **(F7)**, setting up cooperatives where mostly local citizens "share expenses and income from a wind turbine" (Larsen and Sørensen 2001).[64] The advent of cooperative ownership models led to increased public support for new projects; by the turn of the century there was "broad acceptance to wind energy in Denmark", with opinion polls showing at least 70% of citizens in favour of wind energy, compared to just 5% against it (Larsen and Sørensen 2001).

By 2003, Danish sites accounted for over 79% of global installed capacity,[65] including the world's two largest projects launched at Horns Rev 1 (160 MW)[66] and Nysted[67] (165.6 MW). The move from the experimentation stage to the advent of dominant design in Europe's offshore wind niche can be largely attributed to Danish entrepreneurship. Denmark became the first country to prove the technical feasibility of large-scale OWFs based on the design of monopile foundations with permanent magnet generators (Dedecca *et al.* 2016).[68] Leading international global diffusion, Danish manufacturers consequently reaped the benefits of a strong "export advantage" for offshore wind turbines and components (Beise 2001). Denmark has dominated export markets for wind turbine generators for over three decades, ahead of its nearest European rival Germany (Beise and Rennings 2005). By the end of 2018, Denmark's flagship company, Vestas, remained the world's leading wind turbine supplier with over 60,000 installations and a total capacity of more than 100GW; supplying more than 20% of global wind installations in 2018 and dominating the industry thanks to its long-standing success and global operations (IRENA 2019b; GWEC 2019b).

As a result of these unique dynamics, Denmark recently set a national record in 2019 by generating 47% of its electricity from wind energy, split between 29% for onshore and 18% for offshore wind turbines (Lewis 2020). The interplay of key functions across the Danish offshore wind TIS enabled it to become the first country to: (1) launch a grid-connected OWF (Milestone 1); (2) hit the 100MW mark for installed capacity (Milestone 2); and (3) reach both Landmarks 1 and 2. These

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[64] For example, half of Middelgrunden is owned by a cooperative made up of ten thousand private investors, with the other half owned by the local utility Copenhagen Energy (Larsen and Sørensen 2001).

[65] By 2003, global offshore wind capacity stood at 515MW with DK accounting for 79.4% (409MW). Excluding the UK's s 2nd OWF – launched at North Hoyle in 2003 (60MW) – Denmark made up 89.9% of global capacity.

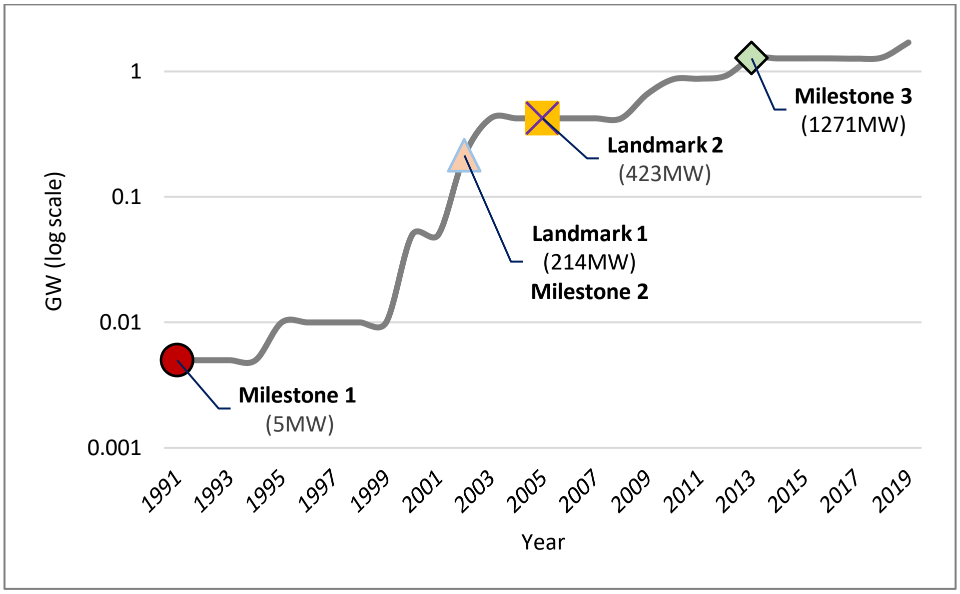
[66] Horns Rev is owned by Vattenfall (60%) and Dong (40%) (Markard and Petersen 2009).

[67] Nysted is owned by Dong (80%) and E.On (20%) (Markard and Petersen 2009).

[68] Bottom-fixed designs (monopiles) remain the viable technology in the Baltic Sea. There are no consented projects for floating wind installations, but commercialization is anticipated towards 2030 (Hüffmeier and Goldberg 2019).

achievements consolidated its place as the outright lead market until the mid-2000s (see Figure 6.1).[69]

Figure 6.1. Milestones and Landmarks of Danish Offshore wind 1991–2019



Source: Author's illustration based on BP 2019; IRENA 2019d, 2019e; IEA 2020

Summary

Historically, the Danish government has provided unparalleled support for offshore wind, backing RDD&D activities throughout the formative phase, mobilizing resources and capital **(F6)**, while allowing cooperative ownership models to flourish. Together, these market formation and upscaling dynamics have reinforced a long-held relationship with wind energy and the future vitality of this affiliation. In effect, Denmark launched a strong offshore TIS off the back of its long-standing as an onshore wind pioneer, supported by its leading global exporter status for wind turbines and high levels of public acceptance. Thereafter, recent investments in offshore wind have emerged as a core part of the country's energy transition strategy, acting as a substitute for onshore wind in the face of mounting saturation pressures and declining growth rates.

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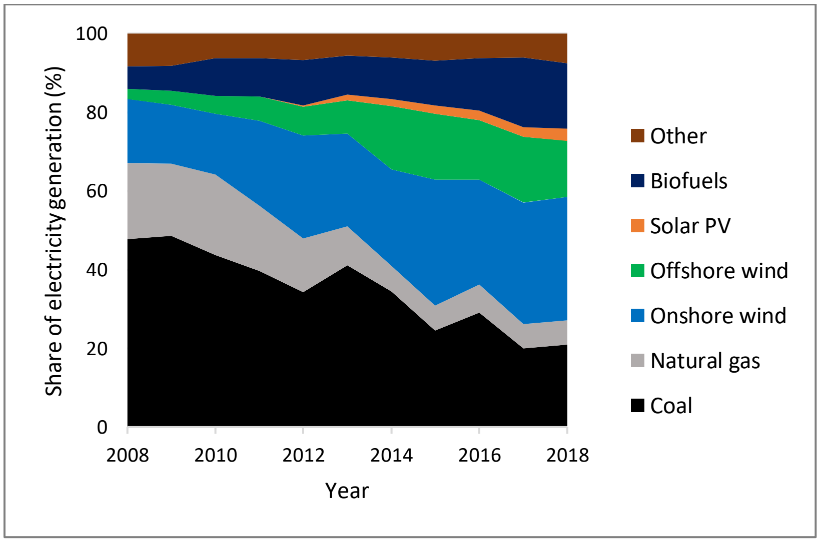
[69] In 2013, Denmark also became the second country to break the 1GW mark for installed capacity (Milestone 3), three years behind the UK.

6.2.2 Offshore wind in the Danish electricity system

6.2.2.1 Electricity generation dynamics

Danish wind energy stands as a revolutionary success story, on land and at sea. Denmark has become synonymous with wind power and turbine manufacturing; nevertheless, its clean energy accolades were hard fought. As recently as 2008, Danish electricity generation composed of two-thirds fossil fuels, with coal two-and-a-half times more intensive than natural gas. Within a decade, this picture has practically been reversed. In 2018, RESs accounted for over 70% of electricity generation, while fossil fuels fell to just 26% (see Figure 6.2.). Since 2008, Denmark has effectively slashed its coal consumption in more than half while cutting natural gas by approximately two-thirds, scaling up wind energy in the interim.[70] It is also a member of the Powering Past Coal Alliance (PPCA),[71] committed to phasing-out coal power production by 2030 and becoming fossil-fuel independent by 2050 (Danish Ministry of Energy, Utilities and Climate 2018b).

Figure 6.2. Evolution of Danish electricity generation by energy source, 2008-2018



Source: Author's calculations based on BP 2019; IRENA 2019d, 2019e; IEA 2020

It is notable that the diffusion of wind energy has also coincided with an expansion of other RESs, mainly bioenergy and solar.[72] With the parallel scaling up of other RESs, wind energy has stabilized at around two-thirds of RE-based electricity generation. Between 2008 and 2013 offshore

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[70] Denmark also imports a small amount of nuclear power from neighbouring Sweden and Germany to meet the remainder of its electricity demand (World Nuclear Association 2019a).

[71] A multi-stakeholder coalition seeking to phase-out of coal by 2050 (Blondeel *et al.* 2020).

[72] Bioenergy accounted for approx. 3 GWh in 2008, doubling to over 6 GWh in 2017, while solar grew from less than 5MW to approx. 750MW by 2017, as capacity quintupled from 100 MW to 500MW between 2013 and 2014

wind grew at a linear rate in terms of its share in electricity generation, following erratic growth patterns during the late formative and early growth phases. Thereafter, there was a period of exponential growth, without a corresponding increase in annual installations. Onshore wind experienced a similar phase of exponential growth between 2009 and 2015, increasing from 15% to 32%. While onshore wind still dominates in terms of total installed capacity, offshore wind operates with more efficiency, as its average capacity and load factors are higher.[73] This technical advantage partly accounts for the disproportionate increase of offshore wind in the total electricity share, climbing from about 8.5% to over 15% between 2013 and 2017; even though annual installations remained stable throughout the period.[74] This parallel growth pattern indicates the presence of an external factor, namely a reduction in electricity demand.

6.2.2.2 Electricity capacity dynamics

Danish electricity supply grew at a rate of 20% between 2000 and 2018, increasing from 12.6GW to 15.1GW, with an average of 13.4GW over the period. Relative to the onshore sector, offshore wind grew faster between 2010 to 2018, from less than 2% of total installed wind capacity in 2002 to an average of just over 19%. This shift is partially explained by the "increasing scarcity of onshore sites with abundant and consistent wind characteristics" (Gazzo *et al.* 2015), compared to an ample supply of premium offshore locations in the North and Baltic seas, which are "suitable for the construction of wind farms with joint grid access" (BMWi 2015). Although offshore wind deployment dates to 1991, no tangible uptake took place until the early 2000s, before take-off in 2003. This period (2001–2003) marked an increase from just 2% of total wind capacity to 14%; where offshore wind remained stable until the next wave of deployment at the end of the 2000s, peaking at nearly 21% in 2010 (see Figure 6.3.). Both technologies yielded about 2–2.5 GWh/year per installed MW between 2008 to 2013; however, offshore wind has since averaged around 4 GWh per installed MW, signalling its technological superiority (IRENA 2019b, 2019c).[75] Additional offshore capacity was installed between 2018 and 2019, however, onshore wind has grown faster since 2013, albeit at a slower rate than in the past. Nevertheless, as the price of

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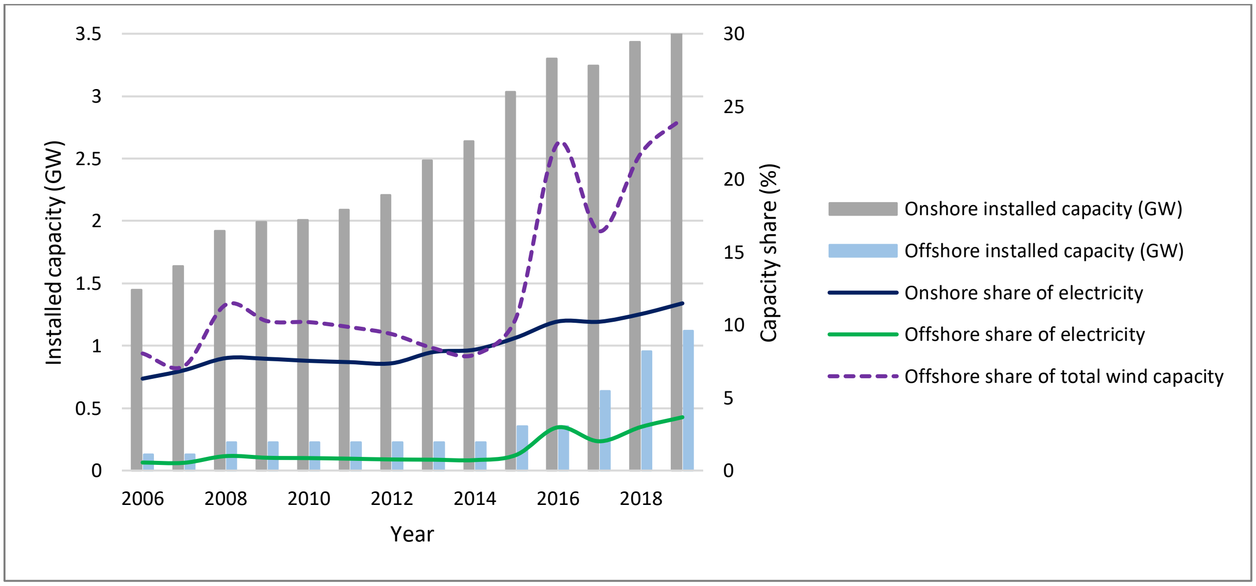
[73] Capacity factor is the percentage of time that the wind turbines are active, while load factor refers to the percentage of the turbine's potential output that is converted into electricity (Delaportas 2016).

[74] Denmark had 1.27GW of installed capacity in 2013 and only increased this marginally to 1.35 GW by 2018.

[75] The extent to which the existing offshore fleet can generate more electricity without a corresponding ramping up of new annual installations will be determined in the upcoming years, as older projects in the North Sea and Baltic Sea require repowering or upgrading.

offshore wind continues to fall, the number of land-based wind turbines will subsequently be reduced from approximately 4,300 to 1,850 by 2030.[76]

Figure 6.3. Evolution wind energy in Danish electricity supply, 2000-2018



Source: Author’s calculations based on Danish Energy Agency 2020; BP 2019; IRENA 2019e; IEA 2020

6.2.3 Feasibility of Danish 2030 targets

6.2.3.1 Introduction

Denmark has achieved unprecedented feats during its long history with wind energy, becoming a paragon of RE-based electricity generation and an exemplar of industrial success with a strong export advantage in the domain of wind turbines. From a historical perspective, there is little reason to doubt Denmark’s ability and commitment to achieving further success in its clean energy transition. Denmark’s electricity mix will continue to be dominated by bioenergy and wind energy, with offshore wind gaining parity with onshore wind by 2030. While proposed plans to accelerate the Danish energy transition have been made clear, the feasibility of its offshore wind expansion program remains underexamined. This is especially true given emerging technological developments and the prospect of multi-gigawatt energy islands towards the end of the decade. The remainder of this section considers existing techno-economic, socio-technical and political drivers that may situate Denmark in a viable position to pursue its 2030 target and to possibly overshoot

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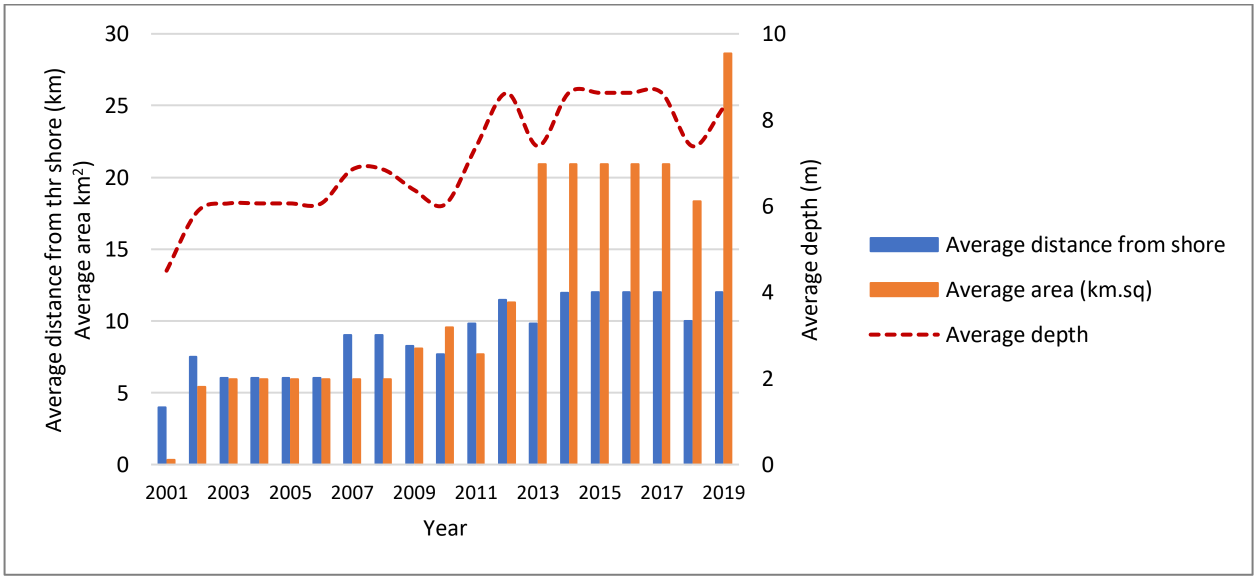
[76] Production is unlikely to be negatively impacted since smaller existing turbines will be replaced with larger ones with higher capacity (Danish Ministry of Climate, Energy and Utilities 2018a).

expectations, as it strives to become the core of Northern Europe's offshore wind energy hub, contingent on a new era of unprecedented electricity interconnectivity.

6.2.3.2 Techno-economic drivers of Danish upscaling

Offshore wind upscaling dynamics are driven by distance from the shoreline, area of the project and the installation depth of monopolies. In the last years, Danish OWPs have remained at an average distance of around 12 km from the shore and at an average depth of 8 m; however, following the launch of Horns Rev III (400MW) in 2019, the average project area has increased from 11.3 km^2 to 28.6 km^2 (see Figure 6.4.). Operating on 49 MHI Vestas V164-8.3 MW turbines, Horns Rev III provides electricity to over 400,000 households at some of the cheapest rates in Europe (Vattenfall 2020).[77] OWPs of this size and area will become the standard in Danish waters in the 2020s, as the government eyes projects twice the size of Horns Rev III, reinforcing positive upscaling dynamics. Gains across key technoeconomic parameters provide a significant boost to Denmark's ambitions, since an additional two projects before 2030 – on top of the current pipeline – would secure upwards of 7GW of installed capacity. To this end, stakeholders have called for at least five more large OWFs before 2030 alongside energy islands to help meet the national objective of reducing GHGs by 70% (Danish Ministry of Climate, Energy and Utilities 2019).

Figure 6.4. Average distance from shore, area, and depth of Danish OWPs, 2001–2019



Source: Author's calculations based on 4C Offshore 2020b; The Wind Power 2020d

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[77] DKK 0.77 per kilowatt hour (approx. 0.10 euros) (Vattenfall 2020).

6.2.3.3 Political and socio-technical drivers of Danish OWFs

"Considering only already concluded political agreements," Denmark's indicative contribution to the 70GW aggregate capacity planned between the NSEC[78] is approximately 5GW (Danish Ministry of Climate, Energy and Utilities 2019). Denmark's political framework for 2020–2030 was agreed upon in 2018, including the addition of three new OWFs with a total capacity of 2.4GW (Danish Ministry of Climate, Energy and Utilities 2018a). Based on its NECP, the deployment timeline will take it from 2.5GW in 2021 to 3.5GW in 2024, before reaching 4.5GW in 2028 ahead of its 2030 target of 5.3GW (Danish Ministry of Climate, Energy and Utilities 2018a, 2019). There is a strong argument to be made that the provisional target, despite calling for fast growth in upcoming years, may be just 'the tip of the iceberg.' In addition to tripling its current capacity, there is growing interest and political momentum towards constructing the world's first energy island in Danish waters by 2030, which will bring at least 10GW of additional capacity online (Danish Ministry of Climate, Energy and Utilities 2019).[79]

Strong support for "offshore wind generation hubs far from shore" – in place of near shore individual projects – has come from the Danish finance ministry, as the government seeks to bolster its share of RESs while supporting decarbonisation (Weston 2020). The upscaling potential of energy islands marks the dawn of a new era: a new socio-technical system is forming to harness the technological potential of 'green' hydrogen, as a power source for the transport sector and heavy industries.[80] At least 4GW of offshore capacity from energy islands is expected to be feasible before 2030, with initial projects split between the North Sea and the island of Bornholm in the Baltic Sea, which is already connected to the Swedish grid for exporting purposes (Weston 2020).

To this end, an initial investment of EUR 8.7 million is included in Denmark's 2020 Finance Act for the purpose of funding feasibility studies, given the expectation that project costs would total around EUR 27–40 billion, with investment coming mostly from the private sector (Richard 2019). Additionally, the Centre for Electric Power and Energy at DTU[81] is heading a research project to

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[78] DK has an important role to play in the NSEC, as it seeks to "create synergies and to avoid incompatibilities between national policies and to share knowledge on international best practices and foster joint strategies where possible and beneficial" (Danish Ministry of Climate, Energy and Utilities 2019).

[79] The government and supporting parties have called for "a fair direction for Denmark", agreeing to undertake a in-feasibility study of the North Sea's first energy island (Danish Ministry of Climate, Energy and Utilities 2019).

[80] Green hydrogen is potentially achievable through Power-to-X technology, which is designed to convert "electrical energy into liquid or gaseous chemical energy through electrolysis and further synthesis processes," by splitting water into oxygen and hydrogen in a CO_2 free process (Siemens 2020).

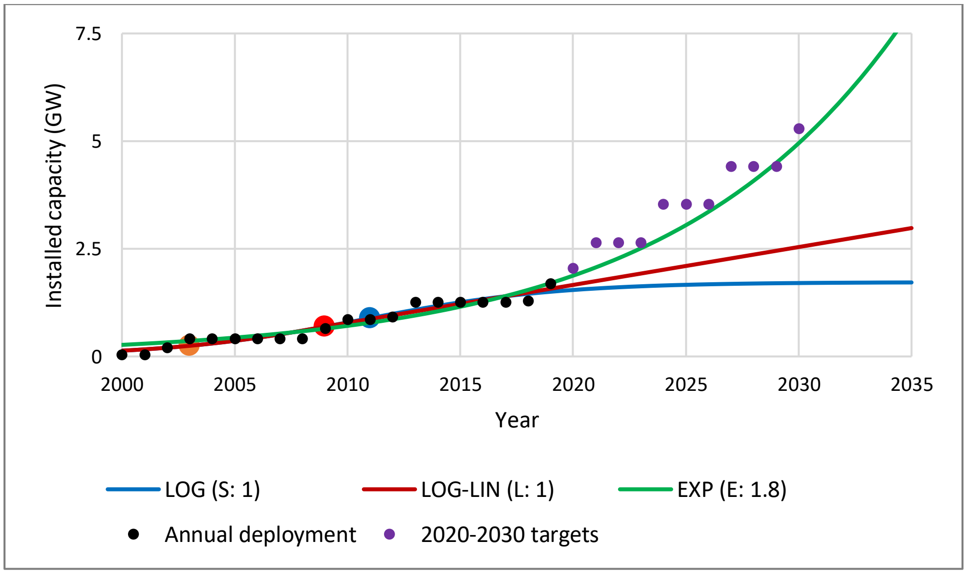
[81] Technical University of Denmark.

assess the technological requirements for connecting artificial islands to neighbouring OWFs (Richard 2019). One of the partners is the Danish operator Energinet and Dutch TSO TenneT is also collaborating on the project (Richard 2019). Clearly, the launch of energy islands will prove to be as much of an economic challenge as a technical one; however, the political will and preconditions for innovation are firmly in place. The feasibility of achieving such transformational milestones will be of increasing interest, as investment pathways become clearer under a formal planning framework.

6.2.3.4 The Danish quest for 5GW+ by 2030

The question remains is exponential growth feasible for Danish offshore wind beyond 2020 and what do growth fits suggest about an increase to 10GW from energy islands? Achieving its provisional 2030 target will require exponential growth; however, based on Denmark's deployment pathway to date, logistic growth or logistic-linear growth suggest better fits (see Figure 6.5.) Notwithstanding, exponential growth is a possibility for Denmark in the future according to the RSS values (LOG, LOG-LIN and EXP are all below 2).

Figure 6.5. DK Offshore wind pathways: Empirical data and fitted growth models with RSS



Exponential growth is the only pathway that would conceivably see capacity increase beyond single digit numbers at any point within the next decades, since logistic growth plateaus at less than 2GW. Logistic-linear growth sees capacity reach no higher than 4.3GW by 2050. These findings are expected since Denmark launched its offshore wind sector three decades ago, reaching Landmarks 1 and 2 in 2003; leading to its inflection point occurring near the end of 2010 with peak growth reached a year prior, following annual deployment of 240MW. Furthermore, 2013–2018 marked a period of stagnation, followed by grid-connection of a 400MW project, verifying the growth fits. In sum, an exponential pathway would see Danish offshore capacity reach 5GW by 2030, just shy of the current national target. Moreover, continued exponential growth through to 2040 results in 13GW of capacity, correlating closely to the current OWFs in the project pipeline combined with the estimated potential from energy islands. The upscaling dynamics of OWFs presents strong support for Denmark succeeding in meeting its current target and moving closer to the 10GW mark over time, irrespective of the advent of energy islands.

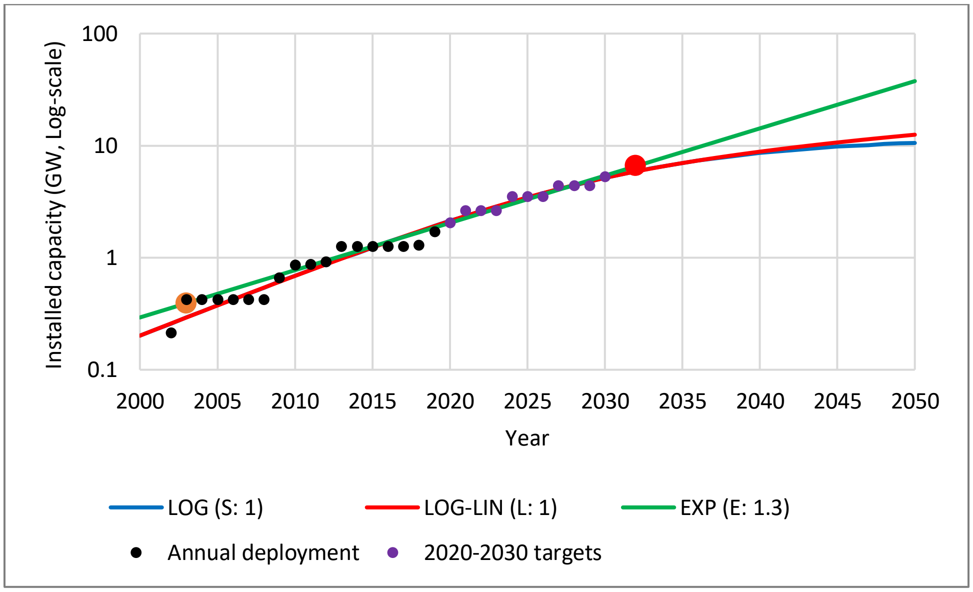
6.2.3.5 Implications for 2050 deployment levels

The final question is what are the implications of Denmark meeting its 2030 offshore target? The expectation would be that meeting the target will add weight to future deployment potential and may drive a further wave of exponential growth, but to what extent does this hypothesis hold true according to growth fits for 2030 to 2050?

Provided Denmark achieves exponential growth ahead of 2030 and reaches an installed capacity of 5GW, the RSS of exponential growth decreases from 1.8 in the previous scenario to 1.3, confirming a significant improvement in growth prospects. Nonetheless, logistic, and logistic-linear remain at 1, providing better fits. Following an exponential growth pathway up to 2030, capacity reaches 37.6GW by 2050. There is a significant impact on logistic and logistic-linear growth pathways, as the inflection point (**blue dot**) moves from 2011 to 2032 (see Figure 6.6.). This raises the ceiling for saturation by more than double; capacity climbs to over 10GW under logistic growth, with logistic-linear growth reaching 2.5GW by 2050, as opposed to 4.3GW in scenario 1.

According to WindEurope's 2050 feasibility study, under optimal conditions – where Europe is politically unified, market incentives are provided (with investments to match) and critically, greater interconnection capacity between countries for electricity trading is secured – Denmark can potentially realise 35GW of capacity by 2050 (Freeman *et al.* 2019). However, up to 25GW would be exported, highlighting the need for greater international collaboration and cooperation to support the development of "offshore hybrid projects" and energy islands, while keeping environmental impacts within check (Freeman *et al.* 2019). Also, a regulatory 'lock-down' on offshore projects, reminiscent of what has happened onshore in certain cases must be avoided. Denmark has available a vast natural resource in its parts of the North Sea and Baltic Sea amounting to around 105,000 km^2 with an estimated ocean eligibility of 45,800 km^2 for OWPs (European MSP Platform 2019b; Caglayan *et al.* 2019). Around 16% of the Danish EEZ would need to be reserved to meet a target of 35GW by 2050. To date, the feasibility of such a scenario remains underexplored.

Figure 6.6. DK Offshore wind pathways: 2030 targets and fitted growth models with RSS



Clearly, there is no substantial difference between logistic and logistic-linear growth pathways under this timeframe. Nevertheless, the findings help parameterise what may be plausible for Denmark based on its past deployment trends and projected deployment levels this decade. Accordingly, Denmark has a high probability of meeting a minimum of 10GW by 2050 under a less ambitious scenario. However, under a more ambitious scenario that ramps up its energy transition aspirations and benefits from strong momentum across the European offshore wind regime, it becomes feasible that Danish waters could host upwards of 30GW in OWFs in the future, granted that its EEZ and maritime framework can accommodate this level of upscaling.

6.3 Summary

Exponential growth is the only pathway that will enable Denmark to realise any measure of its offshore wind ambitions. The feasibility of securing this growth rate is strengthened by the following key drivers:

- Favourable upscaling dynamics across core technical areas such as turbine efficiency, OWF size and capacity factors.

- A world-class socio-technical regime for wind energy development, across both the production side (turbine manufacturing under Vestas) and in terms of RDD&D.
- Strong political commitment towards becoming fossil-fuel independent by 2050.
- A long history with wind energy, steeped in public support and wind energy cooperatives.

As such, techno-economic, socio-technical, and political mechanisms are strongly in favour of Denmark's pursuit of ambitious offshore wind targets for consolidating its clean energy transition. Furthermore, 'the road to offshore wind saturation' should remain far adrift into the future since onshore wind is the older and more 'incumbent' wind technology, already confronted with various saturation pressures. In conclusion, Denmark has in place the key ingredients including economic strength, knowledge networks, political commitment, alongside an increasingly RE-based electricity system to ensure offshore wind targets remain both ambitious and achievable.

6.4 The Netherlands

6.4.1 Early uptake of Dutch offshore wind through the TIS lens

Introduction

Behind Denmark, the Netherlands was the first country to adopt offshore wind energy. Two projects were commissioned in the mid-1990s, Lely in 1994,[82] followed by Irene Vorrink in 1996 (CADDET Renewable Energy 1997; (Bilgili *et al.* 2011).[83] These small-scale projects were constructed in the Ijsselmeer (artificial) freshwater lake,[84] which is approximately 1100km^2 and a vast potential offshore wind resource (Verhees *et al.* 2015). No further deployment happened until 2007 and 2008 when two large-scale projects came online at Egmong ann Zee[85] and Prinses Amaliawindapark (Bilgili *et al.* 2011; van Steen *et al.* 2019);[86] signalling a shift into deeper waters where several-hundred megawatts OWFs become feasible. Towards the end of 2000s, Dutch OWFs were the 2nd largest in the world (after Denmark). However, success proved to be fleeting as the Dutch offshore TIS relapsed, following policy and market resistance **(F7)** and an associated weakening of other TIS functions, resulting in a near decade-long lull in offshore wind uptake.

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[82] Located in the Ijsselmeer freshwater lake at the center of the country (CADDET Renewable Energy 1997).

[83] Running on 28 NordTank 600 kW turbines (Bilgili et al. 2011).

[84] Created in 1932 by the closing of the Zuiderzee bay (Verhees et al. 2015).

[85] Running on 36 Vestas 3MW turbines (Bilgili et al. 2011; van Steen et al. 2019).

[86] Running on 60 Vestas 2MW turbines ca 28 m from the coastline (Bilgili et al. 2011; van Steen et al. 2019).

The first wave of market formation **(F5)**, resource mobilsation **(F6)** and legitimacy **(F7)** was driven by strong "public support in the form of subsidies, tax breaks and other incentives," which acted as a motor of change; firmly positioning the Netherlands behind first mover Denmark and rival early adopter the UK (Verhees *et al.* 2015). However, success became short-lived with inactivity between 2008 and 2015. This reversal was mostly down to weakening government support and preference for cheaper domestic RE options such as biogas and geothermal, at the expense of offshore wind (Wieczorek *et al.* 2013).[87]

Dynamics of knowledge development **(F2)** and knowledge diffusion **(F3)** saw Dutch wind farm constructors form part of the European group of international market leaders, despite lacking government support and a strong domestic market (Wieczorek *et al.* 2013):

> Although the Netherlands is a lag market compared to Denmark, the United Kingdom and Germany, this has not hindered its ability to leverage its industrial resources to participate in the growing international market for offshore wind (van der Loos *et al.* 2020).

In the Dutch case, an advanced socio-technical network and strong industrial participation in the expanding global market was achieved in the absence of an established domestic market (van der Loos et al. 2020), which left its TIS considerably weak compared to other frontrunner countries in the North Sea hub (Verhess *et al*. 2015). As a result, ambitious NREAP targets went unrealised.

Reigniting the guidance for the search

In response to domestic stagnation, the Dutch government reignited its guidance of the search **(F4)** for launching large-scale OWFs. To help meet its 2020 Energy Agreement targets,[88] the government mobilsed resources by reserving EUR 18 billion in subsidies – later reduced to EUR 12 billion – as part of its "Stimulation of Sustainable Energy Production (SDE+) tender and subsidy legislation"[89] (Loyens & Loeff 2015), backing a target of 4.5GW of offshore wind by 2023 (Rodrigues *et al.* 2015). The Energy Agreement also included (short-term) goals to increase RE production from 4.3% to 14% by 2020, and 16% by 2023; in addition to a long-term goal of reaching a 'zero-carbon' energy supply by 2050 (Netherlands Enterprise Agency 2015; EC 2020; Loyens & Loeff 2015). Moreover, a new 'Road Map' calling for a roll-out schedule of 700MW per

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[87] Verhees et *al.* (2015) suggest these periods develop under conditions where 'government contestation' supersedes the climate change and RE agenda, causing disputes around licensing procedures and subsidies, among other issues.

[88] The Dutch Energy Agreement was reached in 2013 after around "40 Dutch private and (semi-) public parties reached a covenant" for developing renewable energy in the Netherlands (Loyens & Loeff 2015).

[89] The Dutch government uses a floating feed-in-premium scheme, in this case granted in tenders between 2015 and 2019 and payable over a 15-year period (Loyens & Loeff 2015).

year for five years, with various financial and regulatory support mechanisms in place, has strengthened the Dutch offshore wind regime (Loyens & Loeff 2015).

The transmission system operator (TSO), TenneT, is the key actor behind realising the deployment schedule, having become "the responsible party for the construction and operation" of the Dutch offshore grid as of 2016;[90] tasked with the building "five standardized platforms of 700MW" for connecting to the onshore high voltage grid via two 220kV-cables (Loyens & Loeff 2015). The appointment of TenneT marks a more cost-effective strategy than the previous approach, which saw each OWF connected individually to the onshore grid under the jurisdiction of its developer (Loyens & Loeff 2015). The designation of TenneT improves the prospects of cost-reductions, achievable through "efficiencies of scale, lower costs of capital, longer amortisation periods and better availability because of network redundancy" (Loyens & Loeff 2015).[91]

From 2015 onwards, the Netherlands supported a capacity jump from around 0.35 GW to 1.125GW within three years, hitting Landmarks 1 and 2 (2015 and 2017) and Milestone 2 (2017) along the way (see Figure 6.7.). The 2017 Gemini project[92] – a 600MW site located approximately 85 km off the coast of Groningen in the North Sea (Gemini 2020; Huurman 2017) – put the Netherlands firmly back on the offshore frontrunner map.[93] In 2018, investments in offshore wind innovation projects amounted to EUR 70 million, signalling a shift towards stronger financial support; government funds reserved for offshore wind RDD&D amounted to EUR 80–100 million in 2019 (approx. 35%–45% of the total budget) (Guidehouse 2019). Recently, the government has taken steps to ensure offshore wind remains an attractive investment by extending the licensing period for OWFs from thirty to a maximum of forty years (Ocean Energy Resources 2020).[94] This move adds long-term security to the investment environment by offering developers a longer period in which to secure profits. By the end of 2019, installed offshore wind capacity reached 1.1GW, amounting to just over three percent of total Dutch electricity generation.

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[90] The 'TSO Built' grid development model was implemented in April 2016 by an amendment of the Electricity Act 1998, appointing TenneT to develop and operate the future offshore transmission system. Beforehand, grid connections were built by offshore wind farm developers (Guidehouse 2019).

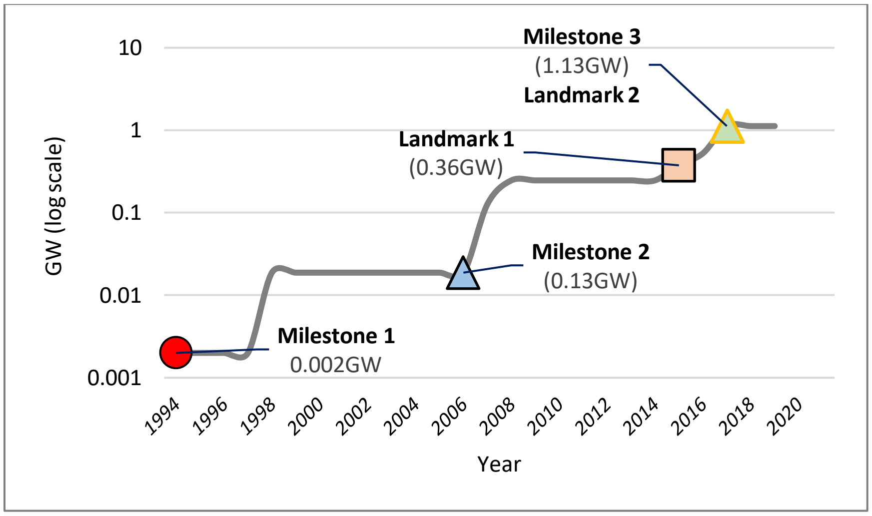
[91] This was the underlying rationale for cutting the SDE+ to EUR 12 billion

[92] Powered by 150 Siemens SWT-4.0-130 turbines equipped with highwind ride through (HWRT) technology, enabling rotor blades to operate at high-wind speeds with minimal exposure to the wind (Power Technology 2020).

[93] Generating 2.6 TWh of electricity annually, meeting the energy needs of nearly 800,000 households while offsetting an estimated 1.25 million tonnes of CO2 emissions per year (Gemini 2020; Power Technology 2020).

[94] OWFs that already have permits can also apply for an extension after 20 years (Ocean Energy Resources 2020).

Figure 6.7. Milestones and Landmarks of Dutch Offshore wind, 1994–2019



Source: Author's calculations based on BP 2019; IRENA 2019d, 2019e; IEA 2020

Past growth patterns for Dutch offshore wind deviate quite significantly from what has been witnessed in other frontrunner countries,[95] confirming a unique deployment pathway that warrants close examination. From 1996 to 2014, a clear S-curve shape formed due to an extended period of stagnation between 2008 and 2014; however, these trends proved to be short-lived and misleading if viewed in isolation. Between 2014 and 2017, offshore wind grew exponentially, equating to a more than four-fold increase in capacity. While has been a two-year gap in further additions, the next wave of large-scale deployment is on the horizon in the Netherlands; set to reaffirm its offshore wind boom while redefining its role in the European energy transition.

Summary

The Dutch case highlights the extremes to which offshore wind deployment may vary over time according to market conditions and the political landscape, in turn influencing the fabric of the offshore wind TIS. Alongside more stable government support for its domestic market, realising NREAP targets will require a further *revving up of life* on Lake Ijsselmeer to capitalize upon its high techno-economic potential. Encouragingly, the 383 MW Windpark Fryslân[96] is currently in the project pipeline as the largest nearshore wind farm constructed on a lake (NS Energy 2018). Additionally, having built its offshore sector off the back of Vestas turbines in the early to mid-2000s, the Netherlands is set to continue this affiliation through the launching of Borssele III and

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[95] Denmark being the exception to this observation.

[96] The site will run on 89 SWT-DD-130 turbines from Siemens Gamesa (NS Energy 2018).

IV; a 731.5 MW OWF featuring 77 MHI Vestas V164-9.5 MW wind turbines installed on monopiles at depths ranging from 16 to 38 metres (Power Technology 2019).[97]

6.4.2 Offshore wind in the Dutch electricity system

6.4.2.1 Dutch electricity generation

By EU standards, the Dutch energy system remains dominated by fossil fuels, contributing to around 80% of electricity generation between 2008 and 2018. Natural gas is the bulk of the fossil fuel base, averaging 54% of electricity generation compared to 28% for coal.[98] Coal has remained stable over time and even increased in the mid-2010s following a strategy of carbon capture and storage (CCS) as part of Dutch energy and climate policy (Asveld 2017).[99] This agenda proved short-lived as the Netherlands joined the PPCA in 2017, affirming its commitment "to phase-out coal-based power by 2030" at the annual Conference of the Parties (COP23) (DTE 2017). In contrast to coal, domestic natural gas production has already entered steep decline due to issues of seismicity, with electricity generation decreasing from by 17 TWh between 2010 and 2013.[100]

The Dutch natural gas story dates to the discovery of the Groningen field in 1959, which became the "balancing field" for the national gas system following the 1973 global oil crisis (Honoré 2017).[101] Natural gas accounted for approximately 69 TWh of electricity generation in 2012, however, this amount progressively fell to around 57, 56 and 52 TWh over the next three years due to ongoing issues of seismicity at Groningen.[102] Nevertheless, until 2016 the Netherlands remained the largest producer and exporter of natural gas in the EU,[103] second only to Norway within the European OECD Honoré 2017).[104] Following events at Groningen, the government enforced strong measures to curtail extraction levels while also imposing a constant rate of annual production, as opposed to following seasonal patterns of demand as per usual (Honoré 2017). Having planned its

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[97] The shallow waters of the Dutch North Sea and good soil conditions make monopiles "the most cost- effective support structure design" for offshore turbines (Guidehouse 2019).

[98] One nuclear power plant in contributes 3.5% to annual electricity generation (World Nuclear Association 2019b).

[99] In 2007, the Dutch government announced the tender procedure for CCS demonstration projects (Asveld 2017).

[100] Natural gas production fell from 81.5 bcm in 2013 to 68.6 bcm, 51.2 bcm and 47.4 bcm by 2016; despite GDP remaining constant at just over 1 trillion USD throughout this period (cbs 2017).

[101] In the 1970s the Dutch government took the decision to conserve its key resources, preserving Groningen as a strategic reserve for future generations (Honoré 2017).

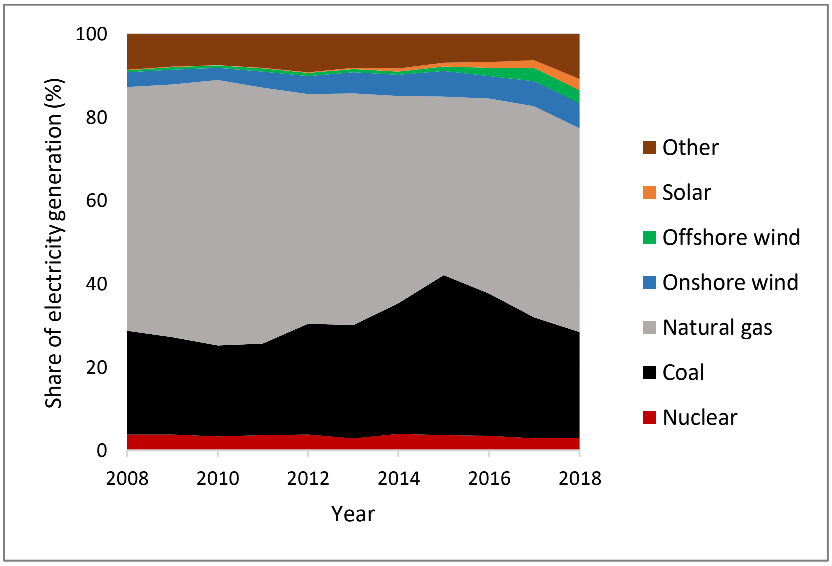
[102] Strong tremors struck the region again in January 2018, leading to a production cap of 11.8 billion cubic metres (bcm) through to October 2020, at the cost of approximately EUR 400 million to the Dutch economy; accelerating the phase out and foreseeable shutdown of the Groningen field within the next 3 to 5 years (Meijer 2019).

[103] Germany, the UK, and Italy are larger markets for natural gas (Honoré 2017).

[104] Organization for Economic Co-operation and Development.

energy system around an abundance of domestic natural gas, RESs have played only a small part to date in Dutch electricity generation (see Figure 6.8.).

Figure 6.8. Evolution of Dutch electricity generation by energy source, 2008-2018



Source: Author's calculations based on BP 2019; IRENA 2019d, 2019e; IEA 2020

The 1% take-off threshold for onshore wind was reached in 2003; however, it took until 2015 for offshore wind to reach this level, with solar energy also crossing 1% in the same year. Since 2015, onshore wind has stabilised with small declines in some years, while offshore wind has increased to just over 3% with solar close behind; together picking up the RE slack caused by onshore wind stagnation.[105] These trends confirm that wind and solar are positioned to become the backbone of Dutch renewable power generation, competing more effectively with the fossil-fuel base than in the past. Together wind and solar made up around 6% of total electricity generation in 2019 while bioenergy accounted for the remainder of RE-based generation, having averaged around 8% between 2008–2018.[106]

The implosion of the Groningen field has acted as a "key catalyst" for reforming the Dutch energy system towards a clean transition,[107] with the Netherlands is set to become a net importer of natural gas by the 2030s (Honoré 2017). Alongside escalating pressure to meet NECP targets, these developments have bolstered political commitment to the energy transition, wherein RESs and

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[105] The rapid uptake of solar PV has seen its generation capacity grow 20-fold since 2011, to 2.2 GWh in 2017.
[106] Bioenergy has fluctuated in a more boom-bust fashion, averaging 5.6 GWh between 2007 and 2017.
[107] In 2017, 98% of Dutch consumers remained connected to a gas grid.

energy efficiency measures are backed as the main policy drivers (Honoré 2017). Public support has also grown given the highly publicized environmental and economic risks of natural gas dependence. Clearly, the Dutch electricity system is characterized by high fossil fuel dependency, while nuclear power plays a minor role (approx. 3.5%),[108] amounting to 85% of total generation. The remaining 15% of electricity generation is filled in close to equal proportions by (1) bioenergy, and (2) wind and solar. Modern RESs are expected to grow significantly in the future, as domestic natural gas production rapidly declines together with the phasing out of coal by 2030.

6.4.2.2 Dutch electricity capacity

Electricity capacity grew at a rate of 33% between 2006 and 2018, from 23GW to 30.5GW with a notably high average of 28.9GW compared to the range. Meanwhile, the Dutch energy transition has been slow to take grip with decarbonisation efforts stalled by a lack of political commitment, manifesting in frequent 'start-stop policies' and additional regulatory hurdles for wind energy. Only since around the mid-2010s has some tangible progress been made towards accelerating the diffusion of RETs. Between 2015 and 2019, combined solar and wind capacity more than doubled from nearly 4GW to around 8.5GW, with solar accounting for around 62% of the growth. Onshore wind contributed 1GW to this increase while offshore wind grew nearly five-fold since 2014 and threefold since 2016.[109] As a result, total wind energy stands at around 15% of current installed capacity, with offshore wind accounting for just over 3.5% (see Figure 6.9.) while solar also meets nearly 13% of electricity capacity.

Offshore wind has lagged onshore wind by more than a decade, taking until 2015 to complete the formative phase. As a result, the offshore share of total wind capacity remained stable at around 10% from 2006 to 2015, before doubling to over 22% following an annual capacity addition of 280MW between 2016–2017. Over time, offshore wind has come to compete on a closer par with its onshore counterpart. While fossil fuels have remained the prominent energy source in Dutch electricity production and consumption throughout its history, wind energy has gradually consolidated a more feasible position to dent this status, as the Dutch RE transition takes grip.

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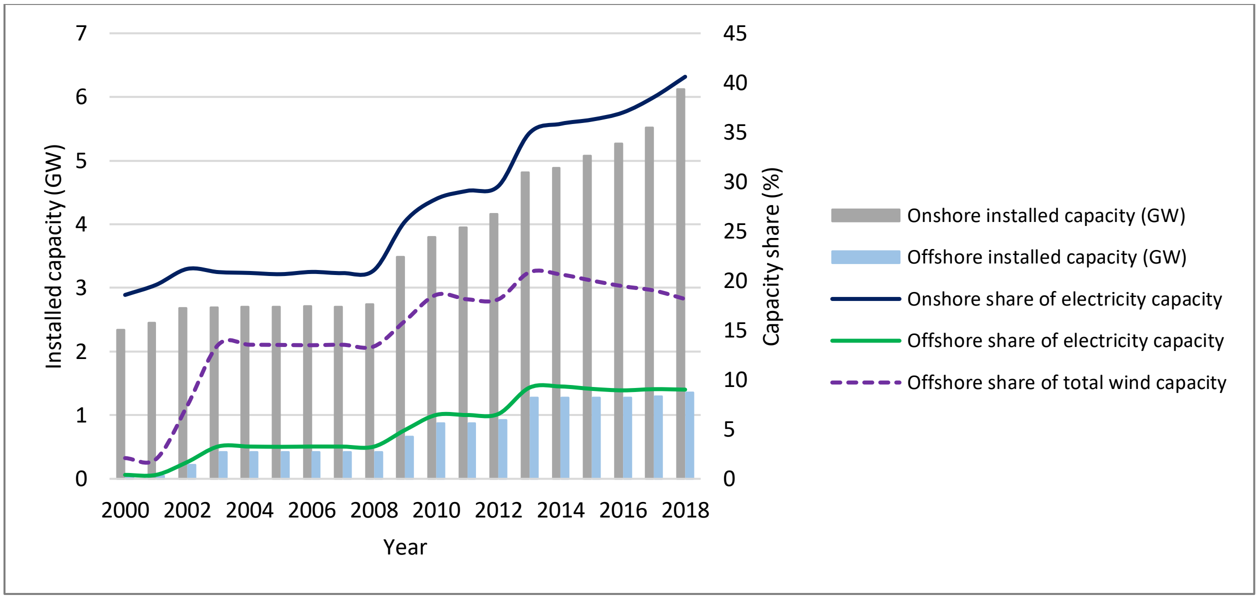
[108] The Borssele nuclear power plant is also set to reach the end of its lifecycle freeing up additional generation space for potential offshore wind uptake.

[109] Offshore wind increased by 750MW during this period, finally breaking the 1GW in 2019

Figure 6.9. Evolution of wind energy in Dutch electricity supply, 2009–2018



Source: Author's calculations based on BP 2019; IRENA 2019d, 2019e; IEA 2020

6.4.3 Feasibility of Dutch 2030 targets

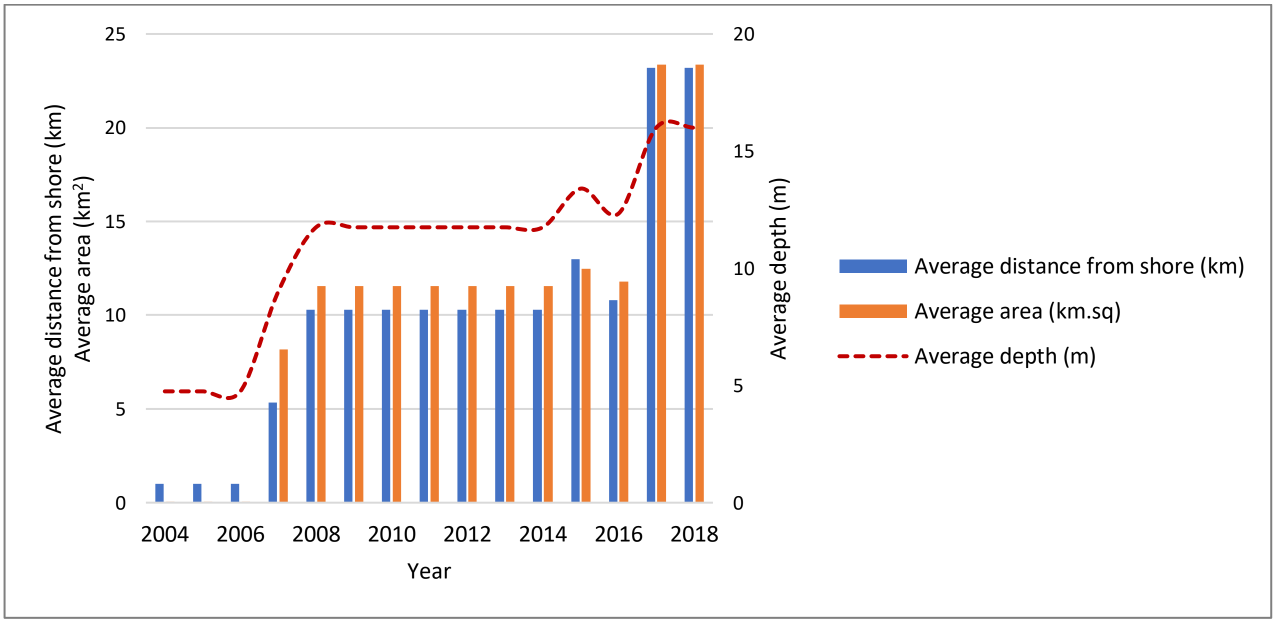
6.4.3.1 Introduction

Dutch offshore wind deployment can be characterized as an outlier compared to other European frontrunner countries. Although the first adopter behind Denmark and a lead market throughout the early years of market formation, the Netherlands became a lag domestic market due to disruptive 'start-stop' policies and unfavourable conditions for offshore investment. Growth was stagnant and periodic until the mid-2010s when a large-scale project came online (Luchterduinen OWF, 130MW) followed by a landmark project with the Gemini OWF (600MW). The offshore wind regime has since grown from strength to strength, supported by several tenders for large-scale projects in the upcoming years, which if fulfilled will see capacity exceed at least 10GW by 2030. Continuity in its offshore roll-out and commitment to an ambitious project pipeline constitute a key precondition for achieving success, through economies of scale, increased market competition and cost reductions (ECOFYS 2016). The remainder of this section considers the merits of the Dutch offshore wind programme and the feasibility of it supporting a ten-fold capacity increase by 2030.

6.4.3.2 Techno-economic drivers of Dutch upscaling

Dutch OWPs were launched in shallow, near-shore waters, following the Danish model. However, the Netherlands has since expanded the techno-economic parameters of its OWFs at a faster rate than Denmark, notwithstanding a period of stagnation between 2009 and 2014. Since the formative phase, average depth has increased from approximately 5 to 15 metres. In 2008, the launch of the Amaliawindpark doubled the average distance from the shoreline and in 2017 the Gemini OWF secured a further two-fold increase, bringing the average distance to around 23 km. A similar pattern has also been observed in the average area of new OWPs, confirming the significant upscaling effect, which is most discernible in the move from 100+ MW projects to 500+ MW projects (see Figure 6.10.).

Figure 6.10. Average distance from shore, area, and depth of Dutch OWPs, 2004–2018



Source: Author's calculations based on 4C Offshore 2020b, The Wind Power 2020d

The Netherlands accomplished a significant capacity leap – including one of the world's largest projects with the Gemini OWF – through moving its operations to deeper waters farther offshore. The Dutch Offshore Wind Act 2015 prohibits wind farm construction within twelve nautical miles (19.3 km) of the EEZ, which partly explains the move away from the coastline over time (Toke 2011; Loyens & Loeff 2015). Nevertheless, the government has demonstrated willingness to compromise on this restriction, showing pragmatism and commitment to the wider agenda of its energy transition, despite potential environmental opposition or conflicts with competing maritime activities. To this end, the areas of Hollandse Kust Zuid-Holland and Hollandse Kust Noord

Holland were enlarged to include a two mile buffer zone between the 12-mile boundary and 10-mile line to realise the planned 700MW build out at a cheaper cost and with less technical risk.[110]

Notably, the current average nominal capacity of operating offshore wind turbines is also set to double to 6MW by 2023, following the realisation of the next wave of large-scale projects (Guidehouse 2019). The standard will soon become 10MW turbines, typically sourced from Vestas or Siemens Gamesa, with rotor diameters between 150–200 metres (Guidehouse 2019). Additionally, Direct Current (DC) connections are needed to connect offshore wind energy on a large scale and across greater distances in a cost-effective way. This innovation is being prioritised by TenneT, as it seeks to secure a DC connection to support 1.2–2GW capacity for the 'IJmuiden Far Offshore' project while minimising spatial impact (Russell 2018). Multiple large offshore DC platforms are currently viewed as the most cost-effective option for realising a Dutch 'Wind Connector' that can supply the UK grid, while offering the potential to convert wind power to (green) hydrogen and investment opportunities for new port infrastructure, maintenance facilities and specialised jobs; (Russell 2018) creating an effective link between techno-economic and socio-technical mechanisms in the offshore sector.

6.4.3.3 Political and socio-technical drivers of Dutch OWFs

The Dutch political process is committed towards transparency and collaborative planning. The Environment and Planning Act of 2017 (*Omgevingswet*) facilitates spatial-economic harmonization and optimization "within the boundaries of a healthy North Sea ecosystem," adhering to the Marine Strategy Framework Directive (MSFD) and the Marine Spatial Planning (MSP) Directive (de Vrees 2019; EC 2014). Updates to spatial aspects of OWF planning and related costs are laid out in the National Water Plan 2016–2021, adding further legitimacy to the offshore roll-out. In tandem, the government has stepped up its energy transition commitments, aiming for a minimum of 27% from RESs to meet 75% of electricity by 2030 (Government of the Netherlands 2020). RE expansion plans include 7.5–8.5GW of onshore additions, alongside an offshore roll-out of 11.5GW by 2030 (approx. 49 TWh), in addition to solar target of 27GW (Tisheva 2019; WindEurope 2019; Stead *et al.* 2020; Bellini 2019). If its offshore wind targets are realised, the Netherlands will become Europe's third largest market behind the UK and Germany.

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[110] Development costs were slashed by approximately EUR 1.2 billion due to savings on connection platforms and cables, alongside cheaper construction, and O&M costs (Loyens & Loeff 2015).

Development procedures have advanced beyond the planning phase in respect to 2023 targets, with five offshore development zones already tendered to a total of 3GW;[111] including two zero-subsidy bids awarded to Sweden's Vattenfall in 2018 for projects of 740MW and 760MW capacity for commissioning in 2022. The following conditions make zero-subsidy tenders feasible: **(1)** the cost of grid connection is covered by the TSO, TenneT; **(2)** the 'one-stop-shop' principle which awards concession, permit and grid connection increases market confidence and project security; **(3)** the Netherlands has a well-established power purchase agreement market; **(4)** the offshore space is characterized by beneficial techno-economic conditions which make for favourable site conditions; and **(5)** cost reductions are realised through an integrated supply chain, which is one of the strongest in the world (Guidehouse 2019). In the absence of zero-subsidy bids, companies bid for a 15-year subsidy grant, which entails a 30-year permit for building, operating, and decommissioning of the project (Guidehouse 2019). Accordingly, the floating feed-in premium scheme and related tender and subsidy legislation have proven pivotal to strengthening prospects for upscaling.

The political feasibility of the Dutch 2030 roadmap for offshore wind power stems from its intricate planning mechanisms and strong policy instruments in support of industrial growth. Notably, the government already has in place a green hydrogen strategy, as it seeks to capitalize upon its extensive port infrastructure and industrial coastal clusters (Parnell 2020). Plans for developing green hydrogen at scale have attracted strong interest from oil and gas companies, with Shell forming part of a feasibility study to assess the potential of building the world's largest 'green hydrogen hub,' while O&G giant Eneco is collaborating on a hybrid project to fuse offshore wind and offshore hydrogen production with existing gas pipelines (Parnell 2020). As a result, O&G companies are competing for offshore tenders, making strong bids alongside established offshore wind developers (Parnell 2020; renews.biz 2020).[112]

The Netherlands is strong on innovation, leading in several areas of offshore wind RDD&D. Dutch companies command approximately 25% of the European offshore wind market, which adds unprecedented strength to the country's offshore wind aspirations (Gov. of the Netherlands, 2020). Technological innovation flows from various research programmes across the private and public

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[111] Borssele I & II (752MW), Borssele III & IV (731.5 MW) and Borssele V (20MW, innovation site) set for commissioning in 2020; and Hollandse Kust Zuid I & II (740 MW) and Hollandse Kust Zuid III & IV (760MW) set for commissioning in 2022 (Netherlands Enterprise Agency and Ministry of Economic Affairs and Climate 2019).

[112] e.g. Vattenfall (SE) Ørsted 9DK) and EnBW (DE) (Parnell 2020; renews.biz 2020).

sector with contributions from corporations, universities, NGOs, regional municipalities, and the government (Guidehouse 2019). For example, TKI Wind op Zee is a leading innovation consortium supporting development and demonstration activities, while the ‘GROW’ consortium is led by twenty industrial and government partners to improve the Dutch offshore wind supply chain (Guidehouse 2019). The Dutch offshore wind socio-technical system has been strengthened by its innovation success, which offers a wide range of scalable solutions to technical challenges.[113]

The 2023 project pipeline also includes the Borssele V Innovation Site. The pilot site (20MW) is specifically designed to accelerate cost reductions by providing the test space for entrepreneurs to achieve innovative breakthroughs, reinforcing functions 1–3 in the offshore TIS (Guidehouse 2019).[114] In April 2020, the Borssele I wind farm supplied electricity to the grid for the first time, ahead of providing power two million households from 2021 (Ocean Energy Resources 2020). Early success at Borssele alongside forthcoming innovative advancements signals that strong uptake is on the horizon in Dutch waters.

For deployment beyond 2023, the government has the following tenders lined up: Hollandse Kust West in 2021 (1.4GW); Ten noorden van de Waddeneilanden in 2020 (0.7GW); Ijmuiden Ver I & II (2GW) in 2023; and Ijmuiden Ver III & IV in 2025 (2GW) (Netherlands Enterprise Agency 2019). These projects will add an additional 6.1GW to offshore capacity by 2030, with 4GW currently reserved for after 2027. TenneT has a critical role to play in facilitating the technical conditions for successful offshore wind upscaling. Specifically, the connection of future projects to the onshore gird will require advanced high voltage direct current (HVDC) technology solutions (Guidehouse 2019). To this end, TenneT is executing a ‘three-phase strategic plan’ to develop “the world’s first standardized 2GW HVDC grid connection to facilitate secure and cost-efficient grid connection” (Guidehouse 2019).

6.4.3.4 The Dutch quest for 10GW+ by 2030

Following disruption to domestic natural gas production, Dutch offshore wind has taken off and is entering a boom period. The question remains as to the feasibility of its offshore wind expansion plans, and whether findings indicate that its targets of 4.5GW (2023) and 11.5GW (2030) will be

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[113] The Guidehouse Offshore Market Report highlights the following key (current) project areas: Slip Joint Connection, Corrosion Fatigue Life Optimisation, Underwater Blinds Against Piling Noise, Gentle Driving of Piles, Wind Turbine Control Strategies, Composite tower for light-weight and low-maintenance wind turbines (2019).

[114] Borssele V aims to maximize the technical potential of monopile foundations for cost-efficiencies throughout the lifecycle, plus revolutionary eco-designs for safeguarding the maritime environment (Guidehouse 2019).

reached on time. The Dutch feasibility question boils down to exponential growth; it is plausible given the offshore wind landscape and which mechanisms support the potential of an average annual deployment rate of nearly 950MW through to 2030. The growth fits illustrate a case where the RSS values are the same, correlating to exponential growth (see Figure 6.11.). The inflection point (**blue dot**) is several years into the future and uncertain (occurring around 2027) while maximum growth rates are also in the future and improbable.

Figure 6.11. NL Offshore pathways: Empirical data and fitted growth models with RSS

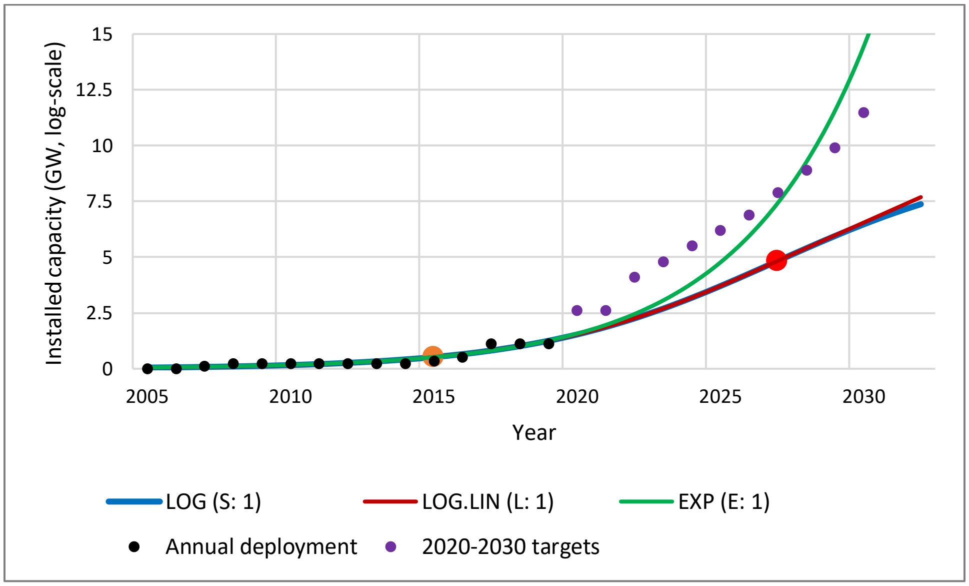

Figure 6.11. presents a starting point for understanding what has happened in the space of Dutch offshore wind so far and what needs to happen in the future. Instead of plateauing at around 6.5GW under conditions of logistic growth, an exponential growth rate would see the Netherlands supersede its 2030 target by reaching more than 14GW.[115] This scenario is plausible provided at least two more large-scale projects join the pipeline in upcoming tenders. In this respect, the Dutch offshore wind industry is lobbying the government to boost its offshore target by a further 7GW to around 18.5GW by 2030, as it seeks to compete with the booming solar sector (Radowitz 2019a). Exponential growth provides a realistic diffusion pathway based on the previous rate of uptake and moreover, the scale of new OWPs. Given the emerging upscaling dynamics, other growth rates are a distinct improbability, especially since Dutch capacity only surpassed 1GW in 2019 (i.e. far from

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[115] Interestingly, exponential growth can only bring capacity to 3GW by 2023, missing the 4.5GW target.

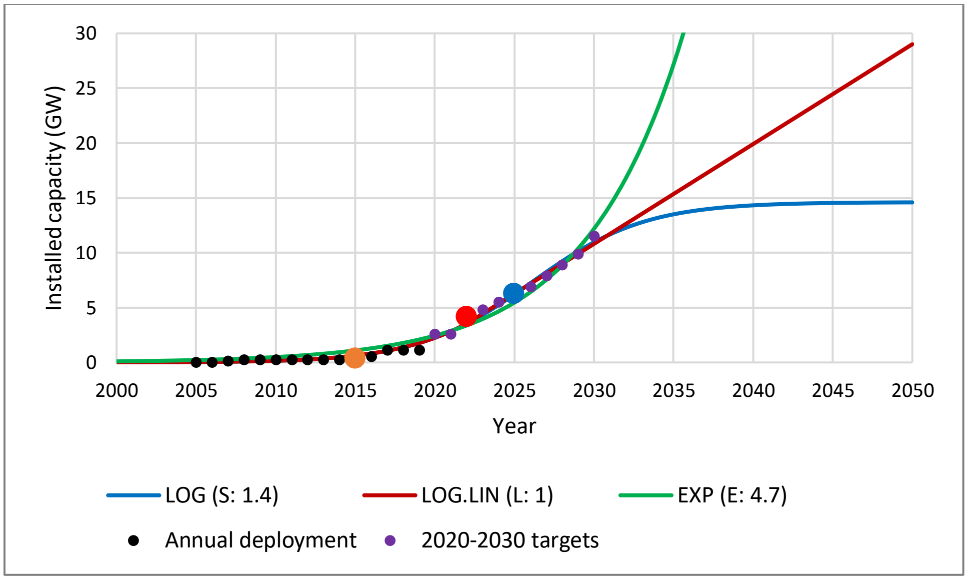
its ceiling). Exponential growth closely matches the government's envisioned deployment timeline and secures the 2030 target on time; however, beyond this timeframe exponential growth becomes unsustainable by today's market trends.

6.4.3.5 Implications for 2050 deployment levels

The final question is whether this growth rate can be sustained beyond 2030? Under the scenario that the Netherlands succeeds in its 'quest' to break the 10GW mark by 2030 – i.e. '**Milestone 4**' – logistic-linear growth becomes the best fit to the data, while logistic growth is the second best fit. Logistic-linear growth reaches around 19GW by 2040 and 29GW by 2050 (see Figure 6.12). Under a scenario that sees Europe reach 450GW of installed capacity by 2050, the Netherlands could contribute around 60GW, quintupling its 2030 levels (Freeman *et al.* 2019).

On the one hand this is feasible, since the Dutch part of the North Sea boasts a potential of at least 50GW installed capacity, given its relatively low water depths, excellent wind conditions and proximity to markets (ECOFYS 2016). The EEZ has a total area of around 64,000 km^2 (European MSP Platform 2019d). To reach 15GW of installed capacity, the government would need to reserve 2% of its EEZ for OWFs, and at least 8% to support the European target of 450GW (Freeman *et al.* 2019; Caglayan *et al.* 2019). Clearly, the former scenario is far more feasible. However, under its current framework and given existing market conditions such a move would incur extremely high economic costs, compounded by restrictions on the maritime environment given various zoning restrictions and other environmental regulations. Furthermore, this level of deployment is only conceivable given significant grid enhancement alongside "strategic planning for storage and Power-to-X projects" (i.e. green hydrogen) in the upcoming years (Freeman *et al.* 2019). Additionally, up to around 75% of this capacity (45GW), would be for electricity trading purposes, as opposed to domestic consumption (Freeman *et al.* 2019). This suggests that the Netherlands may reach around 15GW of installed offshore capacity within the context of its national energy transition to bridge the gap brought about by its phasing-out of fossil fuels. Moreover, the alternative and far more ambitious scenario presupposes that in the future the Netherlands will become Europe's second lead market behind the UK, positioned far ahead of both Germany and Denmark. This scenario is tangible to a degree, but it is more likely that offshore capacity levels remain within a more modest range between 20 and 25GW, which still consolidates the Netherlands' competitive position among Europe's other frontrunner countries.

Figure 6.12. NL Offshore pathways: 2030 targets and fitted growth models with RSS



6.4.4 Summary

After prolonged wavering, the Dutch energy transition has come to the forefront of the political agenda. In no small part has this been due to the demise of its most valuable energy resource, the Groningen gas field. Additionally, progress on the CCS front has been laggard, leading to the Netherlands joining the PPCA. Phasing-out coal will lead to a 25% electricity gap that RESs or other sources will need to fill before 2030, provisionally. Reaching its 2030 target of 11.5GW will see the Netherlands source around 8.5% of its energy from OWFs, amounting to about 40% of current electricity consumption (Gov. of the Netherlands 2020). Clearly, the motivation to deploy offshore wind at scale is there and the stakes are high. The government's commitment to the energy transition is reaffirmed by an increase in its CO_s emissions target from 25% in 2020 to 49% by 2030 (WindEurope 2019). The following conditions make the large-scale deployment of OWFs highly feasible in the Dutch case:

- A rapid fossil fuel phase-out brought due to the phasing-out of natural gas and coal.
- Strong market conditions and investment incentive for RESs.
- A strong political framework for offshore wind deployment which includes a pipeline of projects, upcoming tenders, and a cohesive maritime plan.
- A well-established socio-technical regime for offshore wind with a significant market share of the global supply chain and state-of-the-art RDD&D facilities, located at the heart of the North Sea innovation hub.

- Favourable upscaling dynamics across a range of key techno-economic factors.
- TSO TenneT is the central actor driving developments and strengthening the market.

In sum, the Dutch offshore wind regime is characterized by an advantageous techno-economic, socio-technical, and political environment, which is likely to see offshore wind deployed at scale to reach a capacity of at least 10GW by 2030. Moreover, there is vast potential for long-term upscaling, as the government pushes its energy transition agenda, while backing Power-to-X technologies and targeting synergies across marine renewable activities and oil and gas operations.

6.5 The United Kingdom

6.5.1 Early uptake of UK offshore wind power through the TIS lens

Introduction

Following the privatisation of the energy supply industry in 1990, niche conditions for wind energy deployment in the UK took shape, supported by the introduction of the Non-Fossil Fuel Obligation (NFFO)[116] (Mackinnon *et al.* 2018). The NFFO imposed requirements for RESs in the energy mix, paving the way for RE subsidy schemes including the Renewables Obligation (RO) (Mackinnon *et al.* 2018). The UK's first commercial *onshore* wind farm came online in 1991 (Waugh 2003), the same year in which Denmark *alread*y launched its first *offshore* wind project.[117] The UK launched early RDD&D activities during the early formative phase; however, a lack of funding blocked developments, with Denmark emerging as the innovation core (Kern *et al.* 2014). Notwithstanding, Mitchell and Connor characterize the UK's early RE policy efforts as steeped in "opportunism, cost-limiting caps and continuous adjustments resulting from a lack of clarity of goals" (2004). In sum, the UK remained a relative laggard in the RE arena – trailing far behind frontrunners such as Denmark and Germany – until the launch of its Offshore Windfarm Programme[118] enabled the conditions to propel it towards a potential leadership status (Toke 2011; Kern 2014).

The innovation phase: Milestone 1 at Blyth

Following the launch of the world's first OWF at Vindeby, Denmark in 1991, UK developers drew inspiration from early progress in Danish waters, launching a handful of successful pilot projects

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[116] Kettle (1999) describes the NFFO as "an obligation imposed by an Order requiring the Public Electricity Suppliers (PESs) to secure specified amounts generating capacity from specified sources of renewable energy."

[117] Thus, the UK trailed Denmark and Germany by several years, eventually reaching 1% of electricity generation from onshore wind energy in 2006.

[118] Composed of The Crown Estate, UK Trade and Investment, the Green Investment Bank, RenewableUK and the Offshore Wind Programme Board (GIG 2014).

with the support of a purchase contract from NFFO (Dawley 2014). In 1992, the Blyth Harbour Windfarm served as the UK's first demonstration project (Dawley 2014), planting the seeds for entrepreneurial activities geared towards the launch of the country's first OWF in 2000 (F1):

> The account of the Blyth Offshore Wind Farm demonstrates the roles of key entrepreneurial actors – recombining knowledge, capabilities, and networks – in fostering strategic niche opportunities for the creation of the offshore wind sector in the North East region (Dawley 2014).

In 2000, the launch of the Blyth windfarm marked Milestone 1, as the UK became the fourth country behind Denmark, Sweden, and the Netherlands to enter the global offshore wind market.

Early market formation: Shielding and support from the Crown Estate

The UK seabed assets are under the ownership and management of the Crown Estate and the Crown Estate Scotland (CE),[119] dictating the centrality of offshore wind planning procedures as developers must acquire the rights for construction through the CE (Houses of Parliament 2019; Toke 2011). The prospective conditions for offshore wind deployment in the UK began to materialize in Spring of 2001, following the award of thirteen leases for the development of OWFs, limited to a maximum of thirty turbines each (Toke 2011). The necessary protective space for the UK offshore wind niche was facilitated by the CE, acting as "a trusted actor" and an intermediary between key actors, as it guided the search for offshore wind deployment **(F4)** (Kern *et al.* 2014).

Foremost, the CE supported market formation **(F5)** by identifying and releasing licenses for the commercial development of OWFs (Mackinnon *et al.* 2018). The CE also extended their special competences to play "an entrepreneurial, system building role" **(F1)** for unifying the nation's offshore wind vision (Kern *et al.* 2014). Within the protective space for offshore development, the CE provided "shielding" for an emergent "socio-technical configuration" (Kern *et al.* 2014), in which large utilities and energy companies absorbed the financial risks and high barriers to entry associated with commercial-scale OWPs (Mackinnon *et al.* 2018). The arrival of such actors added credibility and support to the technological space and strategic direction of offshore wind development **(F7)**. In turn, this configuration attracted turbine manufacturers such as Vestas and Siemens to invest in the UK market, driving the upscaling of turbine size during the late formative and early growth phases. Kern *et al.* (2014) refer to the UK formative landscape as defined by

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[119] The Crown Estate is an independent commercial business created by an Act of Parliament, tasked with optimizing the management of the UK seabed over the long-term. 100% of their annual revenue profits are returned to HM Treasury for the benefit of public finances (GIG 2014).

"relatively homogenous networks of powerful actors promoting one socio-technical configuration," namely large-scale OWFs under the jurisdiction of the Crown Estate.

From land to sea: 40GW in the Offshore project pipeline and counting

By the early 2000s, the UK's Engineering and Physical Sciences Research Council (EPSRC) started to pave the way for resource mobilsation **(F6)**, backing wind energy research with funding grants of several hundred thousand pounds, which continued to increase thereafter; doubling to average annual levels in excess of 0.5 billion GBP to help intensify R&D and knowledge development **(F2)** (Kern *et al.* 2014). Alongside funding mechanisms, the government launched a series of innovative support schemes for RE deployment, promoting knowledge diffusion **(F3)** and offshore wind investment (Toke 2011). Initially, land-based RE projects and particularly onshore wind planning had received a boost from planning policy guidance note, PPG 22, passed in 2004 (ODPM 2004). PPG 22 established the grounds for a "criteria-based" approach to RE project planning, whereby planning applications underwent assessment "against specific criteria set out in regional spatial strategies and local development documents" (ODPM 2004); prohibiting local authorities "from declaring 'no go' planning zones for windfarms" (Toke 2011).

Consent for OWFs is dispensed centrally, leaving local authorities restricted to "a consultative role," whereas the opposite holds true for onshore wind planning (Toke 2011).[120] As Toke (2011) documents, this set-up helped facilitate favourable regulatory conditions for offshore wind planning. As onshore wind met increasing political opposition, leading to a scarcity of viable sites and the subsequent removal of subsidy support (Mackinnon *et al.* 2018); offshore projects received widespread support for the most part. This shift added legitimacy **(F7)** to the offshore wind regime and strengthened opportunities for scaling up deployment across different regions of the UK's vast EEZ. As such, offshore wind presented an attractive alternative RE pathway following regulatory issues with onshore wind planning (Kern *et al.* 2014).

The political framework for offshore wind deployment was significantly strengthened in 2006 when the UK government increased its 2020 target from 15% to 20% of electricity from RESs (DTI 2006). In tandem to its revised RE policy, the Renewables Obligation (RO) scheme was devised as "the key support mechanism for the expansion of renewable electricity",[121] making

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[120] The government acts as the intervening body if constraints of a proposed project raise objections (ODPM 2004).

[121] The cost of the RO is met by consumers to enable smooth renewable energy uptake and competition with conventional energy sources, towards economies of scale comparable to mature energy technologies (DTI 2006).

specific adjustments to "incentivize the most economic forms of renewable energy generation," while ensuring higher support levels and investment confidence for emerging technologies such as offshore wind (DTI 2006). Over time, the government amended the RO to remove the risk of Renewables Obligation Certificates (ROCs) oversupply, implementing a 'banding' system to ensure higher accreditations for emerging technologies such as offshore wind.[122]

Throughout the 2000s and well into the next decade, the policy framework for offshore wind remained favourable towards rapid technology uptake. In 2008 – against the backdrop of increasing constraints for onshore wind developments – the newly revamped Department of Energy and Climate Change (DECC) declared offshore wind power a key part of the UK's forthcoming 'energy revolution' (Toke 2011), recognizing it as the country's "best scalable, mass deployable option" for RE deployment (DECC 2012). While the first round of issues for OWPs amounted to around 1.5GW of installed capacity, the subsequent round in 2003 added a further 7.2GW of planned capacity for 2010 onwards (Toke 2011). In early 2010, 'Round 3' marked an even more ambitious long-term deployment pathway, with 31.8GW of issues leased, followed by an additional 6.4GW for Scottish waters and 2GW for project extensions (Toke 2011), bringing the offshore wind project pipeline to around 40GW (DECC 2012). Toke (2011) highlights the magnitude of the UK offshore wind programme, which stood to exceed the French nuclear deployment of the 1970s and 1980s in terms of total capacity. However, to date UK installed capacity remains around the 10GW mark, leaving most of the project pipeline intact towards a 2030 target of 30GW.

Macro-level factors

At the macro-level, the UK's renewable turnaround was brought about due to growing energy security concerns stemming from the depletion of its domestic gas reserve and increasing dependency on imported natural gas; exacerbated by growing environmental and climate change pressures from within the domestic and international socio-political domain (Toke 2011). Shortly after the year 2000, (UK) North Sea gas production peaked and the UK became a net importer of natural gas by 2005 (Toke 2011). Amid other unfavourable changes to the European energy landscape, UK consumers faced steep increases in electricity and gas prices, which brought the issue of energy security to the fore of the socio-political sphere (Toke 2011).

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[122] For example, 2 ROCs/MWh for generating stations accrediting and additional capacity added in 2013/14 and 2014/15, reducing to 1.9 ROCs/MWh for those accrediting or adding capacity in 2015/16 and 1.8 ROCs/MWh for those accrediting or adding capacity in 2016/17 (DECC 2012).

In addition to helping to meet carbon reduction targets, offshore wind benefitted national energy security and industrial strength (Kern *et al.* 2014). Specifically, offshore wind provided the UK with the means to secure a competitive edge in growing EU renewable energy markets, with prospects for global ascendancy. Dawley (2014) identifies the UK's competitive edge in relation to the country's natural techno-economic advantage, stemming from its extensive shallow seabed, relatively high and consistent with speeds. These conditions provided the opportunity to harness the availability of port infrastructure and industrial facilities, and strong competences in marine engineering and oil and gas-related activities, creating strong synergies for seizing the economic opportunity offered by offshore wind upscaling (Dawley 2014).

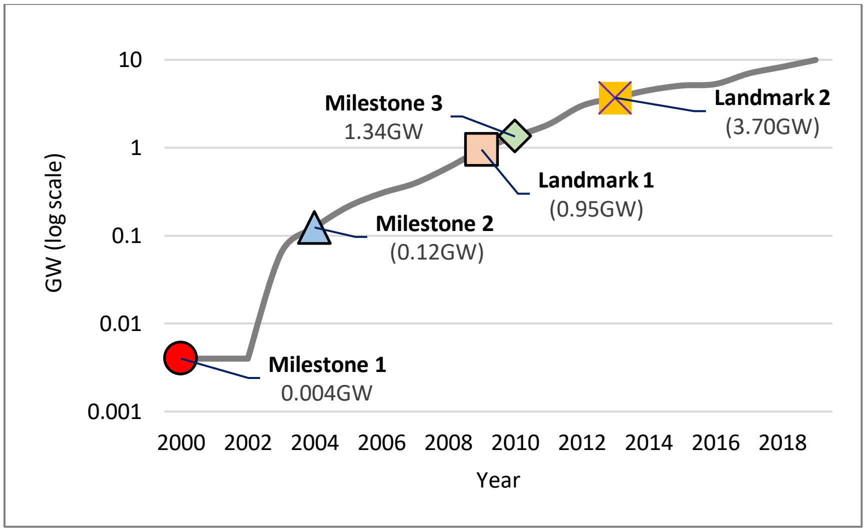
Diffusion beyond the formative phase

Having reached Landmark 1 a year earlier, in 2010, the UK became the first country to reach 1GW of installed offshore wind capacity (**Milestone 3**) (see Figure 6.13.). By 2013, 3.7GW of offshore capacity had been successfully deployed in British waters, three times more than the next lead market Denmark; nevertheless, there remained underlying structural weaknesses across the UK offshore wind landscape. In response to the drop off in industrial development, the UK Offshore Wind Industrial Strategy (OWIS) was launched in 2013 to address the reality that "over 80% of the value of some existing UK installations" had been sourced primarily from Siemens (Germany) and Vestas (Denmark) (Mackinnon *et al.* 2018). The OWIS aimed to reduce rising offshore wind costs, reinvigorate industrial development in ailing regions through "recentralization" of economic support (Mackinnon *et al.* 2018), and ultimately "to complete the economic circle of benefits for UK society as a whole" (Chinn 2014). In turn, the government formalized its strategy for building:

> …a competitive and innovative UK supply chain that delivers and sustains jobs, exports and economic benefits…supporting offshore wind as a core and cost-effective part of the UK's long-term electricity mix" with 50% of offshore industry value generated by domestic means (HM Government 2013).

Given its prioritization at the political level, the growth phase marked a shift away from market-based mechanisms towards a more interventionist approach, overseen by governmental agencies.

Figure 6.13. Milestones and Landmarks of UK offshore wind diffusion



Source: Author's calculations based on BEIS 2019; BP 2019; IRENA 2019d, 2019e; IEA 2020

Summary

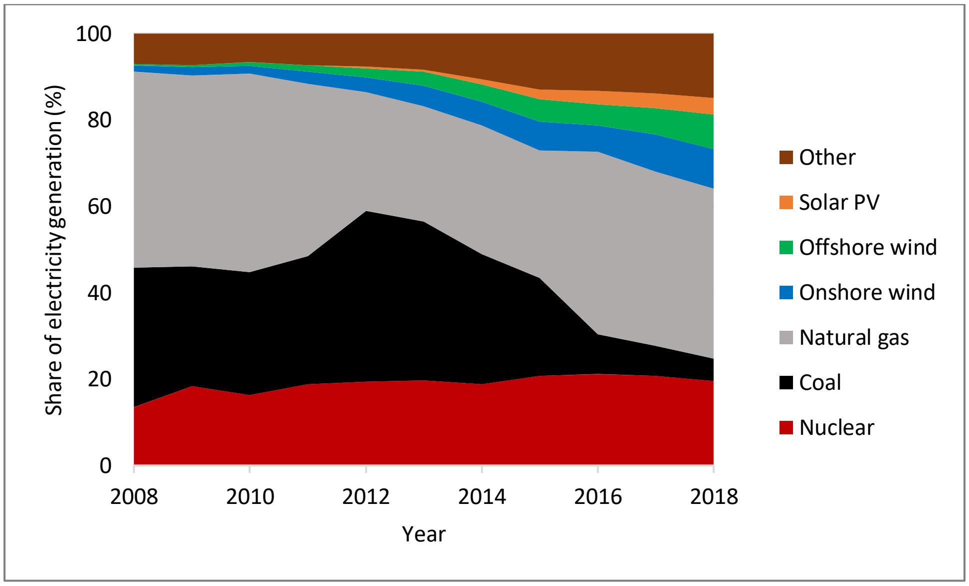
In conclusion, UK offshore wind emerged as a resource interdependent network with strong synergies between its various actors, providing the conditions for strong legitimacy as backed by investment flows, policy support and knowledge networks. The CE has served as an invaluable platform for co-investment and collaboration, bridging the space between industry players and government actors to improve prospects for large-scale offshore wind deployment (Kern *et al.* 2014). On the back its early success and colossal techno-economic resource potential, offshore wind has rapidly emerged as the future backbone of the UK's energy transition.

6.5.2 Offshore wind in the UK electricity system

6.5.2.1 UK electricity generation

Natural gas has remained at the heart of the UK energy system, despite the curtailing of domestic production. Norway is the main exporter to the UK (Norway.no 2020). Consequently, the overall decline of natural gas in the electricity mix has not been pronounced over the period, stabilising at 40% following a significant cut back of around 25% between 2012 and 2015 (see Figure 6.14). In contrast, the UK coal phase-out programme has proven far more impactful, adding legitimacy to its PPCA leadership status. During the 2010s, UK coal struggled to sustain its lead position in the UK electricity system – second only to gas – as power plants reached their end of lifecycle (Littlecoat 2016) and added pressure on the climate change front calls for rapid phasing-out. From 2014 to 2016, the share of coal in the electricity mix fell dramatically from 30% to 9% from which it has not recovered, plummeting further to 5% by 2018.[123] In turn, wind energy has picked up the bulk of the generation gap, scaling up between 2008 and 2018 from 1.5% to 9% and 0.3% to 8% for onshore and offshore wind, respectively. The UK case is unique in terms of offshore wind generating near to parity with onshore wind power, despite take-off coming several years later.

Figure 6.14. Evolution of UK electricity generation by energy source, 2008-2018



Source: Author's calculations based on BP 2019; IRENA 2019d, 2019e; IEA 2020

RESs have grown ten-fold over period, signalling a shift towards a clean energy transition, with the UK is pushing strong to have at least 20% of its electricity generation met by wind energy from 2020, while solar contributes a modest share at 4%. Nuclear energy continues to play a key role in the electricity system; whether as a transition source or a core part of UK energy strategy remains to be seen, as current nuclear build-out plans have met significant setbacks and economic constraints (Thomas and Sheppard 2019). Nuclear has stabilised at close to 20%, consolidating its place as the second electricity carrier behind natural gas in the post-coal era. Some nuclear power companies have viewed offshore wind as a "direct competitor to the long-term viability of their power plants;" however, most regard it as more of a replacement for coal power and a better alternative to heavy reliance on imported natural gas (Toke 2011). Notably, OWPs have become cheaper than adding new nuclear capacity or building gas-fired power plants, which rings true across the NESC (Freeman *et al.* 2019). The UK energy mix is a story of the demise of coal, the

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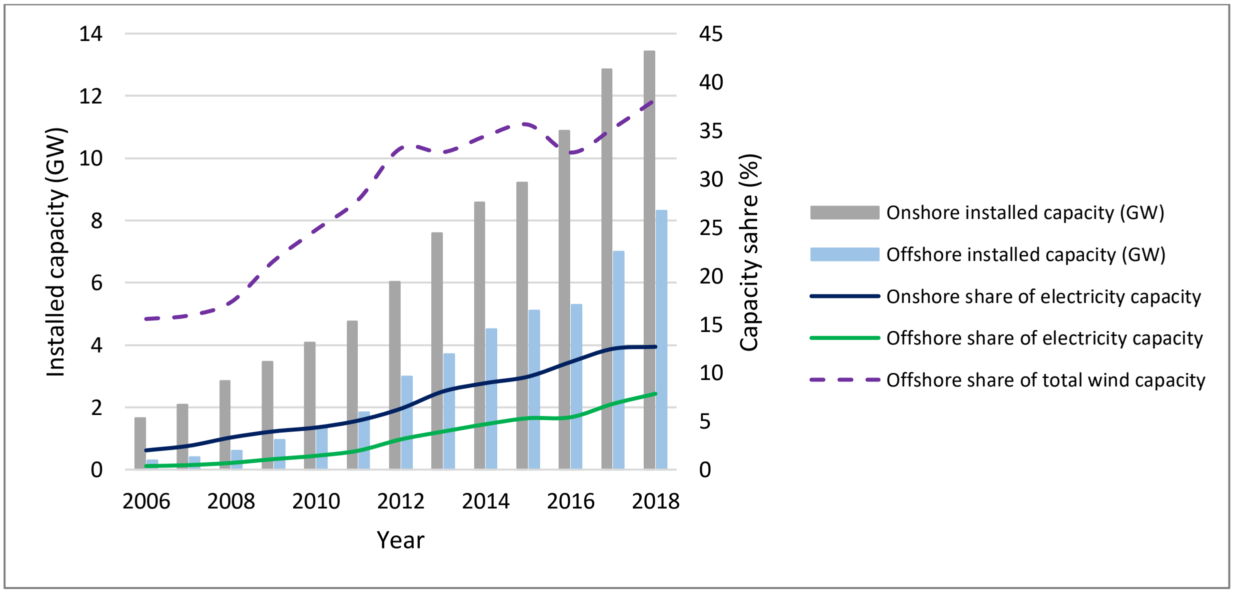
[123] 8GW of coal capacity was retired in 2016 alone (Littlecoat 2016).

rise of wind energy (especially offshore), high import dependency on natural gas and an ambivalent nuclear policy, following the collapse of the British shale gas exploration (Katona 2019).

6.5.2.2 UK electricity capacity

UK installed electricity capacity grew at a rate of 28% between 2006 and 2018, increasing from 83GW to 106GW. By the end of 2018, wind energy accounted for 20.5% of supply, up from just 2.4% in 2006. Onshore wind accounted for 12.7% with offshore wind at 7.8% in 2018. As a result, offshore wind power has secured more than a doubling in the total wind mix over time, moving from the 15–20% range before 2010 to the 35–40% since 2014 (see Figure 6.15., highlighting the nation's offshore wind boom. The last two years (2017 to 2018) show a key trend in the UK wind sector, as onshore installations stagnated and more so when compared to offshore wind, which continued to surge. Onshore wind added just 590MW while offshore wind added 1.31GW. Following 2018, additional OWPs came only taking capacity to 9.45GW, almost sustaining the absolute growth of the previous year. Wind energy trends in the UK show a strong uptake of wind energy at sea, and more so when compared to land where growth rates have declined due to regulatory constraints and public opposition.

Figure 6.15. Evolution of wind energy in UK electricity supply, 2006–2018



Source: Author's calculations based on BP 2019; IRENA 2019d, 2019e; IEA 2020

6.5.3 Feasibility of UK 2030 targets

6.5.3.1 Introduction

In 2008, the UK became the global leader in offshore wind power, having steadily gained ground on Denmark throughout the mid-2000s. Since this time, it has not relented on its leadership status, affirming the early vision of the Crown Estate (CE) for building an ‘offshore wind empire’ capable of propelling its RE crusade. While the UK faces stiff competition from Germany in European markets and China at the global level, the government has pledged commitment to a large-scale roll-out of OWFs over the next ten years, which will see installed capacity reach at least 30GW, while there are surplus gigawatts worth of plans already in the project pipeline. This level of deployment eclipses its European competitors by a significant margin. Upscaling is aligned to the UK Offshore Wind Industrial Strategy (OWIS), which seeks to ensure a higher volume of OWFs are sourced from the domestic supply chain; acting as a major economic stimulus that also solidifies political commitment to climate change targets. The remainder of this section evaluates the feasibility of the UK reaching its 2030 target and considers implications for 2050.

6.5.3.2 Techno-economic drivers of UK upscaling

UK OWPs have exhibited strong upscaling trends since launching in the early 2000s. From 2006 to 2012, the average distance from the shore doubled as developers exploited better conditions while also consenting to the government’s recommendation to build farther offshore. As this became the standard and national targets increased, the average distance from the shore stabilised at 12 km. With the addition of Hornsea Project One (1.2GW) in 2019 – the world’s largest OWF – all techno-economic parameters were raised, with the average distance to the shore reaching 15.5 km. Hornsea Project One was built 120 km from the shore covering an average area of over 400 km^2, dwarfing any other OWF in the UK[124] and testifying to unprecedented upscaling potential. With its deployment, the average area of UK OWPs increased from 38 km^2 in 2018 to 48 km^2 in 2019.[125] In terms of depth, there has been steady upscaling since around 2007, with the deployment of the Barrow OWF leading to a two-fold increase by 2007, which brought the average depth to around 17 metres (see Figure 6.16.). OWPs built in in 2018 and 2019 have seen average depth stabilise at 20 metres. New projects in the UK are being built with High Voltage Direct Connections (HVDC), which will enable smoother possibilities for upgrading OWFs with more powerful

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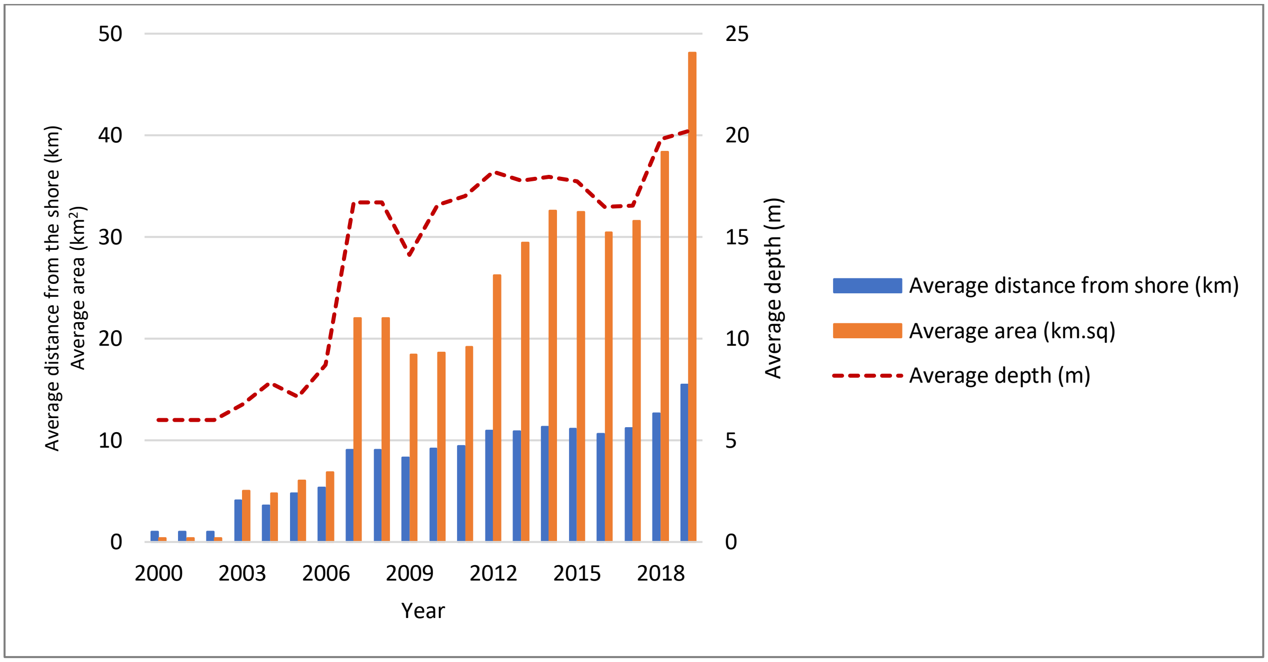
[124] By four-fold in terms of distance and nearly three-fold in terms of area

[125] The average during this period (200 –2019) was just below 20 km^2.

turbines (i.e. 10MW+) in the future, while also improving repowering options in the long-term (renewableUK 2020).[126]

Figure 6.16. Average distance from shore, area, and depth of UK OWPs, 2000-2019



Source: Author's calculations based on 4C Offshore 2020b, The Wind Power 2020d

6.5.3.3 Political and socio-technical drivers of UK OWFs

In 2012, the Offshore Wind Programme Board (OWPB) supported strong ambitions towards driving down the costs of OWFs to 100GBP/MWh for projects signed after 2020 (OWPB 2012), which was realised four years early, with costs falling by nearly 70% since 2015 (renewableUK 2020). According to renewableUK 2020, the Internal Rate of Return (IRR) (i.e. expected return on investment) is the main driving factor behind the cost of OWPs. Since the mid-2010s, the government has put in place a successful scheme for "creating a stable, reliable framework for investment in renewable capacity," through clean power auctions: 'Contracts for Difference' (CfD),[127] which replaced the Renewable Obligation (RO (renewableUK 2020). Since the mid-2010s, the CdD scheme has quickly become the government's principle *mechanism* for decarbonising the electricity grid, bringing the following key benefits to help secure a positive chain effect in the UK energy system: **(1)** It provides OWD owners (i.e. "capital-intensive

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[126] Current turbines have a design life of approx. 25 years, which will increase in the future (renewableUK 2020).
[127] The CfD creates a competitive environment for awarding OWP contracts, with an auction-based system, whereby applicants receive "the auction 'clearing price' rather than the administrative 'strike price' (Mackinnon *et al.* 2018).

projects") with fifteen-year visibility on future revenues, boosting market conditions, transparency and investment confidence; and **(2)** by making the push for OWFs less risky and more cost-effective from the side of the developer, the CfD results in lower net costs to consumers (renewableUK 2020). Consequently, all wind energy commissioned in the UK in 2019 was incentivised by offering CfDs (renewableUK 2020).[128]

The UK Government's 2017 Industrial Strategy together the 2019 Offshore Wind Sector Deal aim for GBP 250 million of industry investment across the supply chain, which will raise the "UK supply chain content from 48% to 60% and lead to a quintupling in exports (GBP 2.6 billion), in addition to a further GBP 557 million for CfD auctions available to offshore wind and other technologies (House of Parliament 2019). It is anticipated that wind energy (onshore and offshore) investment will reach GBP 2.5 trillion by 2040. One of the pillars of the UK strategy is to regenerate ailing regions by boosting investment and employment around new blade manufacturing sites along coastal areas in near proximity to OWP sites (House of Parliament 2019). The regeneration strategy targets a build-up of port infrastructure and a deepening of the supply chain through manufacturing of cables and other key components (House of Parliament 2019). In sum, the offshore sector is a significant driver for the UK economy, bringing around 11,000 high-quality jobs, which is set to reach 27,000 by 2030.

In 2019, the Offshore Wind Sector Deal was signed between the UK government and the Offshore Wind Industry Council, formalising a target of 30GW installed offshore wind capacity by 2030 ('3030' target hereafter) (renewableUK 2020). Following a series of positive developments in the offshore wind industry and stronger policy commitments on the climate change front (e.g. the government has recently pledged its commitment to a legally binding target to reach "net zero" carbon emissions by 2050),[129] ambitions are moving towards 40–45GW for 2030, in line with renewableUK's high-scenario and industry estimates (renewableUK 2020; Houses of Parliament 2019).[130] This may prove achievable since the current UK offshore pipeline – including both consented and announced capacity – is 44GW (Whitmarsh 2019).

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[128] Projects that are not yet grid-connected cannot participate in CfD auctions, which creates risk of deployment backlog given that the average OWP takes ten years to come online (renewableUK 2020).

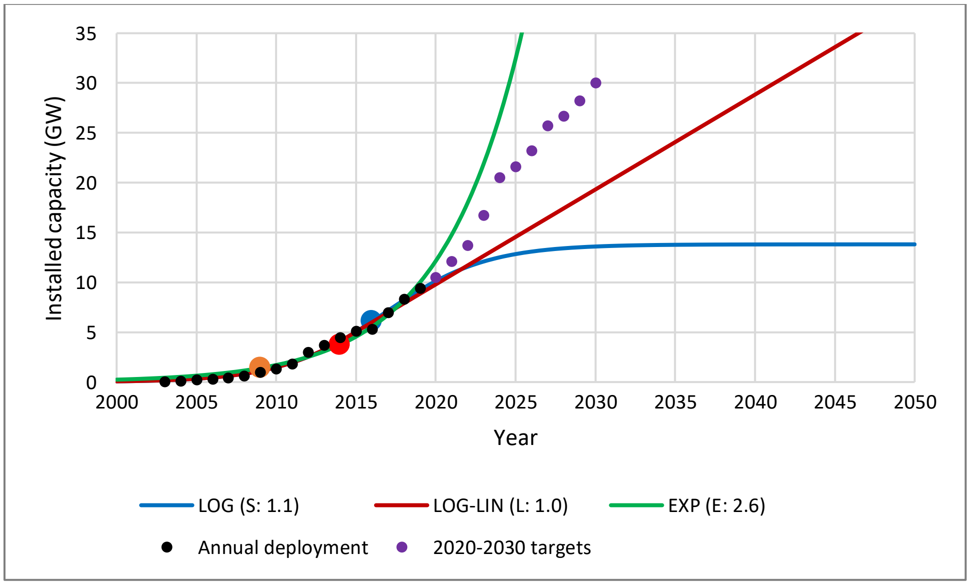
[129] The target is for 2045 in Scotland (renewableUK 2020).

[130] Under this scenario, OWE has the potential to increase to 90GW by 2050 (renewableUK 2050).

6.5.3.4 The UK quest for 30GW+ by 2030

In respect to the UK's '3030 quest,' logistic-linear growth fits the empirical data best followed by logistic growth, with negligible difference between the two pathways. Maximum growth (**red dot**) was reached in the middle of 2014 following an annual capacity increase of 22%. The inflection point (**blue dot**) was reached two years later around mid-2016, with a saturation level of 13.5GW by 2030 under conditions of logistic growth (see Figure 6.17). In contrast, logistic-linear growth takes capacity to 19GW by 2030 (reaching 38GW if extended to 2050). Clearly, linear growth at a rate of 1.39GW after 2015 is inadequate to deliver on the UK's 2030 target; however, if this rate grew to 1.66GW the UK would reach 30GW by the end of the decade. Given the large-scale projects in the offshore pipeline, it is feasible that the UK can fill this modest annual average capacity gap of around 270MW; provided it is on track by mid-decade with at least 21GW already grid-connected. In the case of the UK, the question is not so much *if* it can (i.e. has the capacity and motivation) to triple its current installed capacity, but *when* this milestone will be achieved by.

Figure 6.17. UK Offshore pathways: Empirical data and fitted growth models with RSS

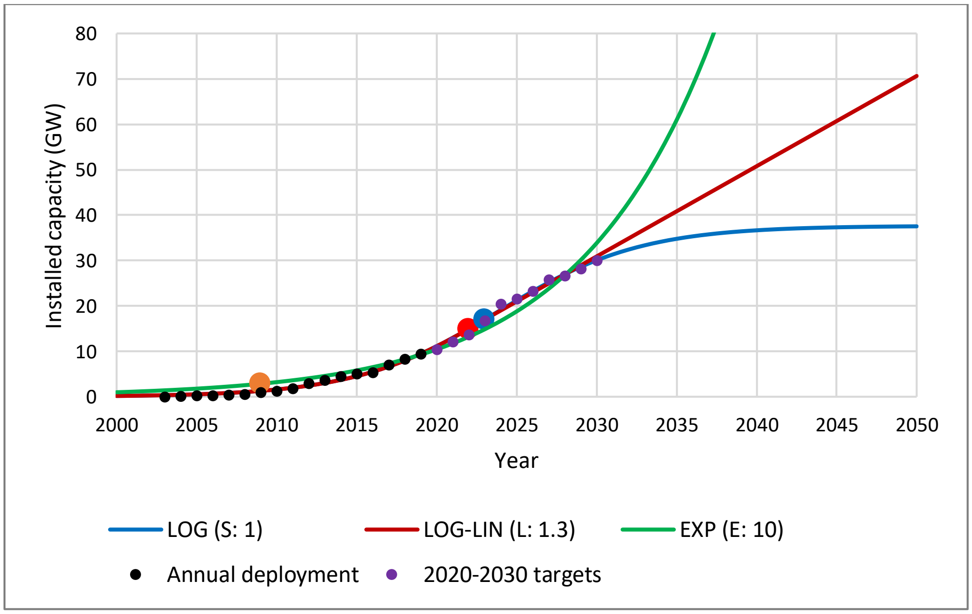


RenewableUK has developed a model to asses feasibility which includes the following variables in its calculations, many of which are incorporated within the analysis of driving mechanism within this study: "projects' construction timescales based on size, distance from shore, number of turbines, array cable length, number of cables and other equipment required…and the decommissioning of projects reaching over 25 years" (renewableUK 2020). The model, as well as the UK Offshore Wind sector, [131] project 2024 and 2025 to be the highest build out rates in the UK to date, with at least 5GW of capacity commissioned during this period (renewableUK 2020). This will follow off the back of a new landmark by global standards, with the Dogger Bank OWPs (3.6GW) planned for grid connection in 2023; bringing a new era of upscaling dynamics to British waters with 12MW turbines in operation (OGV 2020).[132] In addition, **floating offshore wind technologies** will become increasingly competitive in the future and 2GW is likely to be deployed in British waters before 2030 (renewableUK 2020; Houses of Parliament 2019).

6.5.3.5 Implications for 2050 deployment levels

The model indicates that logistic growth is the best fit, followed by logistic-linear growth, with minimal difference between the two. Logistic growth would mean that almost immediately after hitting its 2030 target, UK offshore wind reaches stagnation. This is an improbable scenario since current projects in the pipeline already exceed this ceiling (approx. 37GW). Alternatively, under logistic-linear growth nearly 51GW is deployed by 2040 and 70GW by 2050 (see **Error! Reference source not found.**.).

Figure 6.18. UK Offshore pathways: 2030 targets and fitted growth models with RSS



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[131] Based on a move to annual auctions after the next planned auction rounds in 2021 and 2023 (renewableUK 2020)

[132] Developed by GE Wind Energy, a subsidiary of General Electric (renewableUK 2020).

Logistic-linear growth may prove feasible since the UK has a vast natural resource in its EEZ that is unmatched by other NSEC frontrunners.[133] To reach an installed capacity of 70GW by 2050, the government would need to allocate an estimated 4% of its eligible EEZ area to OWFs (Caglayan *et al.* 2019; Freeman *et al.* 2020), which is a plausible scenario. Key driving factors that support the UK more than doubling its 2030 capacity levels include the advent of floating wind, which is predicted to contribute up to 20GW to 2050 capacity, as it becomes competitive with monopiles (renewableUK 2020). There is also growing interest from the UK's Oil and Gas Authority in assessing the feasibility of artificial islands combining the production of wind-generated electricity with (green) hydrogen (Richard 2019).

6.5.4 Summary

The UK Offshore Wind Sector Deal seeks to safeguard at least 30GW of installed capacity by 2030, with 1GW+ and 14MW+ turbines becoming part and parcel of UK waters. Alongside unprecedented upscaling dynamics, there is a clear, long-term industrial strategy in place, which aims to strengthen the domestic supply chain while increasing the UK's competitiveness in global markets. There is strong momentum in the UK's quest for 30GW+ by 2030, as supported by commitment to the energy transition and climate change policy. The following key factors highlight the driving mechanisms by which the UK may realise its offshore wind ambitions:

- High import dependency on natural gas which diminishes both its trade balance and energy security.
- Regulatory constraints on onshore wind planning and a stalled nuclear program, which stress the importance of offshore wind power in the electricity system.
- Strong pledges to achieve climate change targets and a growing leadership role in this area.
- A strong project pipeline supported by a healthy investment environment.
- Proven success with its Contracts for Difference (CfD) scheme for new OWPs.
- An industrial strategy targeting new supply chains, job creation and infrastructure development.
- Strength in engineering fields and other specialised branches of offshore wind construction, with support from oil and gas knowledge 'hardware' and 'software.'

[133133] Its EEZ is some seven times bigger than the next frontrunner, Denmark.

In conclusion, while the UK falls short of its 2030 target based on past deployment trends alone, the strength of its offshore wind socio-technical system and the wider regime growing around RESs is such that it is likely to overshoot its 2030 targets. This is made feasible by surplus gigawatts in the project pipeline, new breakthroughs in technical innovation and unprecedented strength between government and industry, with the Crown Estate (CE) ensuring the maximisation of the country's major asset, its vast EEZ. The UK can be credited with the 'crowning' of the offshore wind revolution and it is set to push the sector to new heights as the NESC's outright frontrunner.

6.6 Germany

6.6.1 Early uptake of German Offshore wind power through the TIS lens

Introduction

Germany's relationship to wind power resonates strongly with the Danish narrative. The two RE pioneers share close historical ties, with Germany's innovative tradition for manufacturing wind turbines also dating back to the late 1970s. In 1999, a decade after Denmark, Germany became the second country to generate more than 1% of its national electricity from wind energy. This achievement was partly built off Danish knowledge diffusion and technology spillovers. Until recently, onshore wind and solar PV remained the main sources of RE uptake in Germany; however, since the mid-2010s offshore wind has emerged more visibly as the latest "scalable solution" to delivering on the promise of the *Energiewende*[134] (Mackinnon *et al.* 2018). Recently, onshore wind has met increasing constraints in the face of regulatory constraints and public opposition, culminating in resistance to legitimacy after years of rapid growth. Consequently, 2019 saw growth in the offshore fleet outpace onshore wind for the first time in absolute terms, with 1GW of capacity added at sea (1469 turbines) compared to 900MW on land (Knight 2019a).[135]

The innovation phase: Research at Alpha Ventus

Germany's early history with offshore-based projects can be traced back to the early 1990s, strengthened in 1994 when small planning firms with entrepreneurial aspirations recognised the potential of sites in the Baltic Sea off the Rostock Coast (Reichardt *et al.* 2016). During this period, "small, innovative technology providers of onshore wind turbines and onshore wind project developers" pushed for offshore technological advancement **(F1)** (Reichardt *et al.* 2016). The late 1990s bore witness to significant technology transfer and knowledge exchange for offshore wind

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[134] Germany's Energy Transition.

[135] In comparison, solar PV grew by nearly 4 GW between in 2019 (IRENA 2019b).

(F3). For example, as an adaptation of its onshore design (EWEA 2009), German-Danish wind turbine manufacturer Nordex developed the N90-2.5 MW turbine, further solidifying the key network shared between Scandinavia's wind pioneer and Europe's wind giant.

The offshore industry began to receive legitimate support in the early 2000s, following the publication of the Federal Government's 2002 Offshore Wind Strategy **(F7)** (Bruns and Ohlhorst 2011). With the release of this key document, offshore wind RDD&D activities began to launch in earnest **(F2)**, benefitting from high levels of "cross-party political support," with regions such as the Northern Länder[136] incorporating OWPs as a strategic mechanism for boosting industrial regeneration and employment throughout economically vulnerable coastal regions **(F4 and F7)** (Reichardt *et al.* 2016). Ailing cities such as Bremerhaven, Cuxhaven and Emden quickly became boom areas with an estimated EUR 1 billion flowing to their shores, invested in port areas to enable turbine foundations to be loaded onto construction ships (Fröhlingsdorf 2013).

RETs started to receive stronger backing following the introduction of the Renewable Energy Act (EEG), passed in April 2000 by the newly elected red-green coalition government (Oschmann 2010). In 2001, the Federal Maritime and Hydrographic Agency (BSH) granted the first offshore permit to 'Alpha Ventus' (DOTI 2010),[137] followed by approval for the Butendiek OWP in 2002 (Mackinnon *et al.* 2018). Strategic alliances between federal ministries and local research institutes paved the way for early knowledge diffusion **(F2)**,[138] establishing core socio-technical networks to carry R&D breakthroughs from Alpha Ventus to new sites. Nevertheless, during the early years of research and experimentation, Germany's EEZ "lacked a coherent planning regime" (Mackinnon *et al.* 2019) and only in 2004 was the Spatial Planning Law (Raumordnungsgesetz) amended to account for the EEZ (Portman *et al.* 2009). This marked the start of a formal procedure for building a legitimate planning regime and regulatory framework for OWPs. Subsequently, in 2004 Ems Emden became the first grid-connected offshore wind turbine in German waters, located 600 metres from the shore at a depth of three metres and with a capacity of 4.5MW.

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[136] Germany's sixteen constituent states – the Länder – have specific instruments to support offshore wind projects, including the option to subsidise investments on top of EU funding. The Länder are also typically responsible for funding research institutes at the state level, and control strategic decision-making for key infrastructure projects capable of supporting the offshore wind sector such as the building of ports (Mackinnon *et al.* 2018).

[137] In September 2005, the German Offshore Wind Energy Foundation acquired the project rights to the offshore project originally known as Borkum West (German Offshore Wind Energy Foundation 2020).

[138] The Federal Ministry for Economic Affairs and Energy (BMWi-Energie) funded "Research at Alpha Ventus" (RAVE), hosted by the Fraunhofer IWES in Bremerhaven (Mackinnon et al. 2018).

Policy-push measures facilitated the conditions for innovation, industrial growth, and investment confidence during the early years of offshore development, exemplifying strategic planning between the state, science, and industry (Mackinnon *et al.* 2018; Ćetković *et al.* 2016). In 2007, the coalition government proposed an increase to the initial FIT, raising it from 9.1ct/kWh to 11-15 ct/kWh, in the process attracting commercial interest in OWFs from large utility companies. These larger players entered the offshore market by using their capital to absorb existing projects from small developers lacking the financial means to deliver on their plans (Reichardt *et al.* 2016). At the same time, the Offshore Wind Energy Programme provided financing support for smaller market players to develop OWFs, creating a more diverse market landscape in the process.[139]

Market formation: Deployment at Alpha Ventus

Having benefitted from the extended support of the Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety (BMU) (Reichardt *et al.* 2016),[140] Alpha Ventus (60MW) became grid-connected in 2009, marking an early landmark for Germany offshore wind. Alpha Ventus served to demonstrate the feasibility of deep water OWF construction, strengthening the socio-technical offshore wind regime by diffusing knowledge to other industry players across the Germany supply chain (Reichardt *et al.* 2016). The offshore wind industry received further financial support of around EUR 90 million from the Federal Ministry of Education and Research (BMBF) between 2008 to 2010, driving the commercialisation of OWPs including Baltic 1 in 2011 and BARD 1 in 2013 (Mackinnon *et al.* 2018). In 2009, the EEG amendment also raised the Feed-in-Tariff for offshore wind to 13ct/kWh for the first twelve years, including an additional 'sprinter bonus' of 2 ct/kWh for projects brought online before 2016 (Reichardt *et al.* 2016). Reichardt *et al.* (2016) refer to the launch of Alpha Ventus and changes to the Feed-in-Tariff rate as two key events that marked a "tipping point" (i.e. motors of change) in the German offshore wind TIS, helping to initiate the overdue take-off several lagged projects after 2009.

Constraints, bottlenecks, and uncertainty: Resistance to legitimacy post Alpha-Ventus

Following the launch of Alpha Ventus, German expansion grew steadily but large-scale deployment was stalled until 2015, as the offshore wind industry met a series of barriers and constraints. Reichardt *et al.* (2016) define 2009–2013 as a "resource crisis" phase plagued by grid connection problems and acute financial bottlenecks in the aftermath of the global economic crisis.

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[139] Examples of funded projects include Meerwind, Global Tech 1 and Butendiek (Mackinnon *et al.* 2018).

[140] BMU awarded more than 50 million euros worth of grant money allocated for associated research projects.

Technical issues delayed offshore growth while the investment landscape became more uncertain. Additionally, the advent of the "electricity price bake" discussion in 2013 raised doubts over project support and profitability.

Following the high surcharge used to fund RESs, electricity prices spiked between 2008 and 2013, increasing by 32% for residential users and 33% for industrial users (Deloitte 2015). Consequently, the environment minister Peter Altmaier voiced strong criticism against German energy policy, with an influential report – *Competition in Times of Energy Transition* – subsequently arguing to the same effect that the government's energy strategy rewards inefficient suppliers, fails to protect the climate, compromises the energy supply while also exacerbating energy poverty (Spiegel International 2013). This political uprising and tension between energy incumbents and newcomers stalled market formation, despite no actual changes being made to the policy instrument mix at the time.

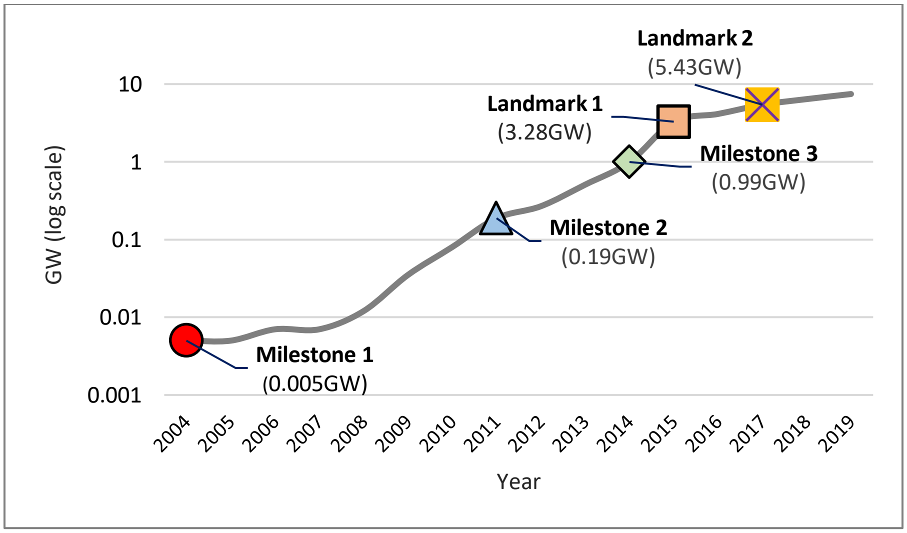
In the wake of Altmaier's electricity price bake crusade, the Riffgat OWF became emblematic of Germany's shortcomings at sea. Riffgat went ahead without power connection to the mainland, therefore instead of producing 'green' energy, its turbine rotors required electricity produced by diesel generators to prevent corrosion (Spiegel International 2013). The significant costs of Riffgat's technical defect – its missing power line – were in turn passed onto taxpayers, making a case in point for Altmaier's argument. Furthermore, from its inception the German offshore wind landscape has faced significant techno-economic challenges. Much of the country's potential deployment zone located in the Northern and Western coast lies within the jurisdiction of National Parks, which has forced project construction into deeper waters at around 40 metres where conditions are rougher and more technically challenging (Ćetković *et al.* 2016). In sum, turbines are generally located far from the coastline and in deep waters (EWEA 2015), which increases the difficulty of securing them to the seabed and achieving grid connection (Mackinnon *et al.* 2018).

Opponents of offshore wind also criticised the government's high subsidy for offshore wind, which was increased to 19ct/kWh, amounting to about fifty percent more than for onshore wind farms (Spiegel International 2013). Furthermore, the government "assumed the liability risk," meaning that taxpayers also bear project costs instead of OWF operators (Spiegel International 2013). Notwithstanding, these very measures added credibility and value to the offshore wind policy mix, improving investment prospects in the face of the resource crisis phase (Reichardt *et al.* 2016) while facilitating a clearer pathway towards long-term scalability (F4-F6).

Diffusion beyond the formative phase

Between 2014 and 2015 capacity tripled from 1GW to over 3GW, as Germany completed its remaining offshore wind milestones and landmarks (see Figure 6.19.); outpacing annual growth in the UK for the first time and consolidating a rapid pathway towards economies of scale.[141] After reaching 1GW,[142] Germany became the second lead market behind the UK, securing an annual turnover of EUR 1.9 billion and cumulative investments of EUR 10 billion, with 19,000 employees in the offshore industry (GWEC 2015).[143] However, following this rapid expansion phase, the government lowered its 2020 offshore wind target from 10GW to 6.5GW (Renewable Energy Act 2014), as a measure to slow the growth of green energy (E&E News 2014). Nevertheless, early years of policy push measures had already given Germany's institutional environment the foundations to pursue "path creation" via a series of effective demand-pull mechanisms and market creation incentives; boosting the potential for long-term upscaling as a strategic vision for industrial growth began to materialize (Mackinnon *et al.* 2018; Lema *et al.* 2014).

Figure 6.19. Milestones and Landmarks of German Offshore wind, 2004–2019



Source: Author's calculations based on BP 2019; IRENA 2019d, 2019e; IEA 2020

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[141] Rivalled only by China in recent years.

[142] Germany already had nearly 1 GW at the end of 2014 and consequently 2014 is taken as date of Milestone 3.

[143] The offshore sector remains dwarfed by its onshore counterpart, which boasted a workforce of ~119,000 in 2014, generating EUR 6 billion in new financial investment, with an annual turnover of EUR 10.6 billion (GWEC 2015).

Summary

German offshore wind has not been without its ups and downs, from the early days at Alpha Ventus to recent political commitment towards a higher 2030 target. Nevertheless, given the success of its onshore industry and its related engineering and manufacturing prowess, the German offshore wind sector was launched in confidence and arguably destined to compete strongly with the UK. The government's political will to promote OWPs in the face of considerable barriers and constraints has proved critical to sustaining the growth the its offshore sector. Notably, the government created transparency and certainty by setting a 2030 target of 15GW in 2014 – recently increased to 20GW – supported by annual tenders of 600 to 900MW (MacKinnon *et al.* 2018). While the industrial and political building blocks are seemingly in place to consolidate stable growth trends, capacity gains will depend upon wider events in the evolution of the Energiewende, as embedded in the techno-economic, socio-technical and political spheres of the energy system.

6.7 Offshore wind in the German electricity system

6.7.1 Germany electricity generation dynamics

The Energiewende has enjoyed some notable successes and appears to be gaining momentum as climate change pressures continue to mount; nevertheless, the German energy sector remains with its flaws and challenges. For example, natural gas makes little contribution to decarbonisation efforts since it has recovered to close to 2008 levels since 2016, stabilizing at around 13%. Excluding its partial nuclear power phase-out, the dynamics of electricity generation have not altered significantly over the course of the last decade (see Figure 6.20.).[144] The exception is nuclear power, which has a long history of socio-political opposition[145] and is set for phase-out by the end of 2022 (Deutscher Bundestag 2011).[146] In the wake of the Fukushima nuclear disaster, and given the history at Chernobyl in the 1980s, the European nuclear regime has largely struggled to regain its legitimacy in the face of growing public and political opposition (Kramm 2012).

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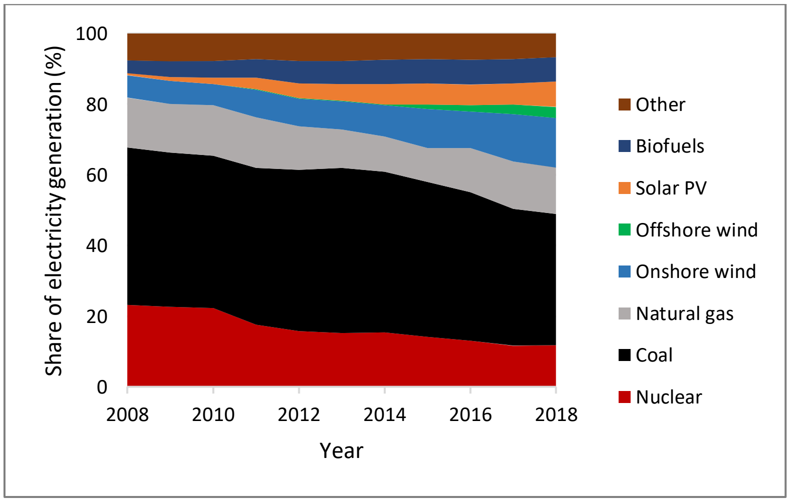
[144] Since 2008, nuclear, coal and natural gas have dropped from around 82% of electricity generation to 62%, however, nearly 60% of this decline is accounted for by the nuclear phase-out.

[145] The anti-nuclear movement dates back half a century to protests of the 1970s, later fueled by the 1986 'meltdown' at Chernobyl ((Jahn and Korolczuk 2012; Rüdig 2000; Appunn 2015a).

[146] Following a brief policy reversal prior to Fukushima, the newly elected government of Angela Merkel reaffirmed its commitment to a nuclear phase-out by the end of 2022 (Kramm 2012; Appunn 2015a; 2018); voting in favor of removing the operating licenses of 8 older nuclear power plants by June 15, 2011, with activities at the other 9 plants limited until end of 2022 (Deutscher Bundestag 2011; Appunn 2018).

Notwithstanding its imminent nuclear policy ‘success,’[147] the German government has tethered its economy to coal production and consumption until well into the 2030s, barring any significant policy overhauls. Thus, nuclear has (almost) ‘bitten the dust’ but coal is powering on. Electricity generation from coal has fallen by less than 0.75% annually since 2008, dropping from around 44.5% to 37%. Germany produces about half of its coal domestically (Jewell *et al.* 2019) and is also the world’s leading producer of lignite (‘brown coal’) (E360 Digest 2020). Nevertheless, Germany is also a member of the PPCA.[148] German coal capacity approximates the combined total of all PPCA members while its share of coal in electricity supply (~46%) is also higher than any PPCA member (Jewell *et al.* 2019).[149] To truly “harness the full potential” of its Energiewende, arguably a more ambitious coal phase-out is needed by 2030 (Topping 2019). Despite laggard efforts and frustrations due to the coal phase-out plan lagging behind “citizens’ timing preferences” (Rinscheid and Wüstenhagen 2019),[150] cost reductions in RE production – coupled to the growing demand for clean energy from the business sector – may provide suitable market conditions to bring about the end of coal before 2038 target (Topping 2019; Oei 2020).

Figure 6.20. Evolution of German electricity generation by energy source, 2008-2018



Source: Author’s calculations based on BP 2019; IRENA 2019d, 2019e; IEA 2020

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[147] The German strategy remains debateable since nuclear energy helps to decarbonise the electricity system.

[148] Set-up by the UK and Canada in 2017 to unite governments, organisations, and businesses (Blondeel *et al.* 2020).

[149] By a 30-yr weighted average, Germany has a younger fleet than PPCA members (Jewell *et al.* 2019).

[150] Germans believe the energy transition has reached 50%, well below other Europeans (RE World 2019).

The electricity generation gap brought about by the halving of its nuclear fleet and the gradual phasing-out of its coal sector has been filled mainly by onshore wind[151] and solar PV,[152] which form the backbone of the Energiewende. In 2018, solar PV also overtook biofuel-based generation for the first time, which has been stable between 6–7% since 2012. By contrast, offshore wind[153] is a newcomer to the energy system having emerged in a meaningful around the mid-2010s. Germany's first OWF became grid-connected in 2009 and it reached Landmarks 1 and 2 in 2015 and 2017, respectively.[154] Offshore wind increased on average by 0.6% between 2015 and 2018, bringing its share of electricity generation to 3%; before increasing to over 4% in 2019, equivalent to approximately 26 TWh and one-quarter of RE production (Knight 2020a). The recent growth of RESs indicates that a declining share of nuclear energy – whether brought about by an aging fleet, policy changes or a combination thereof – in addition to commitment to phasing-out coal represent strong preconditions for offshore wind uptake.

6.7.1.1 Germany electricity capacity dynamics

German electricity capacity grew at a rate of 60% between 2007 and 2019, increasing from 130.6GW in 2007 to more than 200GW in 2019, with the average for the period set at 172.6GW. Onshore wind accounts for 40% of the expansion – equivalent to a capacity gain of 30.8GW – and reached 54GW in 2019. Solar PV accounts for most the remaining capacity gains Figure 6.21.).[155]

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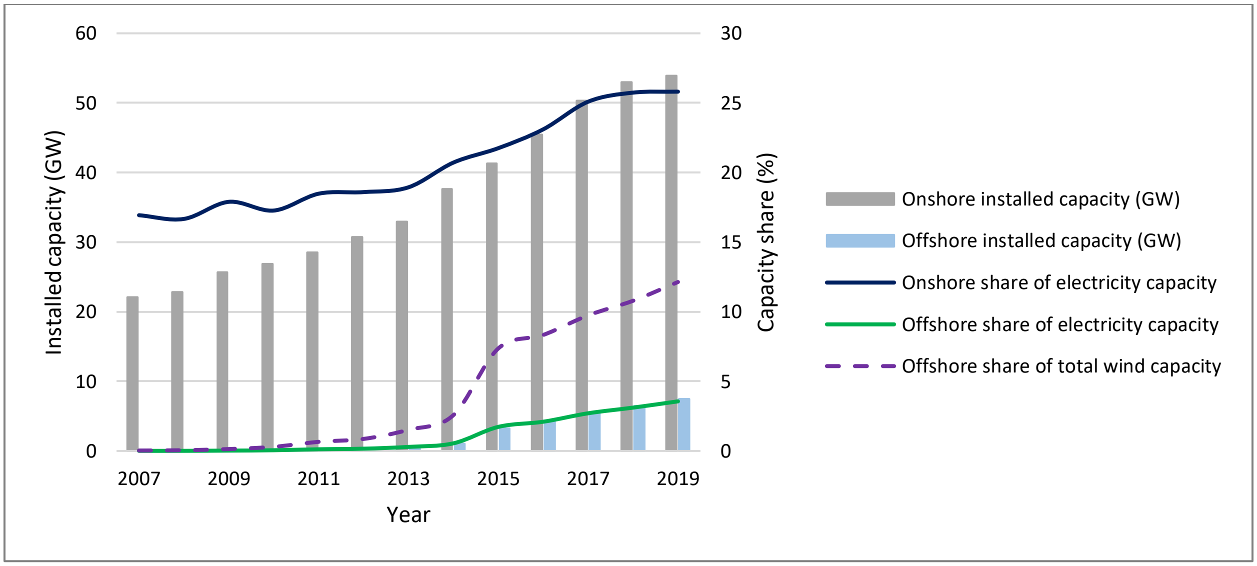
[151] Onshore wind generated 1% of the Germany's electricity in 1999, compared to 2015 for offshore wind.
[152] Solar has been ~ half the size of onshore wind since the early 2010s, growing from 4% in 2012 to 7% in 2018
[153] Onshore wind hit Landmark 1 in 1999, 16 years ahead than offshore wind.
[154] 2015 was also a landmark for onshore wind, as its share in electricity generation exceeded 10% for the 1st time.
[155] Solar reached its first gigawatt in 2004 when onshore was at approx. 16GW; thereafter it exploded to 10GW by 2009 with onshore wind at around 26GW, before taking the lead for the first time in 2011.

Figure 6.21. Evolution of wind energy in Germany electricity supply



Source: Author's calculations based on BP 2019; IRENA 2019d; IEA 2020

Since 2011, onshore wind and solar PV have closely shadowed one another in terms of growth patterns, swapping the lead from year-to-year, with solar slightly behind at 49GW in 2019.[156] Clearly, the Energiewende has very much been the tale of two RE carriers. Although dwarfed by both its onshore counterpart as well solar, offshore wind power has started to stake its claim, rising from less than 1% of total wind capacity in 2012 to over 12% by 2019. Offshore wind experienced its fastest growth rate between 2012 and 2015, increasing from just 2.6% of total wind capacity to 7.4%, reflected by a historic leap from 1GW to over 3GW. Capacity then doubled again between 2015 and 2018, finishing at 7.45GW in 2019, well ahead of the reduced 2020 target of 6.5GW.

6.7.2 Feasibility of German 2030 targets

6.7.2.1 Introduction

The feasibility of the new and more ambitious offshore wind target rests strongly on the evolution of the Energiewende. For example, solar PV may outpace wind energy and leave the offshore regime weakened or alternatively the coal phase-out may stall, potentially offsetting offshore wind growth in the process. Given the complexity of the Energiewende, many scenarios are plausible. Ultimately, growth patterns remain subject to dynamic shifts driven by techno-economic, socio-technical, and political mechanisms, which remain subject to uncertainty. Nevertheless, specific

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[156] Equivalent to an output of 547 watts per inhabitant (sönnichsen 2020).

observations can be made regarding the 2030 target based on past and emergent trends. This section sets out to assess the feasibility of Germany reaching its revised 2030 target and its recently announced 2040 target (40GW), while also taking into consideration further implications for 2050.

6.7.2.2 Techno-economic drivers of German upscaling

German OWPs demonstrate clear upscaling patterns across all key techno-economic parameters: average distance from the shore has increased from around 14 km in 2009 to over 54 km; the average project area has increased from around 12 km^2 in 2013 to 30 km^2; and finally the average depth has doubled to over 27 metres since the early 2000s (see **Error! Reference source not found.**.). Taking projects constructed since 2015 (take-off year), these trends become more pronounced, increasing by approximately 10-15%.[157] Since 2013, five projects have been built 100 km from the shore,[158] three projects have exceeded about 60 km^2 in size,[159] and all of the OWFs in question were built at a depth of about 40 metres, highlighting the extent of consistent upscaling dynamics and the trajectory of future developments. Turbine size is also set to increase significantly in German waters and across the NSEC. Siemens Gamesa Renewable Energy (SGRE) plans to bring the world's "largest and most powerful single-rotor turbine" to the market by 2024 (de Vries 2020), with a 14MW turbine boasting a rotor diameter of 222 metres (the SG 14-222 DD Mark VI),[160] which will raise annual energy production (AEP) by more than 25% compared to the 11MW version of the model (de Vries 2020).[161]

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[157] 63 km for average distance; 34 km^2 for average project area; and 30 m for average depth.

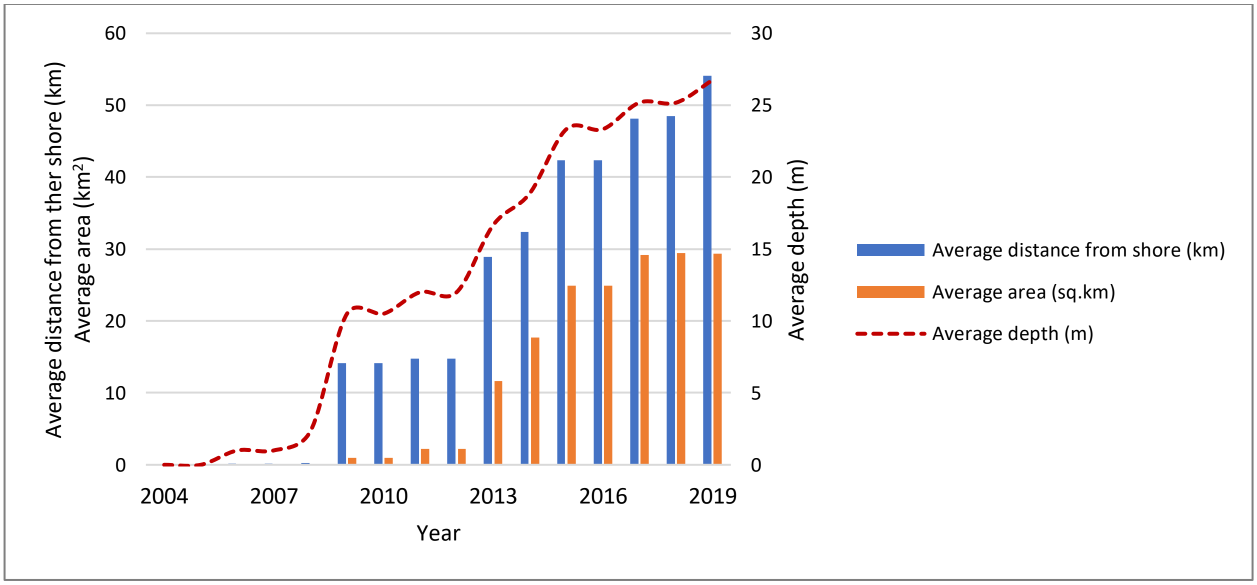
[158] BARD Offshore 1, Global Tech I, Veja Mate, Albatros and Deutsche Bucht.

[159] BARD Offshore 1, DanTysk and Gode I and II.

[160] SGRE has secured "preferred supplier status" for the Borkum Riffgrund 3 OWF (900MW) and as the Gode Wind 3 OWF (242MW), and 140 units have also been ordered for Dutch OWPs (de Vries 2020).

[161] SGRE seeks higher AEP at the project level, as opposed to maxim energy from single turbines (de Vries 2020)

Figure 6.22. Average distance from shore, area, and depth of German OWPs, 2004–2019



Source: Author's calculations based on 4C Offshore 2020b, The Wind Power 2020d

6.7.2.3 Political and socio-technical drivers of German OWFs

Germany overshot its 2020 offshore wind target a year early and will also exceed the current 2020 cap of 7.7GW (Knight 2020a).[162] It is possible that the same pattern could repeat itself in respect to its new 2030 target of 20GW, which has called for the addition of three new offshore connection systems, with nine in the North Sea and the remainder in the Baltic Sea (Knight 2020b).[163] The increased target – reached between TSOs, the federal government and local coastal authorities – has been made possible by resolving legal barriers to free up "2GW of idling (…) offshore transmission capacity to new projects" (Knight 2020a, 2020b).[164] BMWi is committed to realising "the determined, efficient, grid-synchronous and increasingly market-orientated expansion of renewable energies" (reve 2020); tasked with planning and permitting responsibilities, which are integral to ensuring cable connections are integrated optimally with onshore networks, so that decarbonisation of the electricity sector can take hold (Knight 2020b; reve 2020).

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[162] Notably, increased wind generation brought down the average value of wind energy in the wholesale market by c. €7/MWh to only €34/MWh in 2019 (Knight 2020a).

[163] By 2025, it is expected that the offshore grid reaches around 11GW capacity, with the upcoming round of auctions in 2021 set to allocate a further 4.5GW of installations between 2026 to 2030 (Knight 2020a).

[164] The German government allocated 3.1GW of installed offshore capacity through auctions in April 2017 and 2018 for the period 2021–2025, with tenders set for 500MW in 2021 and 2022, and 700MW thereafter) and an average of 840MW/yr from 2026 to 2030 (BMWi 2018; Knight 2020a). Peak deployment is likely to occur closer to the end of the decade to account for the additional 5GW of new capacity.

Stronger market conditions and the urgent need to progress on the Energiewende front have led to the current middle path target. Reaching 25GW by 2030 would call for additional large-scale projects and tenders would need to be approved in a timely fashion before 2025 to realise such ambitions. Encouragingly, Germany has proven itself highly capable of rallying political strength and deploying RETs at scale. Moreover, it has in place a strong relative advantage in the wind sector following its unprecedented onshore success, which has helped drive offshore expansion. According to the energy ministry of Lower Saxony, the increased target is a direct result of technical breakthroughs, with the newly available 525kV cable technology enabling a doubling of transmission capacity compared to the standard 320kV technology (Knight 2020b). Alongside this key innovation, the prospect of green hydrogen commercialisation means that some of the electricity produced by OWFs can be transmitted to other offshore facilities; providing a safety net in case of grid disruptions and a further market-based incentive for investing in offshore wind.

Germany has a strong industrial profile across all areas of the offshore wind supply chain,[165] excelling in turbine production with Siemens ranking as one of the top three global producers in offshore sub-station technologies (Mackinnon *et al.* 2018). Additionally, "sub-national divisions of labour" have strengthened the depth of its industrial offshore base: engineering and assembly in Bremerhaven; R&D and management in Hamburg; and innovation and advanced engineering distributed across key regions of the country's industrial interior such as North-RhineWestphalia (Mackinnon *et al.* 2018). The sector also thrives on its core alliances with transitional utility companies, with German-based utilities (e.g. RWE Innogy and E.ON) capitalizing on their domestic market strength to establish their presence in external markets (e.g. UK , DK and SE) (Mackinnon *et al*. 2018). Germany's industrial strength stems from its established industrial bases across different parts of the Länder, facilitating the conditions for successful branching across manufacturing, engineering and logistical activities related to OWFs (Mackinnon *et al.* 2018).

Germany's offshore industry is characterized by a diverse pattern of geographic growth, achieved through mechanisms of branching and diversification (Mackinnon *et al.* 2018). German firms are accelerating technology advancements in towers and foundation structures,[166] while also

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[165] Lema *et al.* (2014) estimate 200+ companies are active across the German wind industry, with one-third operating in the manufacturing sector and two-thirds active in across other deployment activities (Mackinnon *et al.* 2018).

[166] By 2014, the average capacity of German offshore wind turbines reached 3.7 MW, with a rotor diameter and hub height of 120 and 89 metres, respectively (GWEC 2015).

diversifying away from steel production and processing; constructing the foundations for offshore wind turbines, with EEW[167] becoming a key international supplier (Mackinnon *et al.* 2018). Industrial strength, vast technology resources and a strong socio-technical regime with international reach add significant weight to the feasibility of Germany meeting its offshore wind goals. As it looks to extend the scope of its extensive supply chain and maximize its export advantage, Germany may in turn succeed in overshooting its 2030 target as it invests domestically to further bolster its international presence and potential revenue streams.

6.7.2.4 The German quest for 20GW+ by 2030

Figure 6.23. presents a partial view of key future trends up to 2030. Growth in RESs is set to outpace declines in coal production and the capacity gap left by the nuclear phase-out. RESs will add around 70GW of installed capacity, with offshore wind contributing approximately 17% of the growth while at least 29GW of non-renewable capacity is likely to be phased-out. At present, onshore wind remains by far the dominant wind technology, standing at around a quarter of total installed electricity capacity. However, this gap is set to close as offshore wind scales up at least two-fold.[168] Moreover, proponents of offshore wind argue in favour of a 2035 target of 30–35GW and more than 50GW by 2050, as a measure for balancing the imminent supply gap left by the upcoming nuclear phase-out and the ongoing coal phase-out (Knight 2020a).

Onshore wind is positioned to grow incrementally, whereas solar growth is likely to prove more substantial. In this regard, the government has downsized initial plans for 80GW of onshore wind to 67–71GW by 2030 (Franke and Burgess 2019) while solar targets are being raised to 98GW from an earlier target of 85GW (Enkhardt 2019; Wettengel 2019). Clearly, there is strong momentum behind RE expansion given the current targets and emerging growth trends. The question remains as to how feasible it is for offshore wind to grow from 8GW to 20GW by 2030?

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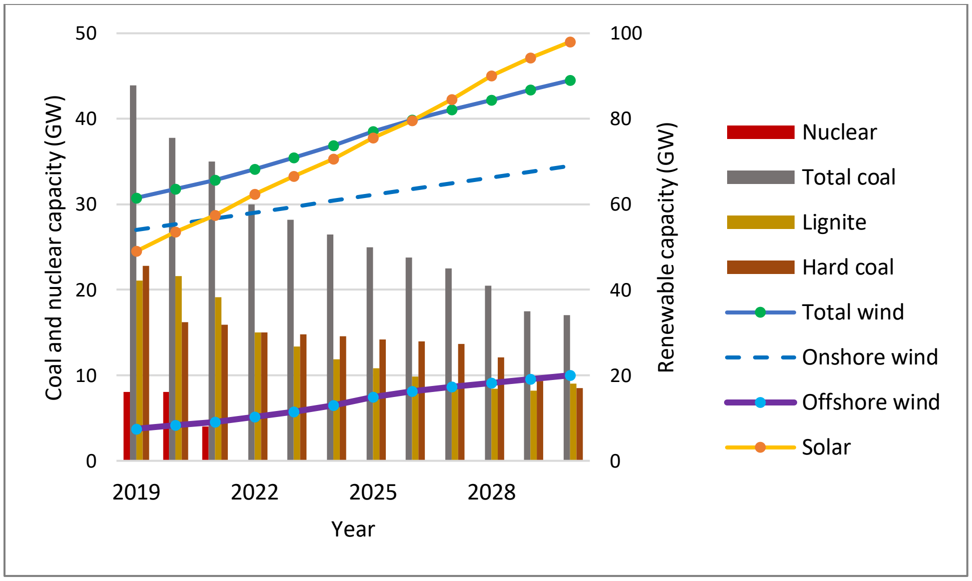
[167] https://eew-group.com/

[168] By contrast, onshore wind could not feasibly double to over 100GW within the next decade, given the policy climate and associated market stagnation.

Figure 6.23. Germany electricity capacity projections, 2020–2030



Source: Author's illustration based on BMWi 2018; IRENA 2019d, 2019e; IEA 2020; Wettengel 2020

The model confirms that maximum growth (**red dot**) was reached at the start of 2014 while the inflection point (**blue dot**) followed just before the end of 2016. In between this period, Germany secured Landmark 1 (**orange dot**), as offshore wind became relevant at the level of electricity capacity. Logistic growth and logistic-linear growth have an equal goodness of fit; however, there is a clear distinction between these two pathways. Under conditions of logistic growth, saturation is reached by the mid-2020s and the ceiling is just 7.7GW, which is implausible given current operations.[169] Therefore, the 2030 target fits the logistic-linear growth model, as well as the empirical data, better than alternative growth models (see Figure 6.24.). Logistic-linear growth would see Germany to hit 21GW of offshore capacity by 2030, having reached close to its original 2030 target of 15GW by as early as 2025.[170] Beyond 2030, logistic-linear growth results in a doubling of capacity, as offshore wind reaches close to 46GW by 2050. In this regard, it is noteworthy that the government initially outlined a 2030 target of 25GW, which was later scaled back to 15GW due to the high technological costs of offshore wind (Wehrmann 2020).

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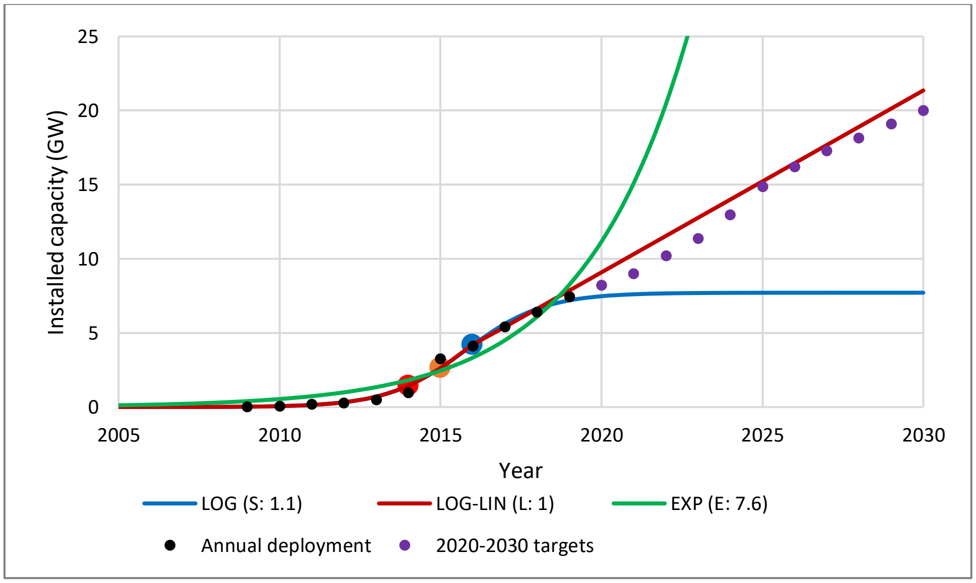
[169] Germany has already surpassed this capacity level accounting for 2020 deployment.

[170] Figure 6.24. confirms that exponential growth is a poor fit for German offshore wind plans beyond 2020. This is due to earlier growth rates in the mid-2010s (i.e. the one-year jump from 1 to 3GW) being unsustainable given the techno-economic constraints and high investment costs of offshore wind.

Figure 6.24. DE Offshore pathways: Empirical data and fitted growth models with RSS

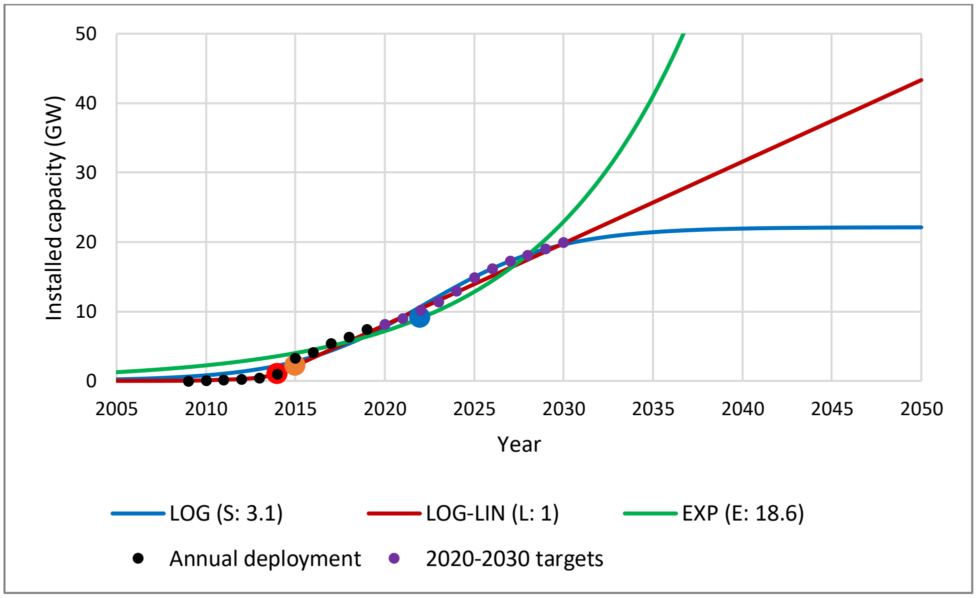


6.7.2.5 Implications for 2050 deployment levels

Should Germany reach its 2030 targets, the rate of linear growth is only marginally affected; reducing the 2050 total from 46GW to 43GW, however, there is a noticeable impact of logistic growth. The 2050 ceiling increases close to three-fold from around 8GW to 22GW, indicating the minimum build-out potential under adverse market and/or political conditions. Given that the government has recently backed plans for 40GW by 2040, there is justification to believe that political conditions in the time of the Energiewende will remain favourable (IEEFA 2020). For 2040, the growth fits suggest a more modest capacity level of 31.5GW with maximum growth in 2014 (**red dot**) and inflection in 2022 (**blue dot**). Notably, this is 10GW higher than the model based solely on empirical data until 2019 (see Figure 6.25.).

Notwithstanding, there are underlying techno-economic concerns that could potentially derail newfound ambitions. The Baltic Sea is a more difficult location for realising new OWPs than the North Sea. Close to three-quarters of the region is within 22km of the coast, which constrains Germany's resource potential in these waters under the current exclusion zone legislation (Freeman *et al.* 2019). Given these constraints – including sizeable areas of Natura 2000 sites – Germany faces higher build-out costs than if the spatial exclusions were less stringent. Germany's EEZ is 56,000 km^2 and around 13% of this area (7,000 km^2) would be needed to support 35GW worth of OWFs (Freeman *et al.* 2019). Under a high ocean eligibility scenario, German waters are restricted to 13,500 km^2 from the total EEZ, therefore, this scenario would call for at least 50% of the available space being utilised (Caglayan *et al.* 2019). This may prove unfeasible by 2040, not to mention that extra zones would be required to support an additional 5GW.

Figure 6.25. DE Offshore pathways: 2030 targets and fitted growth models with RSS



The German grid is also need of enhancement if OWFs are to become a staple of the electricity mix; the onshore grid running from north to south especially warrants investment and upgrading to avoid bottlenecks in the energy system (Freeman *et al.* 2019). Collaboration with its neighbours to realise interconnection expansion and make offshore hybrid project viable is also a prerequisite for upscaling beyond its 2030 targets (Freeman *et al.* 2019). Finally, Fraunhofer IWES forecast that Germany could generate close to 260TWh of electricity from offshore wind by 2050,[171] given a potential capacity of 54GW (Wehrmann 2020). Sustained logistic-linear growth through to 2050 would see capacity fall short by about 10GW; however, as highlighted this may still breach Germany's techno-economic capacity. Clearly, the German offshore wind sector is not without its obstacles to overcome if it is to reach 40GW by 2040 and grow further towards 2050.

6.7.3 Summary

The Energiewende is a complex long-term project, compounded by a range of energy carriers and competing interests. Offshore wind is a relative newcomer to the mix but has quickly emerged as a key part of the post-2020 energy strategy. The German narrative and its TIS, along with unprecedented industrial strength across key strategic areas of the Länder, highlight the foundations

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[171] This the amount needed to reach of 80% power from RE, according to Fraunhofer IWES (E&E News 2014).

that have enabled Germany to rival the UK. However, unlike the UK, offshore wind targets have been revised in both directions; from 10GW to 6.5GW for 2020, and 25GW to 15GW for 2030, but subsequently raised from 15GW to 20GW for 2030, with a newly announced 2040 target of 40GW. Clearly, the momentum shift is in the right direction. Nevertheless, these reversals signal an unstable political environment for offshore wind, mirroring previous U-turns on nuclear policy in earlier decades. Despite these constraints and particularities, German offshore wind development is strongly supported by the following key factors:

- An imminent nuclear phase-out and a long-term phasing-out of coal power.
- Germany is Europe's onshore wind giant, with a well-stablished onshore sector strongly correlated to offshore growth and the potential for securing economies of scale.
- Concurrently, trends of onshore wind saturation create additional space for opportunity.
- Germany is the manufacturing and engineering powerhouse of Europe.
- High economic incentives to grow its offshore wind industry to compete in global markets.
- Increasingly strong (Energiewende-based) political backing with newfound ambitions
- The early to mid-2000s have acted as a strong learning curve for its socio-technical regime.
- Germany can reach its targets by marginally increasing its linear growth rate.

In conclusion, while the offshore wind sector faces challenges and constraints, it appears that a strong political will is in place to ensure Germany maintains its status as a lead market. Political feasibility is supported by strong upscaling dynamics, industrial networks, and an entrepreneurial spirit for achieving innovative success and market domination, as witnessed onshore.

6.8 Belgium

6.8.1 Early uptake of Belgian Offshore wind power through the TIS lens

Introduction

Despite having the smallest EEZ in the North Sea (Elia 2019) and being a relatively late adopter, Belgium has emerged as an offshore wind frontrunner (Hensmans 2017). In the early 2000s, the Belgian federal government provided the motor of change to help guide the search for long-term development **(F4)**, allocating a 156-km^2 area within its EEZ specifically for the construction of OWPs (Hensmans 2017). Following this decisive action, investments flowed readily to the offshore wind sector. This period also saw extensive RDD&D activities **(F1 & F2)**, in preparation for large-scale deployment by the end of the decade. Belgium's geographic proximity to the North Sea hub of innovation helped provide the conditions for accelerated knowledge diffusion **(F3)** during the early formative period. As a latecomer, Belgium launched its first OWF at a comparatively large scale, reaping the benefits of knowledge spillovers from its North Sea neighbours.

Market formation: Deployment at Thorton Bank I

Grid-connected activity got underway in the Belgian North Sea in 2009 with the deployment of 32MW during Phase 1 of Thorton Bank, distributed across six turbines as part of the C-Power OWF (BOP 2019).[172] Market formation **(F5)** and legitimacy **(F7)** soon followed, with both the government and the Belgian population viewing offshore wind as one of the country's "strongest trump cards" towards improving security of energy supply and reducing import dependency (BOP 2014b). High levels of energy dependence on natural gas and reliance on electricity imports made a strong case for offshore wind. Moreover, opposition to nuclear power has intensified following repeated 'black out' episodes during the winter months (AleaSoft 2019).

Belgium's NECP has reaffirmed commitment to a complete nuclear phase-out by the end of 2025, adding momentum to offshore wind's bid to become one of the country's primary electricity sources (AleaSoft 2019). The phase-out is driven by an anti-nuclear political agenda strongly influenced by nearby events, with the Belgian move following in the footsteps of Germany and aligning closely to the French agenda. Notably, Belgium is sandwiched between two European energy giants with its electricity market coupled 40% to 60% of the time with France, depending on the season (AleaSoft 2019). In the face of high import dependence and an ailing nuclear fleet, the Belgian population widely support wind power as a key energy alternative **(F7)**. According to a 2014 IPSOS survey,[173] 70% of Belgians support using RESs to meet the countries energy production while 85% believed wind energy will prove critical to the country's future energy supply (BOP 2014a). A subsequent opinion poll conducted by Kantar TNS in 2017 reported that 87% of Belgians think the government must respect its climate change obligations in view of 2020 targets, with 83% supporting maximum investment in wind energy as part of the country's energy transition strategy (BOP 2017). Notably, Belgium was the first European country to phase-out coal-fired power plants, having shut down its last 470MW of installed capacity in 2016 (AleaSoft 2016).

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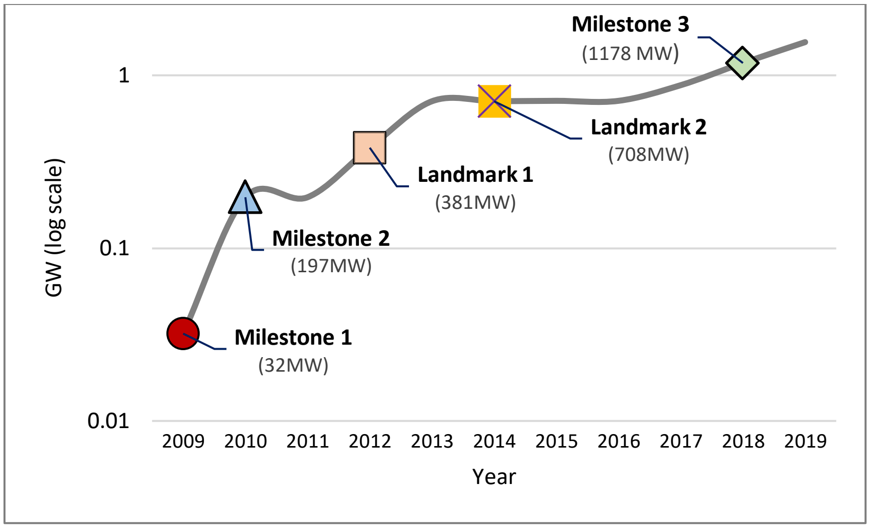
[172] With Phases 2 and 3 of Thorton Bank already completed in 2012, the C-Power OWF became fully operational with 232 turbines generating 2,867 TWh of electricity in 2017 (Hensmans 2017).

[173] Commissioned by three leading renewable energy federations (ODE, EDORA and BOP (BOP 2014a).

Resource mobilisation **(F6)** has been reinforced by subsidy support and the potential for substantial positive externalities. Through the establishment of efficient domestic socio-technical networks with high export potential, the Belgian offshore wind industry brings multiple socio-economic benefits such as economic growth, strengthening of R&D, industrial growth, employment, and clean power generation. According to conservative estimates, Belgian companies were awarded approximately EUR 400 million in foreign contracts for OWPs in 2013 (BOP 2014c). Consequently, Belgium is the frontrunner country that hit its offshore milestones and landmarks within the shortest timeframe (see Figure 6.26.).

Figure 6.26. Milestones and Landmarks of Belgian offshore wind diffusion



Source: Author’s illustration based on BP 2019; IRENA 2019d, 2019e; IEA 2020

Growth beyond the formative phase

In 2016, full financing was secured for the country’s sixth and largest OWP, with a total investment of EUR 1.2 billion from a mix of private[174] and public investors[175] (BOP 2016). This move consolidated rapid market formation **(F5)** and Belgium’s position as one of the strongest newcomers to Europe’s offshore wind boom. The Norther OWF – consisting of 44 MHI Vestas 8.4 MW wind turbines – has acted as further stimulus to industrial growth and employment, creating 1,400 direct full-time jobs in the construction sector and a similar number of indirect jobs for full-time ancillary and support staff (BOP 2016). The offshore wind industry has brought significant

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[174] ABN Amro, Belfius, BNP Paribas Fortis, BTMU, Rabobank, SMBC, SMTB, Société Générale banks (BOP 2016).

[175] The European Investment Bank (EIB) and the Danish Export Credit Agency (EKF) (BOP 2016).

positive socio-economic benefits, supporting about 15,000 jobs across the construction, and operation and maintenance (O&M) of domestic OWFs. (Breyer *et al.* 2017). The addition of offshore wind to the electricity mix also puts downward pressure on wholesale electricity prices for more competitive energy markets (i.e. the merit order effect) (Breyer et al. 2017).[176]

Summary

Belgium's offshore wind plans are supported by well-established socio-technical networks and strong techno-economic capabilities, albeit with the limitation of a small EEZ. Belgium finished 2019 as Europe's fourth largest market with an installed capacity of 1.56GW, following an annual increase of approximately 30%. In terms of offshore wind production capacity per capita, it ranks third behind the UK and Denmark **(**BOP 2019). Offshore capacity is set to shortly reach 2GW, following the connection of the 219MW Northwester 2 and the 487MW SeaMade OWFs. These additions will bring offshore annual electricity generation to around 8TWh, equivalent to around 10% of electricity demand, up from 6% in 2019 (Durakovic 2020). Given its proposed energy strategy and established strategic ties with its neighbours for scaling up offshore wind investments, Belgium has strong momentum to grow its offshore wind capacity to 4GW by 2030 (Breyer *et al.* 2017; EC 2018d). Fulfilling this target will rest heavily on the rate of at which OWFs replace nuclear reactors as a substitute source of electricity generation.

6.8.2 Offshore wind in the Belgian electricity system

6.8.2.1 Belgian electricity generation

As a small, flat, and densely populated country with limited solar potential, Belgium is resource poor, making it highly energy import dependent compared to most of its neighbours (AleaSoft 2019). The two pillars of Belgium's domestic electricity production are nuclear power[177] and gas combined cycles (AleaSoft 2019). Throughout the 2010s, around half of its electricity production was sourced from nuclear power, following the push back of the start of its phase-out program to 2022 (World Nuclear Association 2018). Natural gas met about a quarter of Belgium's electricity demand, adding to its import deficit (AleaSoft 2019). In 2008, renewables were still negligible at less than 1% of total electricity generation. However, by 2009 wind energy passed the 1% threshold

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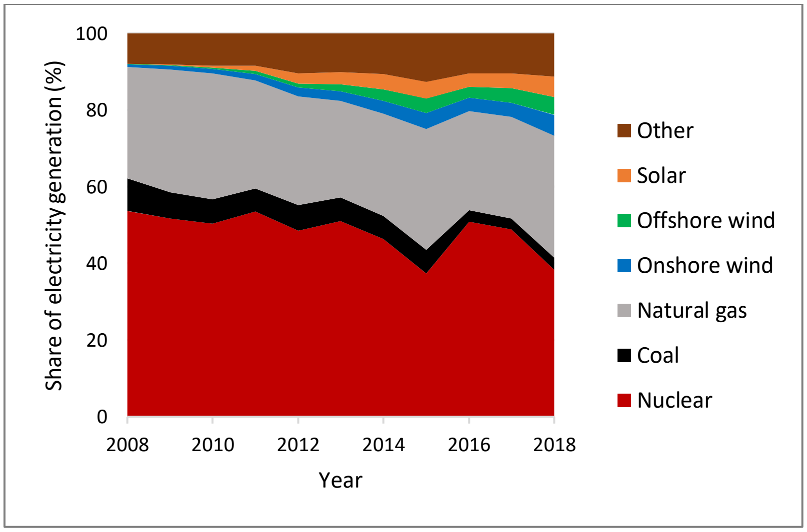
[176] The power price is determined by the merit order: the sequence in which power stations contribute electricity to the market, whereby the power station with the lowest running costs sets the starting point by making the cheapest offer. The increased supply of RESs lowers power prices at the electricity exchange (Appunn 2015b).

[177] Belgium's nuclear history started in 1962 at Mol, as the first European country to install a US-imported pressurised water reactor (PWR) (World Nuclear Association 2018).

while solar PV also reached a 1% share of electricity generation in 2011. Subsequently, combined wind and solar increased to 6%, 10% and 15% in 2012, 2014 and 2018, respectively. Wind generation remains at twice the amount of solar (see Figure 6.27.).

Figure 6.27. Evolution of Belgian electricity generation by energy source, 2008-2018



Source: Author's calculations based on BP 2019; IRENA 2019d, 2019e; IEA 2020

Belgium is part of the European grid, therefore its ability to maximize electricity imports is subject to inevitable sensitivities and uncertainties (e.g. climatic fluctuations) determined by interconnections with its neighbours (Heylen *et al.* 2018).[178] It is forced to secure electricity imports to stabilize supply levels, which diminishes its energy sovereignty (AleaSoft 2019).[179] In 2018, Belgium's electricity import balance stood at 17,405 GWh, equal to 20% of electricity demand (AleaSoft 2019). Deficits in domestic energy supply and high import dependence raises vulnerability to unstable pricing policies, which also creates an adverse investment environment for Belgian companies (BOP 2014b). Moreover, according to Belgium's NECP, energy imports will increase to 90% by 2040 (AleaSoft 2019).

Nuclear nightmares and supply-side shocks

Following a law proposed in 2003 to shut down its two nuclear power plants, Belgium's nuclear phase-out has stalled (AleaSoft 2019). In recent years, the country's nuclear fleet has been fraught

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[178] French electricity demand "is very sensitive to temperature fluctuations due to the intensive use of electric heating;" a 1°C temperature decrease can lead to an additional power demand of 2.3GW (Heylen *et al.* 2018).

[179] 75% of total energy consumption comes from imports. France and the Netherlands are the main exporters, while Germany and Norway are the main electricity exporters to France and the Netherlands (AleaSoft 2019).

with technical problems, with reactor failure leading to blackouts and high economic costs (AlesSoft 2019).[180] The Federal Planning Agency estimate that losses from a one-hour national power cut during business hours is around EUR 120 million (BOP 2014b). Periodic episodes of nuclear shutdown pose a major risk to national energy security, resulting in price inflation with peaks of 500 €/MWh (AleaSoft 2019). Extended shutdowns of its nuclear facilities (Doel 3 and Tihange 2) have further increased the urgency to secure alternative energy sources (BOP 2014b).

Critics of the nuclear shutdown highlight that Belgium's emerging energy strategy results from the politicization of a strictly economic and technical matter (Furfari 2019), calling into question the role of RESs in the country's already import dependent electricity system.[181] Analysts suggest that absent of investment in new generation capacity, Belgium's security of electricity supply will deteriorate with its nuclear phase-out (Fufari 2019). Consequently, the Federal Minister for Energy stated in a recent drafted bill that the seven nuclear power reactors (5.9GW) and some older thermal units, totalling 7.4GW, will be replaced primarily by natural gas plants (Furfari 2019). Planned investments in natural gas suggest a reason why Belgium's RE targets remain less than ambitious.

6.8.2.2 Belgian electricity capacity dynamics

Belgian electricity supply grew by over 30% since 2009, from to 17.8GW to 23.4GW, with the average set at 21GW for the period. While Belgium deployed its first onshore projects in 2000, wind energy only reached 1% share of electricity generation in 2009. This is significant because offshore wind reached the equivalent level in 2012, while also securing a 1% share of electricity capacity in the same year, despite launching only in 2009. Typically, countries that deploy offshore wind successfully already have well-established onshore sectors or at least launched onshore operations many years prior to connecting their first offshore turbine. While this reveals the disparity between diffusion rates, it also highlights how Belgian onshore and offshore wind have developed as more of a dual part of its energy transition strategy. Consequently, the offshore shore of electricity capacity stood at about 6.6% as of 2019, compared to 9.5% for onshore wind. Installed capacity remains modest in both instances, with onshore wind reaching about 2.2GW in 2019, compared to 1.6GW for offshore wind (see Figure 6.28.). Such trends are important to note as future wind targets will reflect past levels and growth patterns. In total, wind energy accounted for

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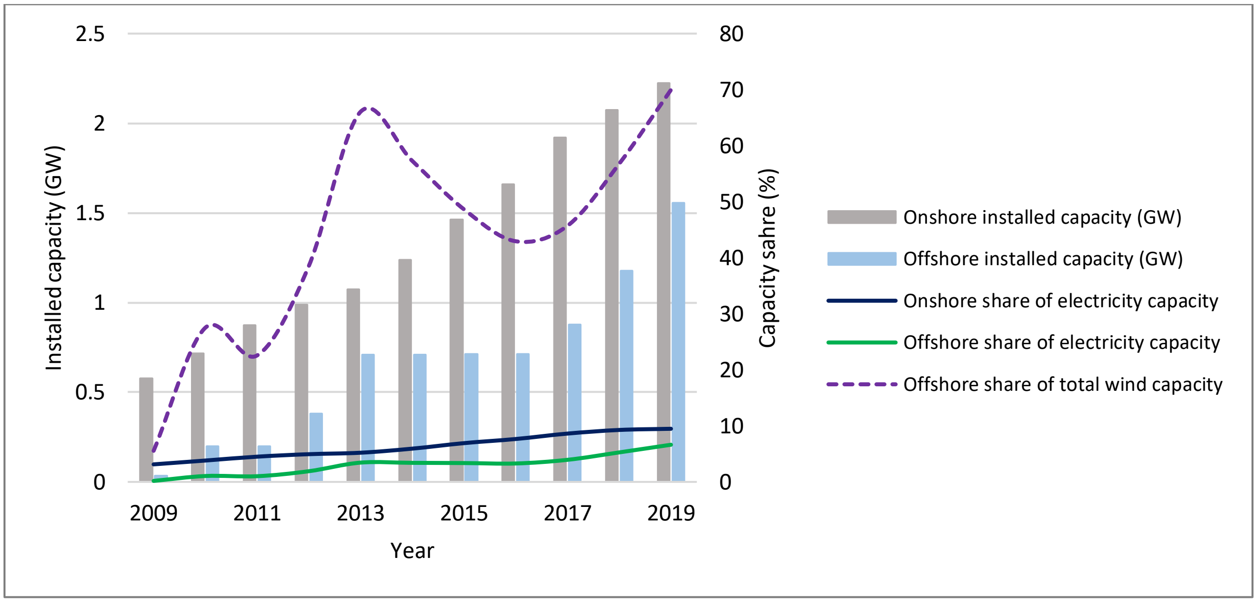
[180] In 2018, 6 of Belgium's 7 reactors were brought offline, leading to an energy security crisis (AleaSoft 2019).

[181] Shutting down depreciated nuclear plants comes at a high macroeconomic cost, since removing a baseload of cheap electricity calls for higher subsidies for RESs such as offshore wind and CHP, in turn raising the wholesale price of electricity significantly (Furfari 2019).

approximately 16% of installed electricity capacity in 2019. Belgian's installed electricity capacity has grown steadily since 2010, averaging 21GW over this period and reaching 23.5GW in 2019. Given its relatively small size, there is clearly limited potential for wind capacity to reach double digit figures; nevertheless, there is still room for additional deployment in the future.

Figure 6.28. Evolution of wind energy in Belgian electricity supply, 2009–2018



Source: Author's calculations based on AleaSoft 2019; BP 2019; IEA 2020; UN Energy Statistics 2020

6.8.3 Feasibility of Belgian 2030 targets

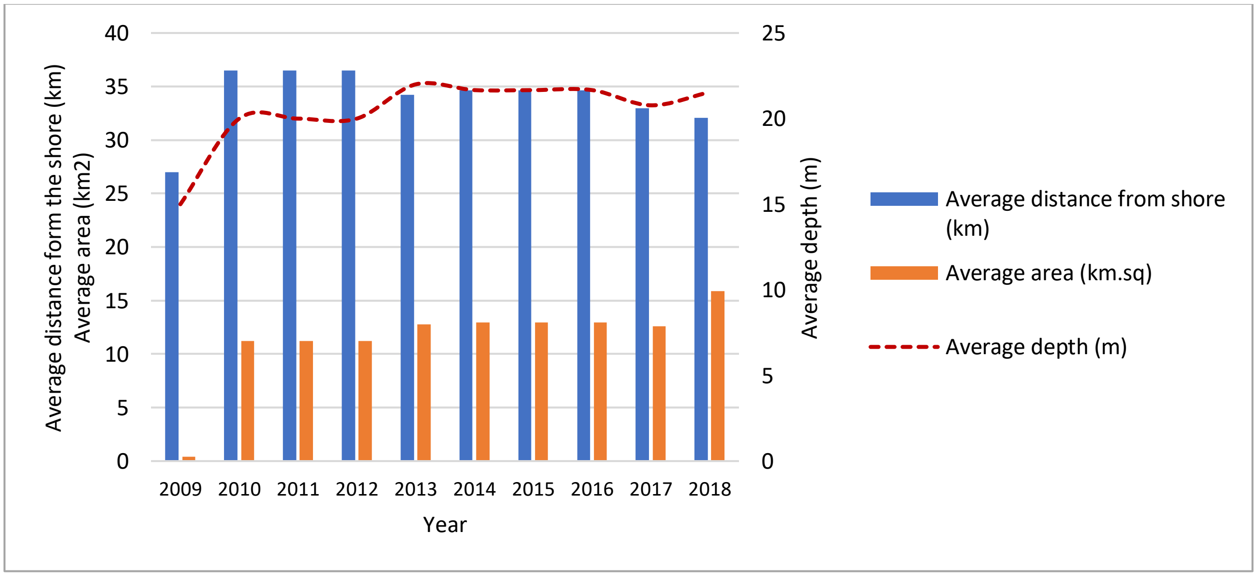
6.8.3.1 Introduction

Belgium has achieved unparalleled success in the offshore wind market, not only by virtue of its size next to most of its NSEC neighbours but also in terms of the speed with which it has penetrated the market. However, it is far from smooth sailing in Belgian waters and moreover on land, where political frictions create an uncertain policy and investment environment, which to date has been largely offset by EU backing. Belgium's land-locked problems stem from 'nuclear nightmares' and 'supply shocks,' as it grapples with an outdated energy system and high import dependence on electricity from France. Given this dynamic mix, the feasibility of Belgium's offshore wind target warrants close inspection, as its quest to reach 4GW by 2030 – a reasonable target relative to the size of is electricity capacity and the spatial constraints of tits EEZ – requires an average annual build-out of approximately 245MW. The rest of this section examines whether this rate is feasible.

6.8.3.2 *Techno-economic drivers of Belgian upscaling*

Belgium presents a unique case of offshore wind build-out, given that upscaling was strongly embedded since the launch of its first OWP in 2009.[182] In 2010, Belwind OWF marked Belgium's ascension into the offshore wind market, with 170MW deployed across 56 turbines. Notably, Belgium reached large-scale commercial deployment without a true formative phase, *leapfrogging* straight into the growth phase with a more than ten-fold increase in capacity between 2009 and 2012. As a result, techno-economic parameters of OWFs have for the most part remained stable, with the average distance to the shore ranging between 30 to 35 km and the average depth fixed at around 20 metres (see Figure 6.29.). However, 2018 saw the area of OWPs increase to 16 km^2 compared to an average of 11 km2, following the addition of large-scale projects at Belwind II (165MW) and Nobelwind (165MW). Overall, Belgium OWPs presents a case of strong upscaling dynamics since its inception, tapping into the potential of deep waters far offshore.

Figure 6.29. Average distance from shore, area, and depth of Belgian OWPs, 2009–2018



Source: Author's calculations based on 4C Offshore 2020b, The Wind Power 2020d

6.8.3.3 *Political and socio-technical drivers of Belgian OWFs*

Belgium is also unique in terms of its institutional structure and socio-political environment, with each of its three regions having its own government (Flanders, Brussels, and Wallonia) (Furfari 2019). This arrangement creates a challenging mix of "federal and confederal features," confounded by Flemish and French-speaking allegiances Popelier and Lemmens 2015). As

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[182] A case could be made that Belgium delayed deployment until the late 2000s to capture economies of scale faster.

Popelier and Lemmens explain, the governing mechanisms that oversee Belgian federalism face the risk of deteriorating into "blocking mechanisms," given its state of "dyadic asymmetry and legitimacy deficiencies" (2015). Belgium's "political stalemate" leads to a lack of conformity in respect to energy policy, as witnessed at the COP 24 summit in Katowice (Furfari 2019). Despite all its neighbours signing "the high ambition coalition," Belgium declined to pledge additional efforts to combatting climate change (Rankin 2019a); rejecting the new EU target of at least 32.5% energy efficiency by 2030 (Rankin 2019b; Lazarus 2018).[183] In this respect, the political environment for supporting RESs is relatively weak by western European standards and there is a lack of impetus to drive up offshore targets beyond 4GW in the near term.

Notwithstanding, Belgium offshore wind has proven resilient and thrived off funding support from the European Commission (EC), in no small part facilitating its current capacity levels[184] (OffshoreWIND.biz 2019). In the past, the EC has ruled that investment support for Belgian OWPs provides "an incentive effect," which helps secure financial viability without "unduly distorting competition in the Single Market," while furthering the EU's energy and climate targets (OffshoreWIND.biz 2018). To an extent, the political feasibility for Belgian offshore wind stems from the European climate change agenda, as opposed to being driven at the national energy transition level. Nevertheless, alongside extensive subsidy support from the EC, Belgium's TSO, Elia, has the obligation to purchase green certificates from generators, in accordance to the "minimum price set by Federal legislation" (Elia 2019). Additionally, the Federal administration has also recently established a "one-stop-shop" to help simplify and accelerate licensing procedures for OWFs (Elia 2019). These conditions add weight to realising the 4GW target.

In terms of its socio-technical system, offshore wind networks are well-established and supply chain mechanisms are firmly in place and well proven for securing future construction. Offshore wind is an equaliser, or at least a partial stabiliser, in an increasingly risk-filled energy transition context that sees Belgium tethered to electricity imports and facing exorbitant costs as its nuclear fleet diminishes. While offshore wind can by no means single-handedly resolve Belgium's energy dependency issues and high economic costs, it provides a significant asset to the country's trade

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[183] Slovakia was the only other country to oppose the new EU target (Lazarus 2018).

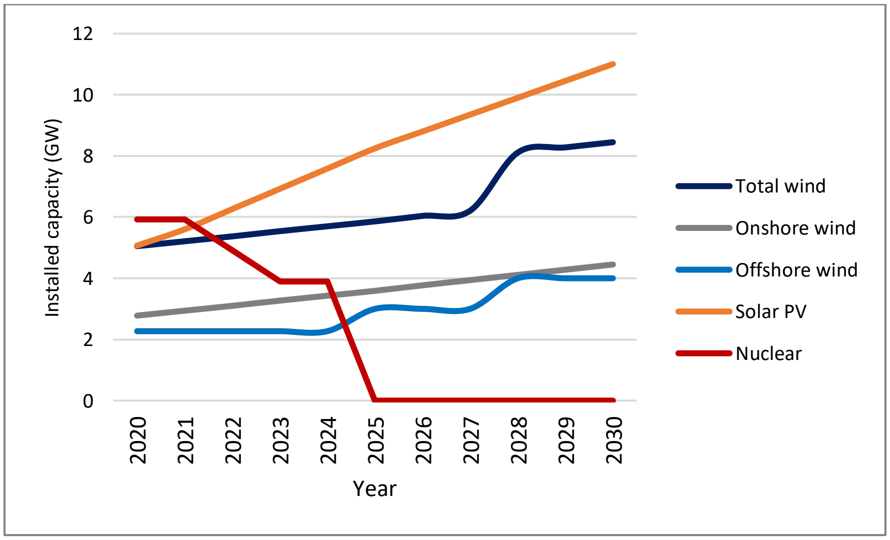
[184] Notably, at the end of 2016, the EC approved a funding packing under EU State aid rules up to a maximum of EUR 3.5 billion for three OWPs in the Belgian EEZ (OffshoreWIND.biz 2019).

balance,[185] which may improve by around EUR 1.4 billion per year in 2030; as the burgeoning offshore wind TIS stimulates gains across Belgium's trade balance (Breyer *et al.* 2017.)[186]

6.8.3.4 The Belgian quest for 4GW+ by 2030

Belgium's ability to continue its offshore wind build-out is embedded strongly in its energy transition plans and related RE objectives, granted that its targets remain less than ambitious by European standards. The single biggest factor in the evolution of the Belgian energy mix is its imminent nuclear phase-out, scheduled for completion in 2025 (see Figure 6.30.), which would see around 50% of the country's electricity supply slashed within a short period of time, leaving RESs to partly fill the void. Solar PV will eclipse wind energy in absolute terms, reaching around 11GW compared to 8.5GW; however, offshore wind's superior capacity factor will compensate for this difference in terms of electricity generation.

Figure 6.30. Belgium's 2030 renewable energy targets and 2025 nuclear phase-out timeline



Source: Author's calculations based on Elia 2019

Belgium's offshore wind expansion plan is clearly scheduled to support its nuclear phase-out, adding momentum to the quest for 4GW by 2030. The data fitting confirms that Belgium has followed an exponential growth path, which is projected to continue. The RSS is same for the logistic and exponential fit (logistic-linear is not reported in this case), confirming an instance

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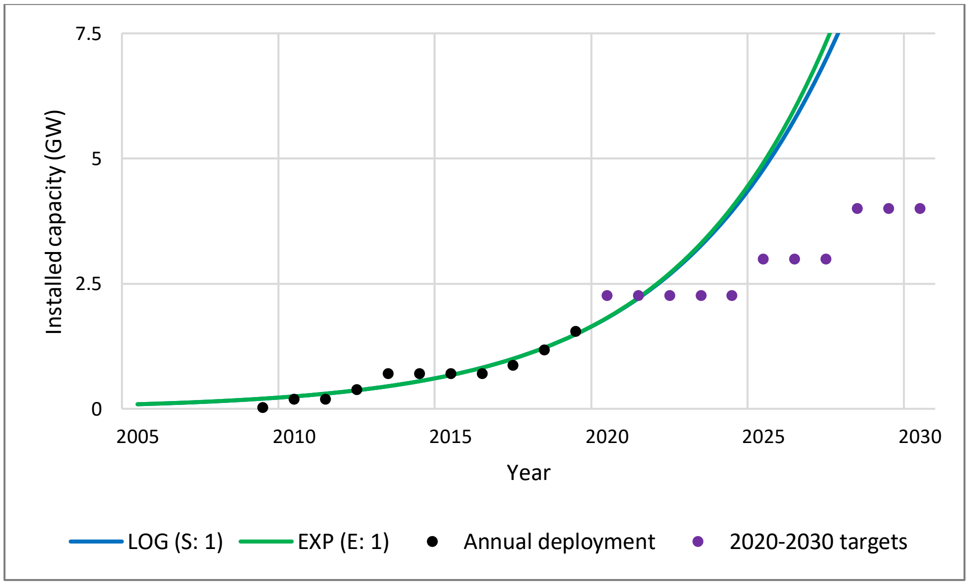
[185] Breyer *et al.* define the trade balance as "the sum of the reduced electricity imports due to higher domestic offshore electricity production, plus the additional exported goods and services of Belgian companies active in the industry, minus the imported goods and services required to build the Belgian offshore wind park" (2017).

[186] EUR 0.5 billion per year avoided imports based on a wholesale price of electricity of 40 euros per MWh in 2016 (Breyer *et al.* 2017).

where the estimates of the inflection point (2039.7) and the maximum growth (4.8GW) are set far off into the future and unreliable (see Figure 6.31.). Belgium would hit 4GW by 2024 at this rate; however, the government has no plans to ramp up deployment to above 2.25GW until 2025. The current pipeline is already close to realisation, while the 'second wave' –provisionally scheduled for post-2025 – is intended to bring capacity to 4GW by 2030. In many respects, Belgium's offshore wind targets are one-dimensional, contingent an imminent capacity jump from 1.56GW to 2.25GW, followed by additions later in the decade to fill the supply gap left by its nuclear phase-out. It appears highly feasible that Belgium can realise these two-stage objectives.

Figure 6.31. BE Offshore wind pathways: Empirical data and fitted growth models with RSS

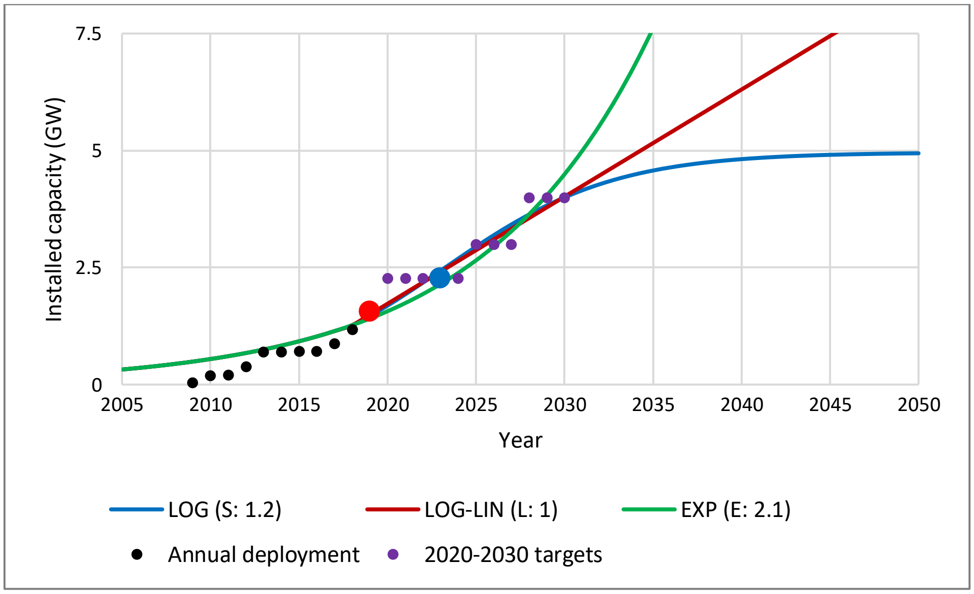


6.8.3.5 *Implications for 2050 deployment levels*

Provided Belgium continues with its offshore wind program, plans beyond 2030 will remain highly restricted in their ambitions. Belgium's deployment potential is limited due to its small EEZ, which has an area of just 3,500 km^2. WindEurope estimated that 34% of this area (i.e. approx. 1200 km^2) is needed to reach 6GW by 2050 (Freeman *et al.* 2019). Clearly, Belgium has a low ceiling for offshore wind, irrespective of its past deployment success and the urgency of energy-related challenges. The growth fits confirm that provided Belgium meets its 2030 targets, it is likely to be on course for logistic-linear growth that would see it reach the 6GW just before 2040; alternatively logistic growth would see its offshore wind capacity saturate at slightly below 5GW (see Figure 6.32.). Either of these scenarios is feasible at this time, although the likelihood is that Belgium will push to maximise its available resource potential.

Belgian offshore wind capacity hinges almost solely on its ocean eligibility limitations, given that its other techno-economic[187] are relatively sound. While it seems unlikely that any country – even one with an extremely small EEZ – would conceivably allocate one-third of its EEZ solely to OWFs, a finer resolution ocean eligibility analysis reveals even worse feasibility prospects for Belgium. Under a high-level scenario, Belgium has available 890 km^2, which if allocated to OWFs would still fall 25% short of the estimated area required to reach 6GW by 2050. The Belgian case is one of extreme resource constraints, irresolvable in the short to medium-term. Nevertheless, Belgium still has an opportunity to remain a frontrunner "in the optimisation of sea space" (Freeman *et al.* 2019).

Figure 6.32. BE Offshore wind pathways: 2030 targets and fitted growth models with RSS



Feasibility would improve under conditions that see the onshore grid reinforced in tandem with "wind farm clustering" for new zones with a vision towards hybrid projects;[188] alongside collaboration with its NSEC partners to address issues of cumulative environmental impacts, which currently prohibit such an intense utilisation of the EEZ for OWFs (Freeman *et al.* 2019). An optimal scenario would see it increase its EEZ through political arrangements and shared corridors with North Sea neighbours such as the Netherlands. This is the only pathway – contingent on hybrid projects and a revised regulatory framework aligned to pan-European governance and a shift in the

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[187] For example, Belgium's 6GW ceiling is based on a higher energy density of 7MW/km^2 (Freeman *et al.* 2019).

[188] Projects where OWFs connect into an offshore electricity connector for multi-country use (Freeman *et al.* 2019).

dynamics of maritime activities – that would see Belgium potentially raise its offshore wind ceiling above 6GW by 2050.

Belgium’s challenges are great both at sea and on land. It will need to increase the flexibility of its electricity system significantly in the near-term to accelerate its energy transition. (Elia 2019). Offshore wind is acting as the driving force for bringing about this change and technological solutions for mitigating the impact of variability on the grid are being sought in R&D facilities across Europe (Elia 2019). Belgium’s links to other members of the North Seas Energy Cooperation (NSEC) and its strong backing from the EU, with Brussels often at the centre of European politics, will improve its prospective quest towards 6GW by 2050.

6.8.4 Summary

There is strong momentum in the Belgian offshore wind sector. The current wave of OWFs will shortly take capacity to over 2GW from just 200MW in 2011; a level of upscaling that has not been witnessed in any other European case. However, the second wave of deployment is delayed until at least 2025 and ultimately the 2030 target is capped at a modest 4GW. This dichotomy indicates that the phase of exponential offshore wind growth in the Belgian EEZ is about to end, a linear trend is set to kick in and thereafter saturation pressures appear inevitable due to spatial constraints. Although the ceiling for Belgian offshore wind is extremely low at an estimated 6GW, securing this capacity leap will nevertheless require strict planning and political commitment. With Belgium’s energy security at high risk in a post-nuclear era, its (electricity) import dependency surging and its economic resilience set to be tested, there is reason to believe the government together with the Belgian Offshore Platform (BOP) will rally resources to maximise the remaining potential of its EEZ while competing in global supply chain markets. The following factors position Belgium to meet its target while opening the door for an additional 2GW of OWFs in the future:

- High motivation to deploy offshore wind due to an abrupt nuclear phase-out that stands to see the domestic energy supply cut in half within a few years.
- Strong political and public support for backing wind energy, both on land and at sea.
- High revenue gains from offshore wind that strengthen its trade balance.
- Financial backing from the European Union and multi-national energy partnerships.
- Proven success with upscaling OWPs and optimising capacity densities far from shore.

In conclusion, while Belgium is confronted with the drawback of a small EEZ and continues to grapple with political frictions within its borders, the Belgian offshore wind regime is strong and has quickly gained the knowledge and experience to deploy offshore wind at scale. Given past success planning large-scale projects in deep waters far from shore and reaching capacity densities higher than its NSEC neighbours, there is high feasibility that Belgium will support an offshore capacity increase to 4GW by 2030 and 6GW by 2050.

6.9 TIS functions and Motors of Change in NESC frontrunner markets

This section synthesises and summarises the results from the Structured, focused comparison to answer **RQ1**: Which processes ("motors of change") determine the early uptake of offshore wind power? Chapter 6 presented five narratives examining the early uptake of offshore wind power in each country through the lens of its Technology Innovation System (TIS). First, the main Actors **(A)**, Networks **(N)** and Institutions **(I)** encountered in each case study are recalled to better frame the findings. With these key players firmly in mind, the main TIS functions/processes that drive the early uptake of offshore wind are identified and finally, areas where the results converge are also highlighted. Table 6.1 presents the main results.

The seven TIS functions are restated here: **(1)** Entrepreneurial activities; **(2)** Knowledge development; **(3)** Knowledge diffusion; **(4)** Guidance of the search; **(5)** Market formation; **(6)** Resource mobilisation; and **(7)** Legitimacy/counteract resistance to change. Market formation **(F5)** presents an area of overlap within the TIS as its placement is closely intertwined with the guidance of the search **(F4)**, therefore results in this area will depend strongly upon the researcher's interpretation of the overall landscape, and judgement of specific (change) events.

Actors, networks, and institutions

The main type of actors, network and institutions are similar in each country, ranging across: transmission system operators (TSOs) and industry groups **(A and N)**; entrepreneurs, scientists, engineers and research hubs thereof **(A and N);** and the state and its representatives **(I)**.

In the Belgian case, its TSO, Elia **(A)** is centre stage alongside the government **(I)** and more broadly the EU/EC **(I)**, as well as groups such as the Belgian Offshore Platform (BOP; **N**).

In the German case, OWFs are supported by its TSOs **(A)**, the federal government including the German Offshore Wind Foundation, and the Federal Maritime Hydrographic Agency (BSH), and similar foundations/agencies, plus the coastal authorities **(I)**. Siemens **(A)** also plays a key supporting role alongside other manufacturers strategically placed across the Länder **(N)**.

The Danish offshore landscape sees its manufacturing giant, Vestas **(A)**, at the forefront alongside other turbine manufacturers and firms in the supply chain, supported by its RDD&D and university hubs, as well as wind energy/RE cooperatives **(N)**. On the governmental side, the Danish Ministry of Energy, Utilities and Climate, the Danish Energy Agency, and the Danish Finance Ministry drive key developments for supporting offshore wind **(I)** in sync with TSO, Energinet (**A)**.

In the Dutch case, its TSO TenneT is the key player **(A)**, while groups such as TKI Wind op Zee, and GROW drive RDD&D activities alongside other innovation consortiums **(N)**. The government is the main supporting body of offshore wind energy through its various departmental agencies including the Netherlands Enterprise Agency and Ministry of Economic Affairs **(I)**.

In the United Kingdom, the Crown Estate (CE) is the key actor **(A)** that bridges together key players in the offshore wind landscape such as members of ORE Catapult **(N)**, which are supported by the government including the Department of Energy and Climate Change (DECC), and the Engineering and Physical Sciences Research Council (EPSRC), and other agencies or councils **(I)**.

Large utilities and energy companies **(A),** and several industrial and business networks **(N)** further shape the TIS, but specific examples are not reported in this study. Together, the country lists provide a snapshot of the main actors, networks, and institutions relevant to the offshore wind TIS.

Motors of change

Table 6.1 provides an answer to RQ1 by summarising the motors of change for each country case. This step identifies the generic processes that determine the early uptake of offshore wind power, in addition to which representative of the offshore wind landscape is driving the change. The guidance for the search **(F4)** is the most important function in the TIS for driving all other processes, especially market formation **(F5)** and legitimacy **(F7)**. The guidance for the search comes from the political arm, driven by the government and other institutions. Alongside **F4**, entrepreneurial activities **(F1)** drive knowledge diffusion **(F2)** and knowledge development **(F3)**, highlighting the importance of market actors in the TIS. Resource mobilisation **(F6)** is a critical motor of change in the offshore TIS, which drives *functions 1 to 3* during the early part of the formative phase (innovation stage) and also drives market formation and legitimacy (*functions 5* *and 7*), as the formative phase nears its end. Resource mobilisation is driven by the government, as well as key actors, such as the Crown Estate in the case of the UK.

Table 6.1. Motors of change in the NESC Offshore wind TIS

Country	**Motor of change (A, N, and/or I)**	**TIS functions represented**	**TIS functions driven**
BE	(1) Government allocation of EEZ for OWFs (2001) **(I)** (2) Strategic alliances between Federal Ministries and local research institutes **(I)** and **(N)**	F4 F4	F5, F6, F7 F2, F3
DE	(1) BSH offshore permit to Alpha Ventus (2001) **(I)** (2) Policy-push strategy **(I)** (3) Increase to Feed-in-Tariff (FiT) (2009) **(I)**	F4, F6 F4 F5	F1, F2, F3 F5, F6, F7 F6, F7
DK	(1) RDD&D test programmes **(N)** with government funding **(I)** (2) Science technology-push and market pull strategy **(I)** (3) Government funding/grants **(I)**	F1, F5 F4 F6	F2, F3 F5, F6, F7 F5, F7
NL	(1) Subsidies, tax breaks and market incentives **(I)**	F4, F6	F5, F7
UK	(1) Entrepreneurial activities (Blyth OWF, 2001) **(A)** (2) Crown Estate as trusted actor bridging key players **(A/I)** (3) EPSRC funding program and FIT schemes/RO **(I)**	F1 F4, F6 F4, F6	F2, F3 F1, F2, F3, F5, F7 F5, F7
	Tally of TIS functions represented and driven	**F1: 2** **F4: 8** **F5: 2** **F6: 5**	**F1: 2** **F2: 5** **F3: 5** **F5: 7** **F6: 4** **F7: 8**

The dichotomy between functions 1 to 3 being driven during the innovation phase, and functions 6 to 7 being driven as early market formation takes shape, is a key finding from the study of the NESC Offshore TIS, supported by the underlying theory of the framework. The analysis also confirms the extent to which collaboration between the government and industry constitutes the backbone of the offshore TIS.

6.10 Causal mechanisms of offshore wind growth in national energy transitions

This section synthesises and summarises the results from Chapters 5 and 6 to answer **RQ2**: What mechanisms drive the growth of offshore wind power? To answer this question, growth dynamics of electricity capacity are revisited for the frontrunner group (see Figure 6.33)., and the following drivers are examined: energy-specific, techno-economic, socio-technical, and political mechanisms.

Electricity capacity

Belgium

Belgium has achieved a fast growth rate since deploying its first OWF in 2009, despite four years of stagnation between 2013 and 2016, it still remained well above Germany and the Netherlands at the time, before briefly surpassing Denmark in 2018. Denmark returned to second position behind the UK in 2019 and Belgium remained in third place. Within ten years, Belgium has sustained a leading share of electricity capacity from offshore wind among the frontrunner group, finishing the last year with its highest share to date. The Belgian case demonstrates that it is possible to grow the share of offshore wind in the electricity supply to more than 6% within a decade.

Germany

Given its huge electricity supply by NESC levels (> 200GW), offshore wind power has made a comparatively small dent in German electricity supply to date, positioning it as a relative laggard alongside the Netherlands. Nevertheless, the growth rate has picked up since the time of take-off in 2015 and discounting previous years, German growth is on track with the UK in the last four years. Germany doubled from 0.016 to 0.035 while the UK also doubled from 0.039 to 0.079, according to the normalisation results. The German case exhibits the smoothest growth pattern, barring the UK, and is increasing at a steady rate, reflected by its climb from 3% to 4% of electricity capacity in the last year.

Denmark

Denmark experienced a stagnation episode like Belgium, with no deployment between 2012 and 2017. This is reflected by the UK reaching parity with it in 2016 before overtaking. Denmark had otherwise led the frontrunner group throughout most of the period. Most critically, the Danish results show that an addition of a 400MW OWF can raise the relative share of offshore wind the electricity sector by a significant amount in a single year (increasing from 0.043 to 0.070 according to the normalised data).

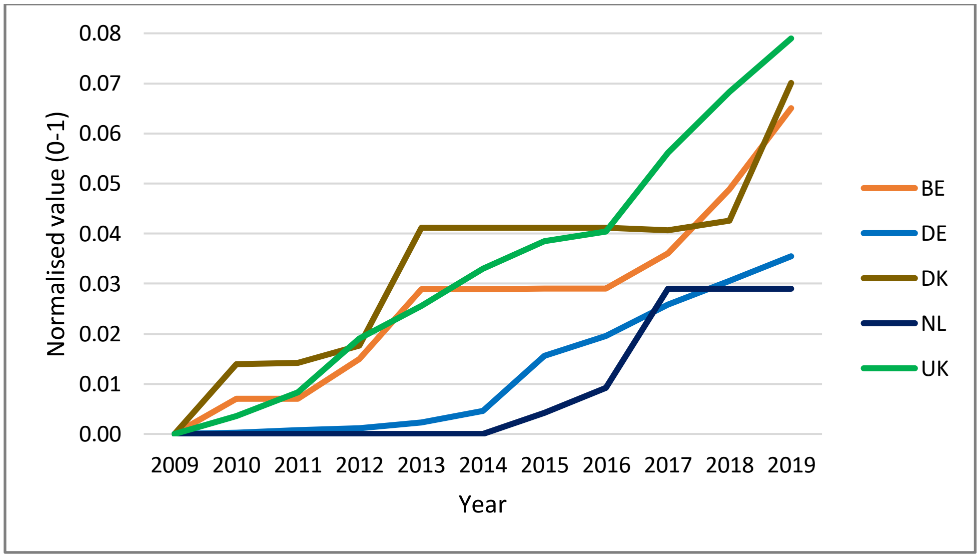
Netherlands

The Netherlands is the clear laggard among the NESC frontrunner group. Until 2014, its electricity did not take-off and only in 2017 with the deployment of the Gemini OWF (600MW) did it begin to climb towards the same level as Germany. It took the Netherlands over twenty years in the offshore market to raise its electricity capacity to the same level that Belgium – a newcomer in 2009 – reached by 2013. The Dutch electricity sector remains highly fossil fuel intensive, which explains the slow rate of penetration.

United Kingdom

As highlighted, the UK overtook Denmark around 2016 and has grown its share of installed capacity at a steady rate. With an installed electricity capacity of 108GW, second only to Germany in the NESC frontrunner group, the UK has outperformed the comparative growth rates of its competitors. This success is attributed to the driving mechanisms discussed hereafter, which have enabled the UK to generate 8% of its electricity from offshore wind in the last year.

Figure 6.33. Offshore wind growth normalised to installed electricity capacity, 2009-2019



Source: BP 2019; IRENA 2019; IEA 2020

Energy-specific mechanisms

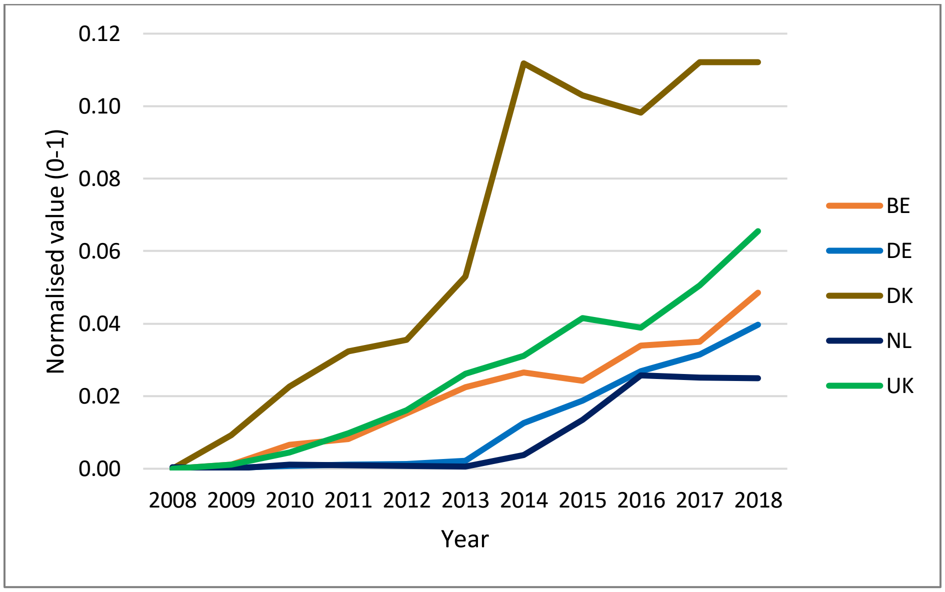
The following energy-specific mechanisms drive the uptake of offshore wind power.

- Fossil-fuel phase outs especially linked to coal with PPCA membership in each country
- Nuclear phase-outs in Germany and Belgium creating a significant supply gap (+ NL)
- Lack of natural gas infrastructure (BE); decline of domestic natural gas (N); high import dependency on natural and (UK and DE).
- Saturation pressures and constraints for onshore wind
- Well-established onshore wind sectors correlate strongly to offshore uptake

- High penetration of RESs in the electricity sector (DK and DE)
- Failed CCS strategy (NL) and wavering nuclear policy (UK)
- High electricity import dependency (BE)

Together these mechanisms determine the rate at which installed offshore wind grows and what contribution it makes to electricity generation (see Figure 6.34.).

Figure 6.34. Offshore wind growth normalised to electricity generation, 2009-2019



Source: BP 2019; IRENA 2019; IEA 2020

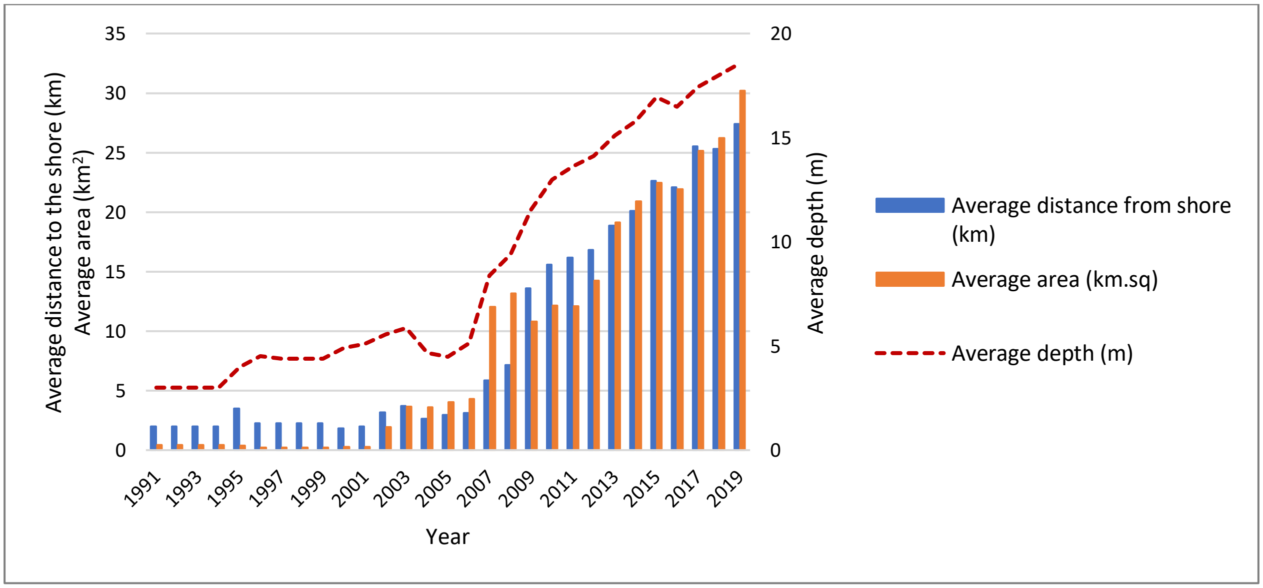
Techno-economic mechanisms

The main techno-economic mechanisms identified within this study that drive the growth of offshore wind power and its diffusion at the level of installed electricity capacity are average distance from the shore, average area, and average depth of OWPs. These techno-economic parameters are critical since they in turn dictate the performance of turbines and efficiency characteristics such as capacity factor and capacity density, while also dictating maritime planning boundaries and other key regulatory aspects of OWF development. Here, the cumulative finding of the results presented in each country case study is presented to better gauge upscaling dynamics at the European level (see Figure 6.35.).

- During the formative phase, average distance from the shore was below 3 km, scaling up to 16 km by the time of take-off in 2011. Since this time, steady gains in each year raised the average depth to 27 km by 2019, close to three times more than the average for the period (9.6 km).

- Average area remained well below 4 km^2 during the formative phase before reaching 12 km^2 by the time of take-off. This tripling was supported in just one year between 2006 with large-scale projects coming online at the time. Since 2007, average area doubled to over 25 km^2 by 2017 and has since increased further to just above 30 km^2 by the end of 2019, compared to the period average of 9 km$^{2.}$
- Average depth tripled from 3 metres in the early formative phase to nine metres by the late formative phase in 2008. Thereafter, it doubled to 18.5 metres in 2019, against an average of 8.9 metres for the period. The growth rate for average depth was highest between 2006 and 2010 and has since slowed down, climbing by about 1 metre in subsequent years.

Figure 6.35. Techno-economic parameters of OWPs in frontrunner group, 1991-2019



Source: Offshore 4C 2020b; The WindPower 2020d

Growth for the average distance from the shore and the average area are closely correlated, mimicking one another closely since the mid-2010s, while the average depth is currently stabilising at around two-these of these levels. The evidence is clear that OWPs are scaling up in terms of their size (area) as construction moves to deeper waters father from shore where economies of scale become more feasible, driving growth in annual capacity additions across the NESC. In addition to the techno-economic drivers showcased in the country case studies and in Figure 6.35, the following mechanisms driver further growth: high capacity factors and capacity densities, new cable technologies, higher transmission capacities, port infrastructure, in addition to good conditions at sea (wind speeds and stable sea beds for monopile foundations) as supported by a vast EEZ (with the exception of Belgium).

Socio-technical mechanisms

The following socio-technical mechanism drive the growth of offshore wind power in the NESC: **(1)** *industrial growth strategies* targeting coastal regeneration with the development of cities and port infrastructure, job creation, strengthening of supply chain mechanisms, sub-divisions of regional labour together with branching and diversification across key sectors (e.g. manufacturing, engineering and logistical activities); **(2)** *economic growth incentives* delivered through trade revenues/export advantage with reduction of dependency on energy imports; **(3)** *synergies between key actors* with large utilities and energy companies working together alongside TSOs, as well as investment consortiums driving commercialisation.

Political mechanisms

Political feasibility for offshore wind power flows from the mobilisation of government, as well as public support. In the case of Belgium, there is high-level support from the EU through subsidy schemes while EU climate change goals drive support for offshore wind. Various decarbonisation targets are now in place (i.e. ‘net zero’ targets) and Feed-in-Tariff (FiT) schemes and Contracts for Difference (CfDs) provide strong support for development plans and investment. Cross-party political support is witnessed in Germany (although not in Belgium) and maritime planning mechanisms are in place. Countries also set-up other special arrangements for improving licensing procedures, such as the ‘One stop shop’ in Belgium.

6.11 Current growth patterns across NESC frontrunner markets

This section synthesises and summarises the results from Chapters 5 and 6 to answer the **RQ3**: Is the current deployment of offshore wind power in the NSEC accelerating, stable or slowing down? The Milestone and Landmarks framework is applied at the European level to contextualise the answer to this question.

The Milestones and Landmarks framework can be shifted away from the national context and applied to the European level, which closely mirrors events at the global level; up until 2015 European frontrunner markets accounted for over 90% of global offshore capacity. The development and diffusion of offshore wind can be classified according to four distinct phases, tracing events from the formative phase up to current developments (see Table 6.2.).

(1) The formative phase of innovation (*1991–2003*) – early adopters join the market: design experimentation, experimental purpose, marinization, oil and gas (O&G) participation and policy experimentation drive developments mainly in small-scale, nearshore OWFs.

(2) Transition phase and early upscaling (*2004–2010*) – Lead markets at the core are well-established: trial and error intensifies as market adaptation takes place characterized by design experimentation, commercialisation, and the start of a dedicated supply chain.

(3) Take-off, growth phase and commercial upscaling (*2011–2019*) – additional frontrunner markets are established: dominant design is established for the North Sea and Baltic Sea (monopile foundations with PMGs), a dedicated 1st tier supply chain is established, large-scale OWPs are approved and launched and countries establish a more transparent timeline for future tenders.

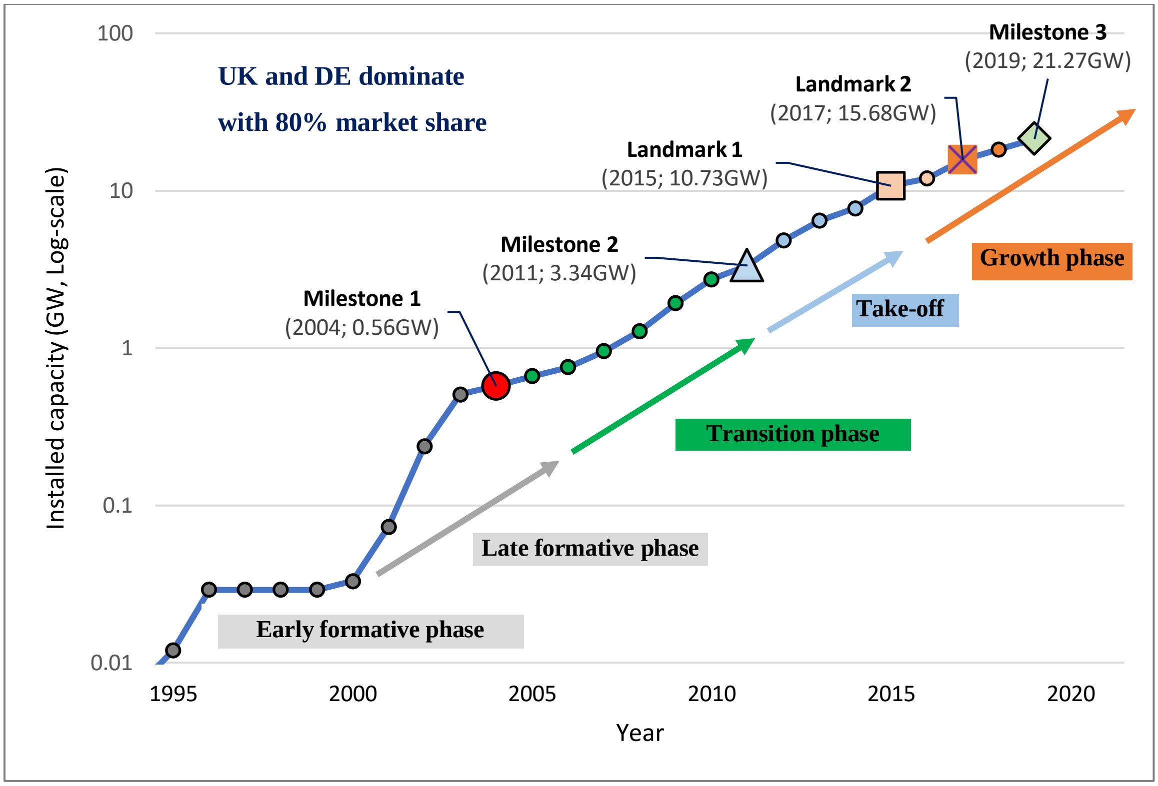
(4) Market growth, upscaling and new designs (*post-2020*) –the rim starts to take shape: diffusion spreads beyond the niche of Northern Europe to emerging markets in other continents; a new core forms around floating wind and other novel technologies; 2030 capacity targets based on NECPs and NREAPs become the standard (see Dedecca *et al.* 2016).

Table 6.2 and Figure 6.36 illustrate the evolution of offshore wind power in Europe, represented almost exclusively by its NESC frontrunners.

Table 6.2. Milestones and Landmarks framework at the cumulative European scale

Phases & Characterization **Milestones & Landmarks**	**Formative** Innovation Phase **Milestone 1**	**TRANSITION** Commercial scale **Milestone 2**	**GROWTH** Market stabilization **Milestone 3**	**TAKE-OFF** Established capacity base **Landmark 1**	**PENETRATION** Competitive generation **Landmark 2**
Event & Definition	Year 1st OWF has been deployed across all frontrunner markets	Year capacity > 100 MW across all frontrunner markets	Year capacity > 1GW across all frontrunner markets	Year OWE > 1% of electricity supply across all frontrunner markets	Year OWE > 2.5% of electricity generation across all frontrunner markets

Figure 6.36. Milestones and Landmarks at the European scale, 1991–2019



Source: Author's illustration based on BP 2019; IRENA 2019d, 2019e; IEA 2020

Having started in the early 1990s with small-scale pilot projects in near-shore Danish waters, offshore wind scaled up through the 2000s in line with diffusion of innovation (DoI) theory to reach its first gigawatt in 2007.[189] During the **formative phase of innovation** (*1991–2003*), growth was erratic and marked by high annual growth rates, interspersed throughout the period. Annual installations doubled on three occasions between 1991 to 2004 (1996, 2001 and 2003). At the same time, there was no deployment in 1992, 1993, 1997 and 1999. Discounting the formative years in which no capacity was added, the average annual growth rate was **90%** (SD: 68.72).[190] By 2003, installed capacity in the NESC reached around 0.5GW, increasing to 1GW in 2007, before exceeding: 2GW in 2010, 5GW in 2013, 10GW in 2015 and 20GW in 2019. The remainder of this section dissects these trends verify the answer to RQ3.

Transition phase and early upscaling (*2004–2010*)

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[189] When the 1GW was reached in 2007, six countries were active in the offshore space at the time with Denmark and the UK dominating the global market, 42% and 39% respectively. The Netherlands accounted for 13% of total installed capacity; the remaining 6% was split between Ireland (25MW), Sweden (23MW) and Germany (7MW).

[190] The average fell to 60.05% for 1991–2003 inclusive; SD: 70.05.

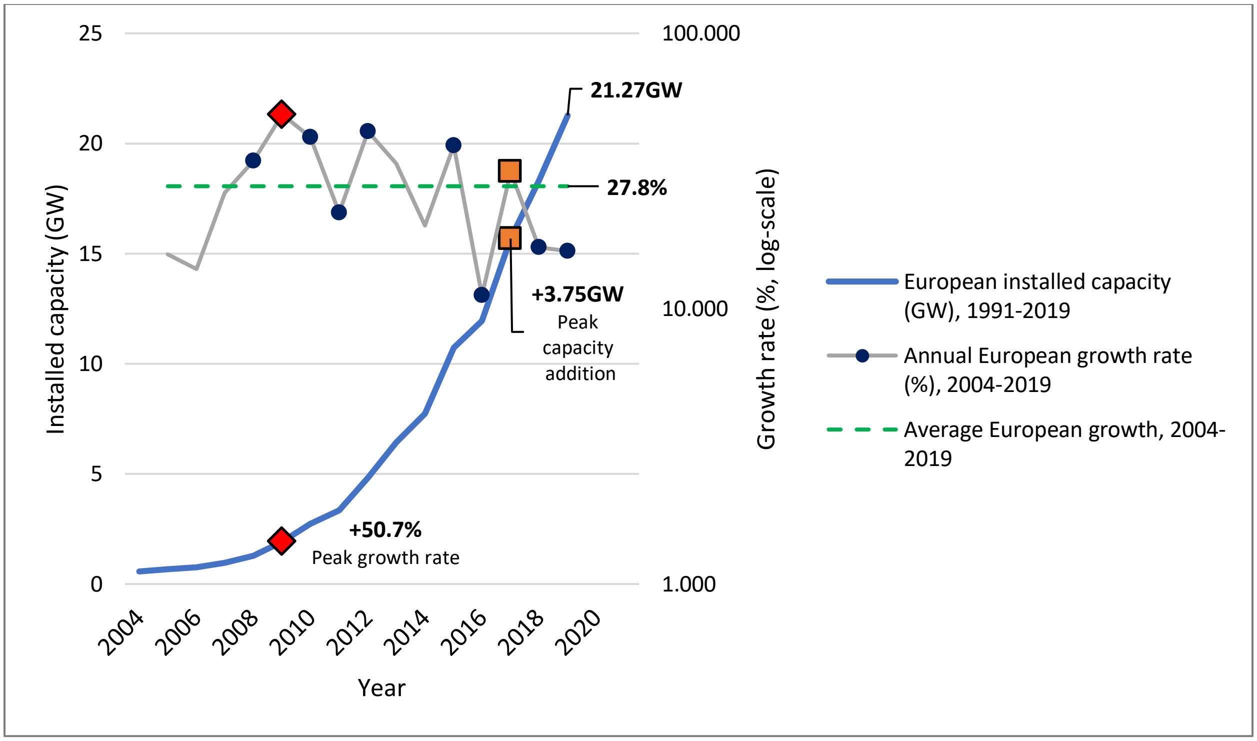
Between 2004 to 2011, the offshore wind market transitioned from the formative phase to the growth phase, reaching take-off in 2011. The transition phase was marked by significantly different patterns than the formative period. For starters, deployment took place in every single year with a minimum growth of 14% in 2006. Peak annual growth came in 2009 following an increase of 50.7%, corresponding to an addition of 0.65GW. 0.35GW were added on average each year between 2004 and 2011 and the average annual growth rate was 29.3%.

Take-off, growth phase and commercial upscaling (*2011–present*)

Between 2012 and 2019, 2.24GW were added on average each year, while the average annual growth rate declined marginally to 26.5%. Throughout the period reported (2004–2019), the average annual growth rate was 27.8% with notable fluctuations as shown in Figure 6.37. Growth was more than 10% below the average in five years (2004, 2005, 2016, 2018 and 2019) and 10% above the average in four years (2009, 2010, 2012, 2015). Most significantly, the growth rate has been in decline during three of the last four years (barring 2017), confirming that European offshore wind energy has already passed through the exponential growth phase; 2015 marked a capacity jump from 7.72GW to 10.73GW (39%) following Germany's tripling up of capacity from 1GW to 3GW. Clearly, such a growth rate has proved unsustainable given existing technological conditions and the current political environment.

In conclusion, the current deployment of offshore wind power in the NESC is increasing in terms of annual capacity additions, stabilising at around 2.5–3GW in the last five years; however, the annual growth rate already peaked in the late 2000s and has declined steadily since this time (see Figure 6.37.). In conclusion, the current deployment path is stable; there is neither a pronounced slowdown nor strong possibilities for exponential growth observed.

Figure 6.37. Annual growth trends for European offshore wind power, 2004–2019



Source: Author’s calculations based on IRENA 2019; IEA 2020

6.12 Feasibility of 2030 targets and the 2050 growth outlook

This section synthesises and summarises the results from the Structured, focused comparison to answer **RQ4**: Is it feasible for NSEC Member States to achieve offshore wind deployment levels compatible with their national targets? This is answered through a feasibility ranking matrix and by assessing the growth fits and projected curves through to 2030 based on empirical data. The ranking matrix is classified as follows: Very high; High; Medium-high; Medium; Medium-low; Low; Very low. Seven categories are chosen to allow for maximum resolution. The 2050 growth outlook is assessed by applying the same methodology under the scenario that 2030 targets are met by Germany, Denmark, the Netherlands, and the United Kingdom.[191] Results are evaluated against WindEuope’s 2050 scenarios (High-scenario and Low-scenario).

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[191] Belgium is excluded from this last stage due to its low ceiling.

6.12.1 Feasibility of 2030 targets

Feasibility levels for the European frontrunner group correspond to a specific rank order extracted from the results in Table 6.3.

1. **Belgium** (4GW target; annual average deployment required: 0.22GW)
2. **Netherlands** (11.5GW target; annual average deployment required: 0.94GW)
3. **Germany** (20GW target; annual average deployment required: 1.14GW)
4. **Denmark** (5.3GW target; annual average deployment required: 0.33GW)
5. **United Kingdom** (30GW; annual average deployment required: 1.87GW)

Table 6.3. Feasibility ranking matrix for Frontrunner group according to empirical data

	2019 Capacity (GW)	**2030 target (GW)**	**Relative increase (2019–2030)**	**EXP (year)**	**Margin (GW, +/-)**	**LOG-LIN (year)**	**Margin (GW, +/-)**	**Feasibility Level (Very high – Very low)**
BE	1.566	4.0	2.6	2024	+0.02	2025	+0.78	Very high
DE	7.445	20.0	2.7	N/A	N/A	2029	+0.13	Medium-high
DK	1.701	5.3	3.1	2030	-0.35	2030	-2.76	Medium
NL	1.118	11.5	10.3	2029	+0.05	2029	-4.96	High
UK	9.445	30.0	3.2	N/A	N/A	2030	-10.68	Very low
Total	**21.272**	**70.80**	(*Average*) *4.4*					

Notably, the country with the lowest target – Belgium – also has the highest level of feasibility, while the country with the highest target – the UK – has the worst level of feasibility. However, it is also important to bear in mind the relative increase between 2019 to 2030 in each country case, as a determinant of ambition. This would see the rank as follows: NL, UK, DK, DE, and BE (see Table 6.3. column 3). Significantly, the Dutch target is far more ambitious in relative terms than observed in any other frontrunner country, set at above three times the UK (10.29 to 3.17). Synthesising the findings, the following points can be made according to the growth fits.

Belgium

Belgium has **very high** feasibility to reach its 2030 target as its past annual deployment trends fit an exponential growth pathway best (logistic growth sees the equivalent additions to 2030). Following this growth rate, it would reach its 2030 target of 4GW around 5 to 6 years early. Its target is both the lowest in absolute terms and the least ambitious in relative terms. Belgium has low ceiling (approx. 6GW) for offshore wind due to its small EEZ, which raises the probability of it reaching an installed capacity of at least 4GW by 2030. The findings for the growth fits mirror the conclusion from the examination of driving mechanisms of Belgian offshore wind growth.

Germany

Germany has recently revised its 2030 target from 15GW to 20GW. Accordingly, feasibility remains **Medium-high** to reach its 2030 targets as its past deployment trends fit a logistic-linear growth pathway best.[192] Following this growth rate, it would reach its 2030 target a year early. Its target is the second highest in absolute terms after the UK and falls into the low to mid-range in relative terms, ranking fourth slightly ahead of Belgium. The findings align closely to the examination of driving mechanisms of offshore wind growth. However, Germany recently became the first country to officially announce a 2040 target for offshore wind – currently set at 40GW – which adds significant weight to it quest to meet its 2030 target early and drives up the feasibility level for achieving this goal to **High** in line with its Energiewende ambitions.

Denmark

For Denmark, there is a **Medium** level of feasibility to reach its 2030 target of 5.3GW, since logistic-linear growth only reaches 2.54GW by 2030; whereas exponential growth falls just 350MW short of the target. Denmark's target is the second lowest in absolute terms ahead of Belgium, but in relative terms ranks alongside the UK in the mid-to-high range behind the Netherlands. Denmark remains Europe's leader in wind energy in relative terms, generating comparatively higher levels of electricity from its wind farms both onshore and offshore. Its pioneering status consolidates the odds of its 2030 target being met on time. Moreover, increased policy support for hybrid wind energy projects and the shift towards green hydrogen shift Denmark's feasibility level to **Medium-high.**

Netherlands

Feasibility is **high** for the Netherlands to reach its 2030 target, since exponential growth is the best fit to the data, reaching 11.5GW in 2029. Under conditions of logistic-linear growth, installed capacity reaches just below 9GW, fulfilling 75% of the national target. Feasibility is lower than in the Belgian case, but higher than for Germany since exponential growth followed through to 2030 would see the Netherlands hit 14.4GW; whereas logistic-linear growth to the same year in Germany

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[192] The RSS for LOG-LIN is 0.723 while the RSS for LOG is 0.805; however, LOG is implausible.

results in only a marginal increase above its 2030 target, reaching 21.4GW. As highlighted, the Dutch target is outright the most ambitious across the frontrunner group and ranks in the middle in absolute terms. The Netherlands faces an imminent energy security crisis due to the curtailing of its natural gas supply. It has strong techno-economic and socio-technical resources linked to its offshore sector, which are now backed more explicitly by the government. The alignment of these driving mechanisms supports the feasibility of a ten-fold capacity jump by 2030. In this case, the modelling exercise is corroborated by the case study analysis.

United Kingdom

Finally, for the United Kingdom the growth fits indicate a **low** level of feasibility since logistic-linear growth fits the empirical data best. However, such a growth pathway allows for a capacity of just 19.3GW by 2030, meeting just two-thirds of the current target. In this case, the modelling parameters do not reflect events on the ground (or at sea), since the UK project pipeline is set to reach 20GW before 2050 and there are surplus gigawatts worth of projects in the pipeline. Moreover, the UK is the global leader in offshore wind power and the will remain the frontrunner in the NESC for the foreseeable future; deploying at scale of the back of a strong industrial strategy and well-established networks between key players across the supply chain, investment landscape and policy arena. Crucially, the UK is the key link in the NESC chain that can support long-term growth and the attainment of targets; there is a strong positive feedback mechanism at work when lead markets such as the UK for offshore or Germany for onshore wind (as well offshore) set ambitious targets and back them up with strong action. Given the evidence provided by other feasibility studies (renewableUK 2050 study and WindEurope 2050 study), it is concluded that the UK may succeed in deployed at least 2GW per year on average this decade, which will see it make its 2030 target. For these reasons, its feasibility status is reversed from very low to **High**.

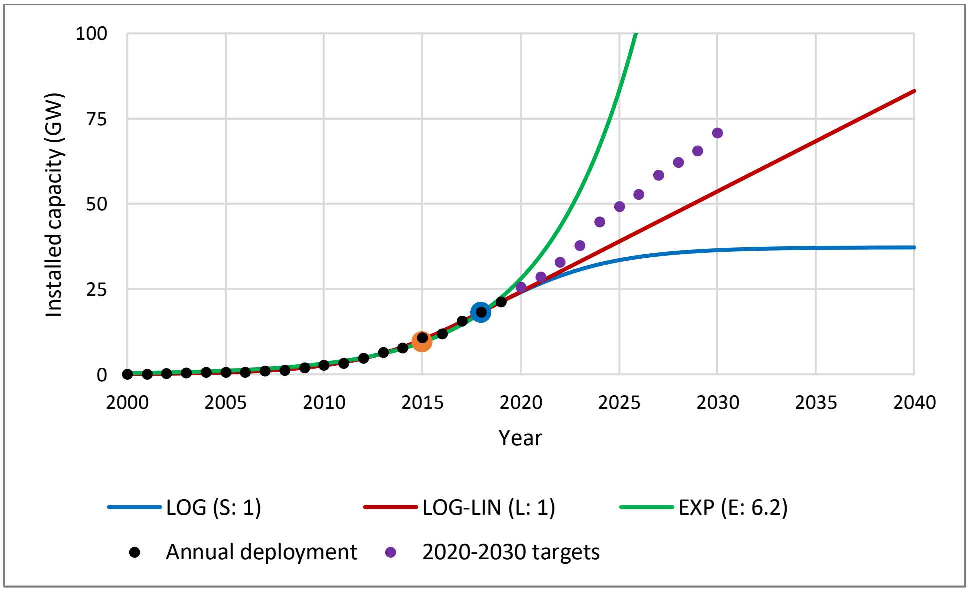
NESC frontrunner group

The function parameters based on the empirical data for the frontrunner group for the period 2000 to 2019 indicate that logistic growth and logistic-linear growth are equally good fits, while the goodness of fit for exponential growth is significantly worse. This confirms that growth is accelerating, albeit slower than the exponent. Logistic-linear growth is the pathway of interest since logistic growth plateaus at around 37GW by 2040; several-fold lower than the estimated ceiling for offshore wind in the NESC. The inflection point (**blue dot**) is reached in 2018, after which time a linear growth rate of 2.95GW kicks in (see Figure 6.38; This would bring installed capacity to 54GW, 83GW and 113GW in 2030, 2040 and 2050, respectively (see Table 6.4).

Table 6.4. Function parameters for Frontrunner group based on empirical data, 2000–2019

Type of fit	2019 capacity (GW)	K (Year^{-1})	L (GW)	T_0	G (GW/year)	RSS (GW)	2030 capacity (GW)	2040 capacity (GW)	2050 capacity (GW)
Logistic (S)	21.272	0.317	37.255	2018.1	2.951	1.254	36.416	37.219	37.253
Logistic-linear (L)	21.272	0.317	37.128	2018.1	2.945	1.253	53.663	83.109	112.554
Exponential (E)	21.272	0.218	22.502	2019	0	7.712	246.752	N/A	N/A

Figure 6.38. Offshore wind pathways for Frontrunner group: Empirical data and fitted growth models with RSS



Under this growth pathway, the NESC frontrunner group fail to meet their cumulative 2030 target of 70.8GW, falling short by close to 25%. Nevertheless, logistic-linear growth would see installed capacity more than double by 2050 from 2030 levels, which is noteworthy. Nevertheless, the focus here remains on the 2030 timeline.[193] The growth fits for the UK have a clear impact on the projections, significantly diminishing the rate of linear growth after maximum growth is reached in 2018 (at the same time of inflection in this case). Accordingly, it can be reported here that the linear growth rate from 2018 onwards would need to increase by around 53% - from 2.94GW to

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[193] As Belgium is subsequently removed for growth projections to 2050 due to its low ceiling (see method in 0).

4.5GW – for the NESC's frontrunner group to meet its 2030 target. While the growth fits indicate that reaching this target is currently off-track, upscaling dynamics across the North Sea and increased political backing for offshore wind, alongside other causal mechanisms strengthening growth, suggest that there is **at least a medium-level**, if not *a high level of feasibility* to reach the 2030 target.

6.12.2 Feasibility of 2050 growth pathways

Feasibility levels for the European frontrunner group correspond to a specific rank order, presented in Table 6.5. Under this scenario – with 2030 targets fulfilled in the NESC – logistic growth results in ceiling of 111GW by 2050; which corresponds to logistic-linear growth in Figure 6.38, confirming the positive impact of fulfilling 2030 targets on 2050 growth parameters. While this scenario (LOG growth) is not implausible, here we are interested in evaluating higher levels of growth potential, which makes logistic-linear growth the pathway of most interest. Moreover, the RSS for LOG and LOG.LIN are similar in this case. Maximum growth is reached at the end of 2022 (**red dot**) while the inflection point is in 2024 (**blue dot**) (see Figure 6.39).

The reference scenarios presented below are taken from WindEurope's feasibility study of European offshore wind in 2050 (Freeman *et al.* 2019): The high-scenario sees 450GW of offshore wind deployed in Europe by 2050 to meet 30% of electricity demand, while the low-scenario is based on installed capacity reaching 230GW.

1. **United Kingdom** (annual average deployment required to meet 80GW: 2.5GW
2. **Germany:** (annual average deployment required to meet 50GW: 1.5GW)
3. **Denmark** (annual average deployment required to meet 36GW: 1.54GW)
4. **Netherlands** (annual average deployment required to meet 60GW: 2.43GW)

Table 6.5. Feasibility ranking matrix for Frontrunner group based on 2030 targets

	2030 Capacity (GW)	**450GW scenario target for 2050 (GW)**	**230GW scenario target for 2050 (GW)**	**LOG-LIN (GW, 2050)**	**EXP (Total, DK only)**	**Feasibility for 450GW scenario (Very high – Very low)**	**Feasibility for 230GW scenario (Very high – Very low)**
DE	20.0	50.0	25.6	43.32	N/A	Medium	Very high
DK	5.3	36.0	18.4	12.51	37.65	Very low; High	Low; V. high
NL	11.5	60.0	30.7	29.01	N/A	Very low	High
UK	30.0	80.0	40.9	70.64	N/A	Medium	Very high
Total	**66.8**	**226.0**	**115.6**	**155.5**	**180.6**	Very low	Very high

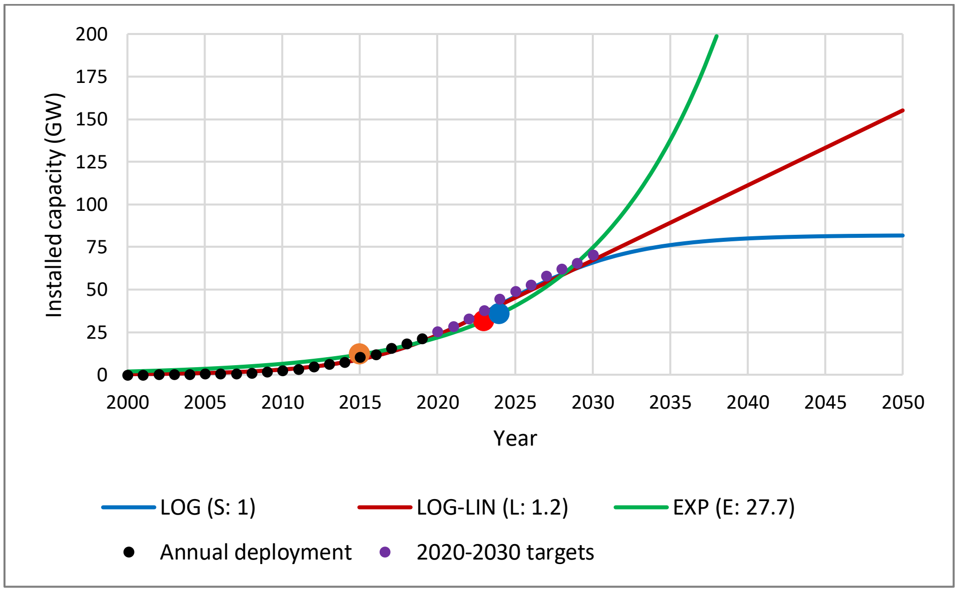
Under this scenario, the findings depart significantly from the results for 2030 shown in Table 6.4. Conversely, the UK is now ranked highest having been lowest previously, while the Netherlands drops from highest to lowest place (Belgium excluded). Under the high scenario (450GW), the countries have the following capacity increase (ratio) to make relative to 2030 levels: DE, 2.5; DK, 6.8; NL, 5.2; UK, 2.7. Therefore, the ranking matrix fits closely to these findings. The UK and Germany need to raise their installed capacity by two-and-a-half times to three-fold, which has **medium feasibility** prospects; whereas a five-fold and seven-fold capacity increase for the Netherlands and Denmark, respectively, yields **very low** feasibility. However, as noted this result changes to high in the case of Denmark should it follow an exponential pathway. Following the modelling results, it is the only country that may have this possibility.

The country-level findings determine the aggregate results. Under logistic-linear growth, the NESC frontrunner group reaches an installed capacity of around 155.5GW, which increases to 180.6GW should Denmark follow an exponential growth pathway (see Table 6.6 and Figure 6.39). Both scenarios fall short of the high-scenario target of 226GW; nevertheless, the results suggest a positive long-term outlook since 72% and 84% of the target is met, respectively. Should the frontrunner group overshoot its 2030 target, which has shown to be feasible under different conditions, the modelling results under logistic-linear growth would draw closer to WindEurope's high-scenario target.

Table 6.6. Function parameters for Frontrunner group based on empirical data & 2030 targets

Type of fit	**2030 capacity** (GW)	**K** (Year^{-1})	**L** (GW)	**T_0**	**G** (GW/year)	**RSS** (GW)	**2040 capacity** (GW)	**2050 capacity** (GW)
Logistic (S)	70.8	0.233	81.891	2024.0	4.771	13.877	79.984	111.141
Logistic-linear (L)	70.8	0.248	71.021	2022.8	4.340	16.127	81.702	155.137
Exponential (E)	70.8	0.123	22.502	2019	0	384.547	253.993	N/A

Figure 6.39. Offshore wind pathways for Frontrunner group based on 2030 targets and fitted growth models with RSS



When the 2050 target is lowered to 230GW all countries secure a high level of feasibility to reach their targets. This is noteworthy as IRENA's REmap Case (2019 edition) European target was set at 215GW for 2050, alongside a target of 78GW for 2030. Clearly, only four countries and ones solely belonging to the NESC block are represented here, yet still they have feasibility to reach at least 230GW. This observation highlights the extent to which RE roadmaps must respond dynamically to internalise changes upscaling dynamics, the rate of technology diffusion and the state of innovation, while adjusting to changes in targets and project pipelines, with Germany being a case in point for this argument (see also section 2.8). Once again, techno-economic, socio-technical, and political mechanisms lie at the heart of growth parameters.

This exercise has extended the analysis to 2050 in a more robust way. There are two key findings to report at the aggregate level:

(1) There is **low-medium** feasibility of the NESC group reaching a 2050 target of 216GW, under WindEurope's high scenario of 450GW for 2050.

(2) There is very **high feasibility** that a low-scenario target of 115.6GW – in line with WindEurope's European target of 230GW – can be met.

These results suggest that a middle-path scenario ranging from around 155GW to 180GW may prove feasible in the future and the upper limit of this range is likely to increase over time (i.e. the ceiling for European offshore wind power will increase) while the range itself will be narrowed as targets are announced – as exemplified by Germany's 204- target – and growth mechanisms become more measurable, albeit while remaining dynamic and unpredictable.

7 Conclusion

The thesis set out to assess the feasibility of installing at least 76GW of offshore wind power in the North Seas Energy Cooperation (NESC) Member States by 2030. The study looked specifically at the 70.8GW of capacity that has been targeted by the NESC's five frontrunners: Belgium, Germany, Denmark, the Netherlands, and the United Kingdom. Assessing feasibility at this level was deemed appropriate to assess the remaining 5.2GW of capacity, which for example is met by the French 2030 target exclusively. The answers to the research question were found by way of a Structured, focused comparison covering the entire frontrunner group and analysing each case by the same methodology. To close, Chapter 7 firstly explains how the research aim was achieved through answering the four questions formulated in Chapter 1. Next, key contributions to the literature are summarised. Thereafter, it acknowledges the main limitations of the thesis and outlines future areas of research interest.

7.1 Fulfilment of the thesis objectives

The first objective of this thesis in contribution to the feasibility assessment lay with identifying the processes that determine the *early* uptake of offshore wind power. The focus here was on the formative phase when offshore wind fills a niche and socio-technical networks begin to form round Research, Development, Demonstration and Deployment (RDD&D) activities. The Technology Innovation System (TIS) framework was employed as way of mapping 'functions' **(F1–F7)**, which underlie the key processes by which offshore wind moves from the innovation phase to towards early marker formation and subsequent growth. The concept of 'motors of change' within the Offshore TIS was adopted to discern between the respective functions, creating a causal network for distilling the order of events. TIS narratives were constructed for each country case to identify generic processes that fit across most, if not all cases, while also building the background knowledge for advancing the study. The emphasis in RQ1 was moving from the specific to the general to understand the processes by which offshore wind develops and diffuses.

Derived from the findings in Chapter 5 and the summary results in Chapter, the key processes – **Motors of change** – that determine the early uptake of offshore wind and the parts of the TIS they in turn drive can be stated as follows:

1. Entrepreneurial activities **(F1)** → *Functions 2 and 3*

2. The guidance of the search **(F4)** → *Functions 1 to 3*, and *Functions 5 to 7*

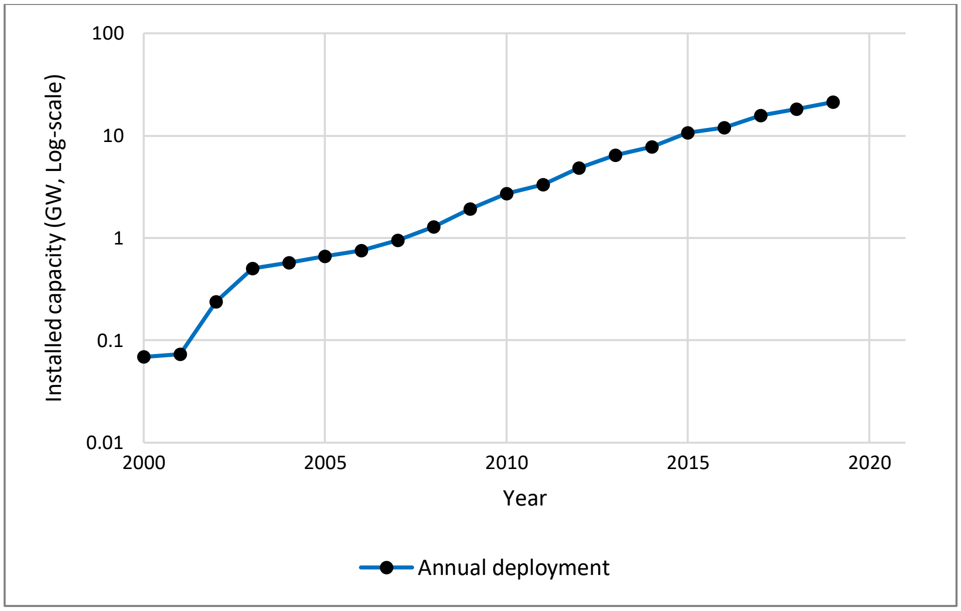
3. Market formation **(F5)** → *Functions 2 and 3,* and *Functions 6 and 7*

4. Resource mobilisation **(F6)** → *Functions 1 to 3,* and *Functions 5 and 7*

Moreover, it can be concluded that from these four functions, the guidance of the search **(F4)** is the strongest driver of change in the TIS, stimulating collaboration between the government and industry to establish the backbone of the socio-technical system. The guidance of the search reaches more functions than alternative motors of change and often subsumes market formation and resource mobilisation with its processes, which seek to establish a clear development path and long-term objectives for offshore wind technologies based on expectations, user demand and socio-political discourses. While companies and the private sector can contribute towards guiding the distribution of key resources, it the government of its institutions that mainly drive development and diffusion. Policy visions and provisional targets provide the necessary conditions for mobilising resources and unifying key actors. The Offshore TIS is strongest when the government-led guidance of the search is complemented by a bridging actor such as the Crown Estate (CE) in the case of the UK and transmission system operator (TSO), TenneT, in the Dutch case. When these conditions are met, opportunities for entrepreneurial activities, knowledge development, and knowledge diffusion **(F1–F3)** are likewise strengthened.

A key tenet of this research study resided lay with analysing past growth patterns corresponding to trends in annual deployment levels of installed offshore wind capacity, as a way of parameterising future growth potential and the feasibility thereof. To proceed meaningful, it was necessary to first verify if the current deployment of offshore wind power in the NSEC is accelerating, stable or slowing down. Figure 6.37 provided the answer to this question, confirming that the exponential phase of growth has come to an end, however, there is currently no marked slowdown to warrant warning signs of premature saturation. The ceiling for offshore wind in the NSEC is multiple times the current capacity and is likely to grow significantly more to at least 2050. Using a log-scale to highlight the findings, Figure 7.1. verifies that the current deployment path is stable.

Figure 7.1. Growth in European offshore wind power, 2000–2019 (Log-scale)



Source: Author's calculations based on IRENA 2019; IEA 2020

The core question of this thesis was one of feasibility. The focus was on 2030 and the discussion was extended to 2050, with a comparative lens to derive a feasibility matrix for evaluating fulfillment of national offshore wind targets across the frontrunner group. Findings at the national level were then aggregated to address the question of the NESC's cumulative 2030 target of 76GW (70.8GW for the frontrunner group). The compatibility of future offshore wind deployment levels with set targets is reported in Table 7.1.

Table 7.1. Feasibility of 2030 targets according to modelling and mechanisms

	Current capacity (GW)	**2030 target capacity (GW)**	**% of Cumulative target**	**Feasibility of 2030 target according to growth fits**	**Feasibility of 2030 target according to mechanisms**
BE	1.556	4.0	4.93	*Very high*	*Very high*
DE	7.445	20.0	25.35	*Medium-high*	*High*
DK	1.703	5.3	7.26	*Medium*	*Medium-high*
NL	1.118	11.5	20.96	*High*	*High*
UK	9.445	30.0	41.50	*Low*	*High*
Cumulative	21.267	70.8		**Medium-low**	**High**

For each country case, the feasibility assessment based on processes of development and diffusion, and mechanisms of growth, yielded equal or better results than the modelling exercise built on fitting growth pathways (logistic, logistic-linear and exponential) to past data points. The country with the highest feasibility for reaching its 2030 target (4GW) proved to be Belgium **(Very high)**, while feasibility was **High** across Germany, the Netherlands, and the United Kingdom. Denmark improved from *Medium* to **Medium-high** based on the evidence collected. The most dramatic finding related to the UK in terms of the model. It received a **Low** feasibility ranking since under conditions of logistic-linear growth it fell more than 10GW short of its 2030 target, thus bringing down the entire NESC frontrunner aggregate. After evaluating the UK Offshore TIS and the driving mechanisms in the wider energy landscape, it was concluded that the UK has **High** feasibility to meet its 2030 target and may possibly overshoot this due to surplus gigawatts in the project pipeline. This finding shifted the aggregate ranking from *Medium-low* to **High.**

7.2 Contributions to literature

This study aimed to provide a comprehensive picture of how offshore wind develops and diffuses in the national electricity mix within the energy transition context, as a means for assessing the feasibility of near-term targets and long-term growth prospects. In grappling with these tasks, three main contributions to the literature were consolidated: **(1)** Analytical narratives of the five key countries in the European offshore wind market; **(2)** a novel conceptual framework for tracking the growth of offshore wind power; and **(3)** a feasibility study linking modelling components with the "three perspectives" framework which yielded a ranking matrix for 2030 targets as well as provisional 2050 targets.

(1) Narratives play a key role in disseminating knowledge. By tracing events over the course of three decades, this study contributed to telling the 'story' of offshore wind power in Europe; allowing for specific events and episodes to be easily digested and recounted across five countries. This from of analytical narrative moves beyond the typical boundaries set in the literature where three countries may form a comparative study (e.g. MacKinnon *et al.* – Norway, Germany, and UK study) or more commonly two countries or cases are reviewed in depth. The approach taken here extends the scope of traditional comparative analysis and benefits from conglomerating the respective cases into one block – the NESC – to assess the aggregate impact of their individual growth pathways.

(2) To the author's knowledge, a tailor-made conceptual framework for capturing developments in the offshore wind landscape at the level of electricity capacity and electricity generation is absent from the literature. **The Milestones and Landmarks Framework** provides one option for situating offshore wind growth within the broader context of national energy transitions. It performs this function by situating gains in electricity capacity (GW) along the Milestones spectrum, in this case scaling up ten-fold. The UK with its 9.945GW of installed capacity in 2019 was just short of reaching *Milestone 4* with 10GW (after this Milestone, the scaling effect would be reduced accordingly). Landmarks divert from absolute markers to cover relative shares of electricity capacity and electricity generation in the national context. The first landmark is set at the year in which 1% of electricity capacity is sourced from offshore wind, corresponding to ‘take-off’, and the second landmark denotes the year in which 2.5% of electricity is generated from OWFs. This study found that Landmark 2 typically follows two years after Landmark 1. Applying this kind of framework is of interest to see if results such as this hold for other energy sources. Additionally, the framework has a high degree of fluidity and can be easily adjusted to account for the parameters of other energy technologies. The Milestone and Landmarks framework provides the conceptual toolkit for tracing key events that change the narrative order.

(3) While feasibility studies are common in the literature, relatively few attempts have been made to evaluate offshore wind power and as described in section 2.8, the tendency is for offshore wind to be subsumed more broadly under ‘wind’ energy, with onshore carrying more weight. Feasibility studies go hand-in-hand with energy roadmaps, providing an important tool for setting energy policy that is also sensitive to climate change parameters. This study made a two-fold contribution by examining two timeframes: **(1)** 2020 to 2030 based on past trends (i.e. empirical data); and **(2)** 2030 to 2050 based on the assumption that 2030 targets are met (i.e. empirical and hypothetical data). This enabled for more than one scenario to be examined and allowed room for comparative exploration. Similar to the Milestones and Landmarks framework, a ranking matrix provided a simple way to capture the meaning of numerical data. However, the main contribution here is a first look at the NESC’s prospects for scaling up deployment rates through the strength of techno-economic, socio-technical, and political drivers. It is observed that techno-economic upscaling dynamics bring added feasibility while also driving the competitive landscape and the race for innovation and new designs (i.e. dominant product designs). The “three perspectives” framework has been harnessed as way to verify if the modelling results fit the reality.

7.3 Limitations of the study

Models are inevitably sensitive and imperfect tools. The one used to assess growth in this study requires refinements and this is seen within the results, especially for the UK case. The model is highly sensitive to data points near the end of the time range, which presents the possibility of skewed results and anomalies. Several variants of the deployment data were tried for some of the countries to review the differences and as a learning mechanism, however, the UK model was not adjusted. Further calibration would be an area for future work and study, as described in the final section. The model cannot differentiate between projects that are deployed in phases or ones that come online at maximum capacity, which is wider problem with interpreting growth data for the offshore sector. This also leads to ambiguity between offshore wind farms (OWFs) and offshore wind projects (OWPs), which is why a distinction was made within this study when evaluating techno-economic parameters (distance from the shore, area, and depth of OWPs). In this regard, there is further difficulty since various projects are listed with a range for given parameters, which can be wide such as 22–40 metres for depth. Measures were taken in this study to account for these kind of data points; however, it remains a limitation that a more robust methodology could not be adopted. Finally, the offshore wind landscape is an incredibly dynamic space as shown, which means the parameters used here may soon become obsolete, as the average project size and turbine size come to dwarf those of prior years. This transformational shift has been flagged throughout various parts of the country case studies and it remains a limitation that the model could not be built to factor in upscaling dynamics.

7.4 Future research agenda

This study selected the NESC as its point of interest, however, the geographical niche of Northern Europe is not the only area of interest, especially when it comes to floating wind technologies. A comparative study of the Offshore Floating TIS in France, Portugal and Spain is of interest, as these countries form their own hub. According the WindEurope 2019 study (Freeman *et al.*), France will rival German and Denmark by 2050, which makes it a country of notable interest, not least because of its nuclear phase-out policy. This study has also drawn attention to the push for ‘hybrid’ projects geared towards green hydrogen. A scenario analysis factoring ‘green hydrogen uptake’ in the electricity sector would provide a complementary perspective on another potential driver in Europe’s energy transition. Furthermore, the switch to new cabling technologies (i.e. high voltage direct current) may help facilitate the realisation of wind energy islands, which remains an understudied research area.

The literature review has drawn attention to the importance of pan-European governance and system integration if the aforementioned projects are to be realised. The NESC provides a starting point for investing how a more collaborative and synergistic offshore wind sector can be consolidated, especially in a post-Brexit environment which sees the UK also exit the NESC. The impacts of political events on the maritime environment and the need for cumulative environmental impacts also remains underexplored in the literature. Finally, the impact of developments in the onshore wind sector are of significant interest. It has been observed within this study that two-fold mechanisms are currently at play: countries with established wind sectors can build their offshore sector faster, while constraints and associated saturation pressures on land are driving the shift of turbines to the sea. Notwithstanding, the onshore gird will have to grow and develop to support offshore upscaling and onshore wind has a pivotal role in securing this aim. For these reasons, the future research agenda should consider a similar analysis for onshore wind at the cross-national comparative scale, before assessing onshore and offshore wind within a comparative framework under the lens of feasibility and growth mechanisms.

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