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Is the supply chain ready for the green transformation? The case of offshore wind logistics

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ABSTRACT

The transition from fossil fuel-based energy systems to renewable energy systems is a cornerstone of the green transformation to decarbonize our economic systems and mitigate climate change. Given the urgency of effective climate change mitigation, renewable energy diffusion needs to accelerate drastically. Among the many constraints to renewable energy diffusion, the important role of the supply chain is often overlooked. Therefore, this article addresses the role of the supply chain in the renewable energy diffusion process. Using the offshore wind energy sector as a case, this article presents an analysis of supply chain readiness to ascertain the role of the supply chain in the green transformation. Examining Europe and China mainly within offshore wind logistics, the research findings show that this segment of the supply chain constitutes a key bottleneck for accelerated deployment. For Europe, the key findings indicate that legislation for offshore wind beyond 2020 is necessary to ensure the implementation of the required investments in logistics assets, transport equipment, and personnel. In China, the key findings indicate that the Chinese supply chain of wind energy is mainly organized around onshore wind. Key bottlenecks exist, predominantly in logistics, and this article identifies specific areas of the supply chain where international collaboration and knowledge transfer may speed up deployment.

1. Introduction

There is growing consensus that a green transformation of our economy is necessary in order to avoid significant reduction in human wellbeing resulting from multiple environmental stresses including pollution, biodiversity loss, and climate change [1–4]. Climate change mitigation is a cornerstone in the green transformation and depends on a sweeping process of ‘creative destruction’ in which new renewable energy sources replace old fossil fuel-based sources. Reaching the targets for renewable energy will hinge on both technological change and massive public and private investments [5,6]. Diffusion, so far, has been varied in different geographies [7–10]. This article analyzes an often overlooked - yet crucially important - element in the transition to renewable energy systems: The ability of the supply chain to support precipitous growth and rapid technological change. This is not a trivial issue. Deployment numbers need to be exponential rather than linear. To reach current targets, the renewable energy industry would need to double its capacity every seven years for the next seventy years [11]. Such an expansion of capacity at the sector level is unprecedented in history. The challenge is grand but a mitigating factor is that the doubling of renewable energy capacity is not equal to a doubling of the numbers of workers and factories in the renewable energy industries. This is because of technological change where the energy generation capacity of each unit produced and installed is gradually increased. Yet, the technological changes pose their own challenges to the supply chain. Nowhere is this clearer than in the offshore wind power industry, the focus of this article.

Whereas wind energy has been used for electricity production at an industrial scale since the 1980s [12], the advance in offshore wind energy production is much more recent. It was not until the mid-2000s that governments and energy firms started to move from experimental pilot projects to full-fledged deployment [6,13,14]. Offshore wind is projected to play an important role in the future energy mix of many countries as further onshore wind opportunities are becoming constrained and because offshore wind provides better wind speeds as well as more area for installing larger farms which enable electricity production at scale [15]. While crucially important to future climate change mitigation efforts, offshore wind depends on a transformation of supply chains. The offshore segment differs from the onshore segment as it tends to use larger wind turbines and because the installation process at sea depends on entirely different technologies and skillsets. In particular, the offshore wind segment depends on

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challenging shipping and logistics processes which are entirely novel or which at least are new to the main constituencies who have hitherto been involved in electricity production [16]. That is why this article is particularly focused on shipping and logistics as a case study within the overall supply chain for offshore wind power.

Our research sets out to answer the following questions:

a) How ready is the supply chain for the exponential expansion of offshore wind?
b) What are the key barriers, bottlenecks, and/or constraints to offshore wind diffusion?
c) Are there differences between Europe and China as the largest markets in this regard?
d) How can the diffusion challenges be addressed with new solutions?
e) Where will the solutions come from?

The main contributions of this article are as follows:

First, we bring the supply chain perspective into the debate about renewable energy technologies in the context of climate change. Most discussions focus on the availability of different technologies to mitigate climate change or the availability of finance [17–20]. The crucial question of whether the supply chain is ready to buttress widespread deployment tends to be overlooked. The offshore wind industry provides an exemplary case of supply chain readiness for diffusion of renewables.

Second, the analysis is based on conceptual advances supplemented by our case study work in mainly Europe and China. Most articles have discussed basic value and supply chains mainly in the context of the onshore segment [21–23], or have reviewed supply-chain trends without a fine-grained analysis of the many steps involved in deployment [24–26]. This article decomposes the supply chain for offshore wind to make an analysis of sub-supply chains per life-cycle stage of offshore wind farms.

Third, this article provides a cross-continental comparison of shipping and logistics capabilities for offshore wind power. Prior comparative work has focused on policies and innovation systems [27] or has researched broader technological trajectories [28]. This article provides an in-depth analysis of the offshore segment in order to identify specific leverage points for future deployment.

This article is organized in five sections. Section 2 provides background and framing for the empirical analysis. In Section 3, we identify the main barriers, bottlenecks, and constraints challenging offshore wind diffusion and analyze to what extent and how supply chain readiness differs between Europe and Asia. Section 4 discusses ways forward by reviewing solutions for each of the main challenges for diffusion. Section 5 brings together the insights and conclusions.

2. Renewable energy systems: The role of the supply chain

Current scientific scenarios for reducing carbon emissions to avoid climate change [29] are far more demanding than the current political targets.[1] According to climate change scientists, the current political targets for carbon emissions reductions are not ambitious enough to avoid a two degree Celsius rise in the global average temperatures [20,30,31]. However, even the political goals far exceed the transformative capacity of the key sectors involved in the green transformation. The transformative capacity for renewable energy is limited by a number of barriers, bottlenecks, and constraints which we will look at in the next subsection.

2.1. Barriers, bottlenecks, and constraints

Within this article, these terms will be used as follows:

- *Barriers* are elements in the supply chain that slow down, hinder, or block the diffusion of offshore wind and renewable energy. Academically, barriers to diffusion can be traced back to the medical sciences, veterinary sciences, and physics. The opposite of a barrier are factors that facilitate or enable the diffusion of offshore wind and renewable energy.
- *Bottlenecks* are imbalances in the supply chain where the supply chain capacity is smaller than the demand. Traditional mathematical, statistical, and economic approaches to bottlenecks include capacity planning, queuing theory, calculations of optimal supply/demand balances, and simulations of the equilibrium. Goldratt and Cox [32:139] define a bottleneck as "…any resource whose capacity is equal to or less than the demand placed upon it."
- *Constraints* are challenges faced by certain resources in the supply chain that cause the capacity to be less than optimal compared to demand. Within math or engineering, constraints equal conditions that must be satisfied by the solution in question. The theory of constraints [33] outlines that for a broad definition of a system "…at least one constraint exists that limits the ability of the system to achieve higher levels of performance relative to its goal".

In the case of wind energy, the output is estimated to be 372 gigaWatt ("GW") of installed capacity per annum as of end, 2014 [13,34]. The output surpassed 400 GW during 2015 [35] with China as the world's largest market for wind energy. Using scenarios for 2050, the wind energy output required will be between 1600–4000 GW per annum [36]. There is a massive shortfall in current industrial capacity to meet an output of this scale. There are many well-known bottlenecks when it comes to producing and installing wind energy technology on an adequate scale to support the green transformation. These include:

- Scarcity of sites for new turbine installations[2] [15]
- Technologies for dealing with intermittency [13]
- Financial resources [17–19]
- Government policies [19,37–40]
- Subsidies and tariffs [18,41,42]
- Human capital and skills [43]
- Storage capacity for wind energy after production [34]
- Grid expansion and interconnection [44–46]

Acknowledging constraints in all of these areas, this article is focused on a particular set of constraints – those found in the supply chain. In order to provide a framing for the analysis, the next subsection starts by outlining the role of wind power in climate change mitigation.

2.2. Diffusion of wind power for climate change mitigation

Wind power is a central technology when it comes keeping global temperature increases below two degrees Celsius by ensuring that carbon-dioxide emissions peak and then decline before 2020 as e.g. observed in the European Union ("EU") 20-20-20 policy to reduce dependency on fossil fuels by 2020 [47]. During recent years, a boom in global wind power supply has been witnessed taking wind power output from 17 GW in the year 2000 to 372 GW in 2014 [13,34]. In a 'moderate scenario' according to Global Wind Energy Council [36], this output number will grow to 1480 GW in 2030 while in an 'advanced scenario' it will grow to 1934 GW. This latter scenario expresses a best

[1] Such as EU's 20–2020 regime; China's 12th Five Year Plan, and international agreements within the UNFCCC.

[2] Arising from local opposition, referred to as the NIMBY "not in my back yard" movement and decreasing returns on investment as the best sites are taken.

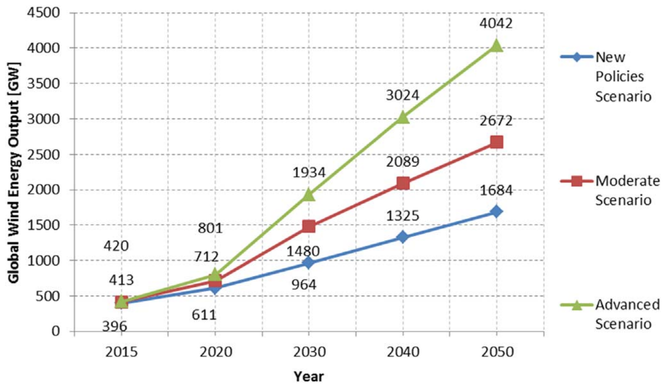

Fig. 1. Global wind energy output scenarios by 2050 measured in GW (Derived from [36]).

case wind energy vision "…which could only occur with a robust climate regime in place and the kind of political will to tackle the climate challenge across most of the global which has been missing to date…" [36:13]. In this 'advanced scenario' as depicted in Fig. 1 below, wind power capacity would reach 4042 GW in 2050 with a potential to constitute 25–30% of the world's electricity consumption [36:11] by then.

The challenges involved in such an ambitious scenario are enormous. It is highly dependent upon reducing the time scale involved in building technological capabilities, boosting the upstream capital goods industries as well as the underlying supply chains [48], and the generation of real cost savings [19,49].

Compared to onshore wind, the diffusion of offshore wind is more demanding and it is also more likely to be affected by supply chain bottlenecks. Globally, 10,000 wind turbines equal to 50 GW of offshore wind generating capacity will be installed during 2016–2025 [50]. As will be discussed, there are many bottlenecks that are general to wind power diffusion (shortage of rare earth materials, lack of skilled personnel for operations and maintenance "O & M"), while other bottlenecks are specific to offshore deployment (e.g. shortages of vessels, trained personnel, port infrastructure). To overcome these bottlenecks, a major transformation is required across the entire supply chain. Utilities are the main constituencies responsible for transforming supply chains. The next subsection addresses the main utilities and their offshore wind activities in Europe as well as China in order to provide context for the analysis.

2.3. The organization of wind power markets: The role of lead firms

The wind market is highly concentrated with the top-ten wind power original equipment manufacturing ("OEM") firms producing 71,8% of turbines installed in 2014 [34]. The capacity of these firms has grown rapidly over the last 10 years. Richter [51] argues that the utilities will play a major role in the green transformation because they control the electricity generation, electricity distribution, and electricity retail value chains to a large extent. Within the offshore wind market, the very significant upfront capital expenditure ("CapEx") commitments put the utilities in the leadership role for each project [19,49] as firstly, developers and then respectively as operators. As project leaders, developers and operators become the 'lead firms' of the total supply chain. This means that the logistics strategy of the developers will have significant ramifications for the logistics set-up of the rest of the supply chain.

With most offshore wind installations situated in Europe thus far [15], the primary experience and skills reside with European utilities. The developer constituency group of Europe has so far been dominated by utilities [14,15,52]. If we compare the business models of these European developers/utilities, the Danish government took a lead role early on in the development of offshore wind early on [51,53]. As a result, Danish state-owned utility DONG Energy is now the leading developer and operator of offshore wind farms globally as measured in already installed capacity and development pipeline [14,34]. The DONG Energy strategy has been to embrace the entire offshore wind farm construction process and to use in excess of 200 contracts to build an offshore wind farm [54]. To craft, manage, and supervise the many contracts including their implementation, DONG Energy employs in excess of 1600 people in their offshore wind energy business. This so-called *"multi-contract business model"* is very much contrasted by most other European developers where much fewer contracts are awarded in larger "contract packages" [55]. This larger group of non-DONG Energy developers is characterized by each firm having smaller number of employees. Due to having less employees, the non-DONG Energy developers are mostly relying on engineering, procurement, construction, and installation ("EPCi") firms to take on very large, individual contracts with a very wide scope of responsibilities and significant contract value. Depending on the contracting structure at the utility firm level, the overall 'lead' in the supply chain and decision making center of gravity changes which makes it complex for a single supply chain constituency to be part of both markets: In the multi-contracting market segment, small and distinctively defined contracts are offered for different slivers of the offshore wind farm value chain whereas EPCi firms and wind turbine OEMs [55,56] have specialized in taking a very large responsibility within the supply chain where the utilities go for very large individual contracts, referred to as *"single contracting business model"*.

In China, the 'big 5' utilities are tasked to implement the majority of the very aggressive national offshore wind strategy which is closely aligned with the Five Year Plans of China at a country level [57]. In the 12th Five Year Plan, central targets for offshore wind in China were 5 GW by 2015 and 30 GW by 2020. With only 487 MW installed as of the end of 2014 [13,34], the 2015 target was hard to reach even with the June 2014 decree providing a national Feed-In-Tariff for offshore wind issued by the central government in Beijing [58] valid up to the end of 2016. This Chinese offshore wind Feed-In-Tariff has been called for by industry and academia constituencies alike [59–62] for several years and is critical for diffusion forecasts to be realized [13,34,50]. The option for the individual provinces to "further top up" the centrally provided Feed-In-Tariff levels [63] is an important factor in reaching the overall targets for offshore wind in China.

From our China case study, it seems clear that the 'big 5' Chinese utilities generally resemble the DONG Energy multi-contracting model with an even stronger degree of vertical integration in the supply chain [56,64,65]. Similarly, the other and smaller developers seem to be challenged with a lack of economies of scale, more limited financial capabilities, and therefore critical challenges in terms of how to realize the implementation of offshore wind farms [66].

For wind energy, supply chains are becoming increasingly global [52] for the wind turbine itself as argued by Yuan et al. [57] "in China a system capable of manufacturing key components as blade, gearbox, generator, variable yaw system, wheel hub and tower is established." However, technological advancement is quite rapid which Yuan et al. [57] acknowledge; "…domestic components manufacturing can hardly keep up with the trend of global technology development." During the recent financial-economic crisis, a situation arose globally with austere financial policies that cited overcapacity in the markets and effectively put major projects on hold in many countries. Many wind power OEM firms can produce wind turbines, however, the main challenge lies in developing technologies to meet the demand for mega-turbines in the future. Moreover, a key challenge for expansion of direct production is the coordination of up- and downstream linkages which span many industries. The value chain may be thought of as being divided between a preparation chain, a manufacturing chain, a deployment chain, and a re-deployment chain (see Table 2ii) below).

To compare within Asia, our case study efforts in South Korea indicate that this 'runner-up' market for offshore wind in Asia

Table 1
Visits to offshore wind farms during research project.

Name of offshore wind farm visited	Country	Life-cycle focus	Timing of offshore visits
Anholt OWF	Denmark	Installation & Commissioning	April 2013 and September 2015
Middelgrunden OWF	Denmark	Operations & Maintenance	March 2015
Horns Reef I OWF	Denmark	Operations & Maintenance	June 2015
Longyuan Rudong Intertidal Trial OWF	China	I & C and O & M	July and October 2016

Table 2 i)
Offshore wind farm supply chain lead firm groupings and examples.

Activity	Project management and financial planning
Sub activity	Wind farm design
Supply chain lead firm	Utilities
Lead firm examples	DONG Energy, RWE Innogy, Vattenfall, Iberdrola, Statoil, Statkraft, Guodian Longyuan, China General Nuclear, Daneng, KEPCO, Masdar

(realistically, the second most ambitious after China) has developed a more 'modest' target of 2.5 GW by 2019 [15,67] and 7.5 GW installed by 2030 [68]. The first larger South Korean wind farms will be erected as test sites where several OEMs exclusively of South Korean origin are allowed to participate up to 2017 in order to give the local OEMs an installation base and O & M 'testing grounds'. Utilizing an effective strategy to test and improve the quality of the home market technology supported by extensive academic studies [69–71], our research indicates that the South Korean OEMs will initially try to enter the very lucrative neighbouring market of China where the quality standards are somewhat lower than those of Northern Europe. As the quality rapidly improves in the combined South Korean and Chinese 'home markets', South Korean OEMs will also wish to compete for a share of the more lucrative European and US markets: Our emperical data indicates that this may include possibly on-shoring production in Europe and the Americas to supplement South Korean exports as was also seen in the case of the South Korean car and consumer electronics industries.

A number of Chinese state-owned mega-firms (e.g. Guodian, China General Nuclear, Huaneng, Three Gorges, China Communication Construction Company) as well as South Korean conglomerates (e.g. Korea Electric Power Corporation, Hyundai, Doosan) are in the process of getting into the offshore wind business [15,56].

There is only little focus on the industrial capacity required to support the transition to renewable energy systems [72]. While all observers seemingly agree that wind power needs to play a major role in the green transformation, the main bottleneck is typically discussed as a question of finance, not as scaling up capacities. In this article, we discuss this issue as both direct production capacity and as upstream and downstream linkages. In the next subsection, we review the existing literature in the field from different angles.

2.4. What does the literature tell us about renewable energy supply chains?

Only limited attention has been paid to renewable energy supply chains in the scholarly literature. In the literature focused specifically on supply chain management, there has recently been a surge of interest in sustainability performance of supply chains [73] and some recent analysis has been targeted specifically towards reduction of carbon emissions [74]. However, these studies have been aimed mainly at the environmental impact of supply chains in manufacturing industries (resource use, transportation, recycling) rather than on supply chains in the energy sector, let alone renewables. One important exception is the paper by Halldórsson & Svanberg [75] which provides a conceptual framework for analyzing energy supply chains from energy sources (raw materials) to consumption. They show that various steps in energy supply chains overlap while other elements are specific to specific energy types (coal, oil, gas, biomass etc). In their paper focusing on supply chains for various renewable energy forms, Wee et al. [76] define conversion cost, location constraints, and complex distribution networks as barriers to generation and utilization of renewable energy. They argue that the barriers may be overcome "through the involvement of governments, researchers, and stakeholders in the development of renewable energy". The downstream distribution and use of energy is based on a shared source availability of electricity (coal, nuclear, solar, wind etc.) whereas the energy conversion step is specific to each source. However, there are many overlaps when it comes to upstream supply of technology for different energy sectors. The implication is that analysis must transcend the specific sector in question: "Building up supply chains of, e.g. wind energy requires producers to become attractive customers of suppliers of turbines and maintenance services already developed in other industries such as automotive and aerospace" [75:70]. This seems particularly important in offshore wind for example, as there are many overlaps with the offshore oil and gas sector (vessels, floating cranes, maintenance service, de-commissioning, etc.).

In the energy and sustainability literature focused on the role of renewables in low carbon transformation, the specific topic of supply chain capacity has been surprisingly absent [77]. One example is a recent study of the European onshore and offshore wind energy installations [25] which reveals a decoupling process between the onshore and offshore supply chains. The authors argue that this will result in higher research & development costs for those firms active in onshore as well as offshore wind which should be accounted for by policy makers in the form of subsidies and regulations.

Conversely, in the supply chain management and logistics literature, very little focus has been given to renewable energy supply chain except the aforementioned paper linking supply chain management and energy using three different trajectories of which the energy supply chain is one [75]. Within areas of marine planning and offshore wind planning, little attention has been paid to the topic of shipping and logistics. A few exceptions include a review of all decision support tools for offshore wind [78] which includes logistics within three segments (overall project cost segment, installation, and O & M), a comprehensive guide to offshore wind farm installation [79], a decision support simulation tool for logistics strategies during the offshore wind farm construction phase [80], and a simulation tool for logistics considering weather and vessel costs during the installation phase [81].

Within the area of O & M, a comprehensive literature review for offshore wind O & M logistics exists [82] and in addition, several papers provide some input regarding shipping and logistics including simulation of offshore fleet operations optimization [83], a verification and validation of four O & M models of which three have a shipping/logistics/maritime component [84], a proposed approach to O & M where logistics is a key focus regarding availability [85], and a PhD thesis focusing on safety (subassembly operations and crew transfer) and efficiency (optimization of maintenance support organization) of O & M [86]. With this review of existing literature as a point of departure, the next subsection introduces our case study used to generate the empirical data to support the research findings of this article.

2.5. Data collection

This article seeks to assess bottlenecks for offshore wind supply chains. No statistical data exists to measure the discrepancy between supply chain capacity and current/future needs, nor is there an established method for produce such measurement.

Table 2 ii)
Offshore wind farm life-cycle activity summary with examples from Europe and Asia.

The wind farm supply chains		Development & consent (D & C chain)	Installation & commissioning (I & C chain)					Operations & Maintenance (O & M chain)	De-commissioning (De-comms chain)
			Inbound				Outbound		
			WTG inbound	BOP inbound			Construction/installation /commissioning		
			WTG	Foundations	Cables	Sub-station			
Sub activity		Surveys	Assembly Modules production	Assembly Modules production	Manufacturing	Assembly Modules production	Installation landside Installation BOP Installation WTG	Preventive maintenance Unscheduled maintenance Contingency maintenance	WTG de-commissioning BOP de-commissioning Site restoration
Supply chain lead firm		Utilities Government authorities	WTG OEMs Module OEMs	Foundation BOPs	Cable OEMs	Sub-station OEMs Foundation OEMs	Utilities EPC providers WTG/BOP OEMs Shipping companies Logistics companies	Utilities EPC providers WTG/BOP OEMs Shipping companies Helicopter companies	Utilities Government authorities Shipping companies Logistics companies
Main firm examples	*Europe*	Crown Estate	Siemens Wind Power	Bladt	Nexans	Semco Marine	A2SEA	World Marine Offshore	DONG Energy
		Energinet.dk DONG Energy Vattenfall	MHI Vestas LM Windpower Gamesa Areva (Adwen)	Bilfinger Rambøll Per Aarsleff	NKT	Bladt ABB	Fred Olsen DSV Baltship Seajacks	N-O-S Esvagt Blue Water Shipping	Vattenfall Crown Estate Energinet.dk
		RWE	GE Alstom	Ambau			Van Oord	DONG Energy	Swire Blue Ocean
	Asia	Longyuan	Goldwind	CCCC/ZPMC	Zhongtian Technologies	ZPMC	SBSS	SINO-HITECH	CGN
		KEPCO	Titan	China Offshore Oil Eng	Qingdao Hanhe	CGN	CCCC	SEwind	
		CGN	United Power	Nantong Ocean Water	Ningbo Orient		Longyuan Zhenhua	Envision Energy	
		Daneng	Haili	Jiangsu Daoda Heavy	Fujikura Shanghai		Daneng		
		Huadian	Sinovel	Haili			Profundo		

This research used a case study approach focusing on the world's largest markets, Europe and China. We focused on critical embedded sub-unit cases [87], namely the leading offshore wind developer and operator in Europe (DONG Energy) and China (Guodian Longyuan). The primary source of information for our case studies are 30 formal interviews with interview layout defined by Kvale & Brinkmann [94] conducted within the shipping and logistics sphere of the supply chain in and around these firms. The interviews were conducted in the period from November 2014 through October 2016. The interviews were divided equally between Europe and China. There are limits to the methodology used in this research as the studies were exploratory in nature. The use of critical cases enabled an insight into the situation as it looks from the vantage point of the most advanced offshore wind farm developers in Europe and China, but extrapolation of the results needs careful interpretation. We hope that the conceptual framework and methods used here will enable further, large scale survey research.

Our case study builds on prior research on the wind power sector with focus on China and a comparison of innovation paths for wind power between China, India, Germany, and Denmark [88–92].

In Europe, we opted to mainly use a single-company case study approach within the leading offshore wind farm developer and operator firm [14,93]. In China, several advance study trips with pre-interviews had to be made to build the relationships enabling the authors to gain access to the interviewees and as such, the total research time spent in China amounted to approx. 2 months. In Europe, the interviews were conducted over a 4-month period from November 2014 through February 2015 with interview guides and interview planning carried out from July through October 2014. In China, the interviews were carried out during 2 research trips taking place over a 4-month period from July 2016 through October 2016. In Europe, each interview lasted between 60 and 90 minutes and each interview was largely based upon the interview guide developed for the purpose. In China, the different interviews lasted from 45 minutes to 7.5 hours and contained different elements of translation and clarification during the meetings even though the interview guide had been prepared in a written presentation format in advance, using both English and Chinese characters. In Europe, 14 of the 15 interviews were audio taped and later transcribed with full consent from the 17 interviewees. In China, many more people attended each meeting (from 2 to 8 interviewees including translators and observers in each of the meetings) and audio taping was not permitted or not possible. In Europe, one of the interviews was supplemented by participant observation. In China, 12 of the 15 interviews included an element of participant observation. Our European case study has been published [93]. Our China case study is in the process of being published.

For the South Korean part of our case study, South Korea visits were supplemented by email follow-up and discussions with relevant stake-holders in the UK, Denmark, and the US during 2014 and 2015.

In the period from 2013 to the end of 2016, our case study efforts were supplemented by additional participant observation and semi-structured interviews [24,94]. These included site visits and semi-structured interviews pertaining to four offshore wind farms [54,95] as depicted in Table 1. In addition, our research efforts included the participation in a 20-month long cross-industry cost reduction initiative pertaining to the logistics part of the O & M life-cycle phase, conducted from August 2014 through April 2016. The research findings from this case study were supplemented with an in-depth analysis of 11 significant studies on offshore wind levelized cost of energy with focus on the logistics share of Operational Expenditure ("OpEx") and O & M costs. This case study is in the process of being published.

3. Supply chain constraints

Section 2 outlined a number of bottlenecks for the diffusion of renewable energy. In this article, we do not deal with these 'relatively known' bottlenecks. Instead, we focus on a largely overlooked issue: The constraints in the supply chain. Our perspective is both upstream and downstream, we focus on CapEx, OpEx, and the cost for de-commissioning/site abandonment ("AbEx") [130]. To further focus and exemplify, we put the logistical challenges contained in the supply chains in the center. The logistics and shipping support to the offshore wind industry has not been researched in much detail as a stand-alone topic; it usually forms part of a broader supply chain review [43,55,89,96]. In the next subsection, we will review the different supply chains within the life-cycle of an offshore wind farm including the associated shipping and logistics challenges faced.

3.1. Logistical challenges in offshore wind supply chains

Building on BTM a part of Navigant & Poulsen [16], Poulsen et al. [54,95], and Poulsen [24], a wind farm life-cycle can generically be split into four key phases:

- Development & consent
- Installation & commissioning
- Operations & maintenance (O & M)
- De-commissioning

Table 2ii) above outlines key activities/sub-activities within the offshore wind farm cradle-to-grave life-cycle and identifies the sub-supply chains for each of the life-cycle phases.

As outlined above, utilities act as wind farm developers/operators. As the offshore wind farm supply chain lead firm, these firms maintain overall project management and financial management functions for the duration of the entire wind farm life-cycle [97]. Each wind-farm life-cycle phase contains several bespoke supply chains:

1. In the *development & consent* phase, special geophysical, geotechnical, ornithological/mammal, and other survey vessels enable different *surveys* to be carried out as part of the site *planning* efforts. Sometimes, survey aircraft are also used and surveys may continue into the construction phase [97]. The surveys are executed to ensure that the offshore wind farms can be built in the right locations with the least impact on animal life [98,99] or nature in general [100,101], and are based on the correct conditions/assumptions e.g. the seabed being made available to the developer [54]. The timing is often in advance of awarding the offshore wind farm sites to developers as well as during the bidding process.
2. The *installation & commissioning* phase has a distinctive *inbound* and a substantially different - but similarly very distinctive - *outbound* supply chain. In the *inbound supply chain*, key offshore wind farm components such as nacelle, blades, tower, foundation, cables, and sub-station are assembled/built using very different manufacturing and shipping/logistics processes. By far the most complex individual wind turbine module is the nacelle which in some cases consists of up to 65,000 individual parts and components [91]. The assembly process is sometimes a combination of certain sub-assembly routines, just-in-time practices, on-site warehousing, and vendor managed inventory [102]. In other cases, key suppliers are co-located within the nacelle assembly plant premises to ensure effective transfer of pre-assembled components to be mounted in the nacelle [103] and smooth factory/plant logistics. The somewhat nascent and not yet industrialized offshore wind industry is often compared to the automotive industry in terms of how especially the component assembly/manufacturing process could be improved [104–107]. However, to illustrate the diversity of the inbound supply chains involved in assembling/manufacturing, BVG Associates [108] (2014) conducted an extensive UK offshore wind supply chain readiness study for the UK Crown Estate where parallel sectors considered include aerospace, composites, nuclear, oil & gas, and rail as well as automotive. Transport giant DP-DHL

furthermore included truck assembly, fibre optic cables, and shipyards in their analysis of relevant parallel industries [109]. The *outbound installation & commissioning phase* for offshore wind farms includes construction of land-based structures such as onshore sub-stations, ports, storage sites, and warehouses. In addition, the installation of offshore Balance of Plant components such as cables, offshore sub-stations, and foundations may happen with different supply chain constituencies acting as lead supply chain firm [55] for different parts of the process such as the export cable, offshore sub-station, array cables, offshore accommodation solutions, wind turbine foundations, and finally wind turbine erection/installation/commissioning.

3. The *O & M phase* has a *preventive servicing* supply chain which can be scheduled in advance as different parts and modules are expected to come to their end-of-life. This supply chain lives for the entire duration of the offshore wind farm operational phase which can be some 20–25 years or possibly longer. Because of the predictability of this planned supply chain coupled with the long duration of the life-cycle phase, the field is starting to be researched in greater detail. Studies include a general review of O & M transport logistics organization literature [82], O & M fleet size optimization modelling [110], and O & M logistics planning [83]. Studies from the offshore oil & gas sector may also be useful given the more mature stage of development here [111,112]. However, when unpredicted break-downs to individual wind turbines occur, *unscheduled maintenance* is needed. This maintenance is more expensive and also more logistically challenging [113]. This requires a different and very flexible logistical response where the break-down is first diagnosed and then repaired. An unexpected *stoppage of the entire offshore wind farm* due to e.g. a broken cable or a mal-functioning sub-station is the worst challenge of an offshore wind farm operator: According to Møller et al. [114], shipping and logistics capabilities are critical when a wind turbine or the entire offshore wind farm break down. The response warranted is different for the entire farm compared to a single wind turbine.
4. The *de-commissioning* phase has only been tested in a very limited manner so far for offshore wind according to Feld [115]: Only a few met-masts and LiDAR buoys have been de-commissioned. During 2016, 5 offshore wind turbines at Yttre Stengrund in Sweden were fully decommissioned according to Patel [116] and another 11 turbines at Vindeby, Denmark will follow also in 2016 [117]. Conversely, wind turbine de-commissioning for onshore wind farms is now taking place fairly frequently [118,119]. A project called Offshore De-commissioning of Installations ("ODIN-Wind") has been established by the Technical University of Denmark and industry partners led by NIRAS [120]. As part of the on-going O & M efforts described above as well as de-commissioning, different parts and components are brought to shore for refurbishment and/or recycling according to Møller et al. [114]: This reverse supply chain flow is, however, still very immature for offshore wind at this time.

In addition, Table 2i) outlines examples of actual supply chain constituencies including those acting as lead firms within the respective activities. It should be noted that differences exist for different activities and sub-activities across different geographies. One example is the developers in China who wish to remain in control over 'all parts of the offshore installation process for the outbound supply chain': According to Zhang [64], the wind turbine installation scope is kept 'in-house' for now and not outsourced to the wind turbine OEM nor EPCi providers as is the case in Europe. Elaborating further on this matter, Xu [65] highlighted that it is "...necessary for Chinese developers to first gain full control over the sub-processes and then only later-on decide upon strategic insource vs. outsource and make vs. buy decisions in terms of both logistical matters and the actual supply chain..." itself. Both Zhang [64] and Xu [65] explained that this was attributed to internationalization aspirations as also described by Zhang et al. [56]. In Europe, it is common that the leading wind turbine OEMs act as supply chain lead firms responsible for the wind turbine installation and commissioning process [55]. In Europe, some wind turbine OEMs aspire to become full EPCi or turnkey providers of complete offshore wind farm solutions including Balance of Plant components [121]. In the next subsection, we identify logistics and shipping bottlenecks in Europe and China.

3.2. Logistics and shipping bottlenecks: Europe and China

During a wind farm life-cycle, a wide range of vessels are used. This includes geophysical survey vessels (development & consent phase), cable laying vessels (installation & commissioning phase), and wind turbine installation vessels (installation & commissioning, O & M, and de-commissioning phases). In the Anholt offshore wind farm case [54,122], more than 100 different individual vessels were used during the development & consent and installation & commissioning phases comprising 17 different vessel types.

For monopile/transition piece wind turbine foundation installation, different gravity based systems have been tried, and quite often a piling hammer mounted on top of a heavy-lift vessel or barge was the preferred solution. In the Anholt case [54], the heavy-lift vessel "Svanen" was used to hammer the monopiles into the sea bed and the transition pieces mounted on top. A layer of special grout has acted as the "glue" between the monopile and transition piece where the two converge. For earlier installations in the North Sea, instability of this grout layer has caused challenges and may need to be replaced [24,123]. Supposedly fairly straight-forward to construct to specifications transition pieces were ordered for one wind farm project in the UK from China which were constructed near Shanghai and transported to the UK by the manufacturer [124]. Subsequently, a dispute arose on quality issues in the monopile construction and this caused a lot of extra work and cost for the original owners (Fluor in partnership with Scottish and Southern Energy) and the Chinese provider of the monopiles. Although seen as a damper on further integration of large Chinese components (and potentially wind turbines), there is no doubt that inter-regional transport of both wind turbine and Balance of Plant components will increase in the future as global competition gets under way.

The findings of our case work in China indicate that the wind turbine generator part of the Chinese supply chain is fully developed whereas the Balance of Plant component supply chain seems to be lacking behind. Also overall financial modelling, project management, shipping/logistics, O & M, and de-commissioning solutions [64,65] have not been fully developed for offshore wind in China. The already approved near-shore and inter-tidal offshore wind farms have now been activated and swiftly moved into the installation & commissioning phase along with key "real offshore" projects. A total of 44 projects were activated in June 2014 with the new Feed-In Tariff. Given the relatively low offshore install base up to 2014, our research findings indicate that a number of wind turbines may face quality challenges with e.g. rust and corrosion once operational: This was the case for the initial European offshore wind turbines and is also the case for current Chinese onshore wind turbines. Our research findings also indicate that it will be challenging for China to install the many offshore wind farms at the desired pace given the lack of experience including lack of installation assets and trained personnel. However, as was the case for onshore wind in China [89], close alignment exists between the national goals as set out in the Five Year Plan and the execution of the supply chain process. As such, the revised 2020 target of 10 GW of offshore wind in China may still be reachable.

3.2.1. Offshore wind farm construction logistics

For offshore construction, wind turbine installation vessels are used in the North Sea and as a shortage in the supply of these vessels was predicted during 2007–2008, different risk mitigation strategies were pursued by wind farm developers/operators, EPCi firms, and utilities. Denmark-based state-owned utility DONG Energy acquired wind turbine installation vessel operator A2Sea in 2009 and subsequently sold 49% of the firm to wind turbine OEM Siemens Wind Power [24]. A2Sea now operates in a public-private partnership set-up and with financially strong owners, A2Sea contracted a Chinese shipyard[3] to build further wind turbine installation vessels which have since then been delivered. Constructed to comfortably install 4 MW wind turbines, the 2 most recently delivered A2Sea vessels may not be fully suitable to install wind turbines yielding an output of 6, 7, 8, 10, 12, or 15 MW. Therefore, the vessels were to some extent already "too small" once delivered to A2Sea in Denmark from the yard in China as the weight of nacelles, length of blades, and height of towers will cause the vessels to have challenges carrying the larger wind turbines to the installation site and for the cranes on the vessels to perform the installation task.

3.2.2. Offshore wind farm operations logistics

Once operational, a 20–25 year O & M period commences in order to service the offshore wind farm. Here, the O & M tasks require technicians, personal protection equipment for the technicians, spare parts, tools, and sometimes major wind turbine modules or components to be transported to the wind farm site for scheduled preventive maintenance or ad-hoc emergency maintenance. To transfer technicians, their gear, tools, and spare parts, helicopters, transport vessels, and crew transfer vessels of different kind are used along with accommodation platform and accommodation vessel solutions. To replace entire wind turbine modules or components, smaller wind turbine installation vessels are often utilized to e.g. replace a blade or gear box. In other cases, it is necessary to lift off the entire rotor and nacelle to be able to perform major overhauls to nacelles which have been damaged or are malfunctioning. These operations may take place in rough seas causing the technicians to be seasick while making transfer operations from the vessels to the wind turbine challenging as the technicians need to alight the crew boats in affected by wind and waves in order to access the stationary monopile/transition piece construction upon which the wind turbine is mounted.

3.3. Supply chain readiness comparison: Logistics in Europe and China

In Table 3 below, the correlations between offshore wind farm lifecycle phases, the different supply chains involved (discussed above), the different financial terms used (CapEx/OpEx/AbEx), and the overall value chain structure (planning chain, manufacturing chain, deployment chain, re-deployment chain) have been depicted. Based on the inter-regional case study work performed, key European and Asian firms/constituencies within each sub-activity have been listed as outlined by the squares for each supply chain. China has been chosen as our specific Asian comparison market[4] due to its relative mature state compared to the rest of Asia [13,15,34,50] and we have deselected Americas in our analysis because the most promising market in the US [13,15,34,50] has no significant install base yet except the 5 Block Island turbines erected off Rhode Island in August 2016 (in the US, Siemens Wind Power had been selected as the supplier of wind turbines for the more significant Cape Wind Project which was, however, subsequently delayed). Traffic light colour codes (red/orange/green signifying logistical readiness) have furthermore been applied in Table 3 to highlight the present logistics and shipping status of the supply chain in Europe (outer square) and China (inner square).

The findings outlined in Table 3 indicate that the logistics and shipping market supporting the offshore wind energy industry is more mature in Europe in the form of a more ample supply of assets, personnel, systems, procedures, as well as knowledge. This mainly has to do with the diffusion of offshore wind in China vs. Europe: By the end of 2014, China was the world's largest onshore wind market with almost 115 GW of installed capacity [34]: Conversely, China had an offshore wind install base of 1 GW compared to Europe's 11 GW of offshore wind track record by the end of 2015 [138].

3.3.1. Global wind turbine supply chain and largely European offshore wind experience

The research depicted in Table 3 furthermore shows that China's journey towards offshore wind is building upon the technological advancement trajectory from its giant onshore wind industry [23,89] and ensuing supply chain. As a result, key onshore / offshore wind farm wind turbine components such as nacelle, rotor, and tower are in reasonable supply, also for offshore wind. However, the findings similarly indicate that when it comes to the Balance of Plant supply chain/manufacturing base, offshore wind farm construction, component installation, commissioning, O & M, de-commissioning, and recycling, the offshore wind industry in China is just starting to take off. As such, the Balance of Plant supply chain and surrounding logistical infrastructure may be considered more of a regional European capability so far.

3.3.2. Weight and size of components: Direct impact on logistics

With new offshore wind turbine requirements for 5, 6, 7, 8, and even larger MW output ratings, nacelles are already weighing above 350–400 t[5] in total. This puts a lot of pressure on the OEM designers/engineers to talk to the shipping and logistics planners early in the design phase in order to ensure that the final nacelle can indeed be transported [125]. Often, transport considerations need to include country and/or regional infrastructure such as roads, bridges, tunnels, and ports [126]. Modularized construction and ultimate final assembly in port areas are the latest tools utilized by OEM's such as Siemens Wind Power and MHI Vestas in Denmark.[6] Testing is also required especially before serial production and for this purpose, Denmark has developed a large-scale test-bench at LORC near Odense and an onshore test site in Østerild near Aalborg where offshore wind test machines need to be transported to for testing. With wind turbines yielding 10–15 MW presently under design in China, South Korea, Denmark, Germany, and the US, the transport challenges will only be further exacerbated.

When it comes to foundation production, the steel structures are very large and heavy. Consequently, a manufacturing location near to or in a port area is therefore preferred. During site visits to construction sites of tripod foundations in Germany,[7] monopile/transition piece foundations in Denmark,[8] and foundations in China,[9] it was found that in almost all cases, port proximity and port access is a crucial factor when selecting a site for offshore wind foundation production. Foundation producer Bladt Industries in Aalborg, Denmark uses areas at both the Port of Aalborg and LORC to have enough space for both wind turbine foundation construction and production of offshore wind high-voltage alternating current transmission sub-station top side structures/foundations. Similarly, Shanghai-based ZPMC division of the China Communication Construction Company EPC conglomerate utilizes a dedicated 2+ square-kilometre site with a 3-kilometre port

[3] Interviews with A2Sea in Denmark (April 2013), interviews and site visit with the owners of the Chinese yard/construction facility ZPMC (September 2013), and site visit to the Chinese yard COSCO Nantong/Qidong (October 2015)

[4] Our case study work in Asia also comprises offshore wind developments in India, South Korea, Japan, and Taiwan

[5] Discussions with OEMs in China (September 2013) and Denmark (February 2014)

[6] Visit to the Port of Esbjerg (December 2013)

[7] Visit to the port of Wilhelmshafen (March 2011)

[8] Visit to LORC (August 2013) and interview with the port of Aalborg (December 2013)

[9] Visits to Nantong, China (September 2013; July 2015; October 2015)

Table 3
Life-cycle phases, supply chains, and correlation with CapEx/OpEx/AbEx as well as chain view.

Wind energy supply chains							
Wind farm phase	Development & Consent (D&C)	Installation & Commissioning (I&C)		Operations & Maintenance (O&M)			De-commissioning (De-comm)
The wind farm supply chains	*D&C chain*	*I&C - Inbound*	*I&C - Outbound*	*O&M - Preventive*	*O&M - Unscheduled*	*O&M - Contingency*	*De-commissioning chain*
Activities & Firms	***Supply chain I***	***Supply chain II***	***Supply chain III***	***Supply chain IV***	***Supply chain V***	***Supply chain VI***	***Supply chain VII***
	Seabed surveys: Geo, Energinet.dk	Nacelle assembly: DHL, DB Schenker, Goldwind	Foundation installation: MPI, Van Oord, Swire Blue Ocean	BOP servicing: Bilfinger, DONG Energy, Bladt Industries	WTG breakdown: DBB Jack-Up, Total Wind	BOP breakdown: Semco Marine	WTG de-commissioning: Swire Blue Ocean
	Animal surveys: Geo, Energinet.dk	Blade production: Give Goodwind, Mammoet, Jutlandia	Cable laying: Global Marine Systems, SBSS, CT Offshore (A2SEA)	WTG servicing: World Marine Offshore, DONG Energy, N-O-S		Grid breakdown: ABB, Siemens Energy	BOP de-commissioning: Van Oord, GeoSea
	Port surveys: DNV-GL, WSS, Blue Water Shipping	Tower manufacturing: Give Goodwind, Mammoet, Blue Water Shipping	Offshore Subst. Inst.: Semco Marine, Swire Blue Ocean, Longyuan/Zhenhua	Landside support servicing			Site restoration: Energinet.dk, CGN
		BOP components: Combi-Lift, DHL, Van Oord, Longyuan/Zhenhua	WTG erection: A2SEA, Longyuan/Zhenhua, Fred Olsen Windcarrier, Longyuan/Profundo				
	CapEx			OpEx			AbEx
	Preparation chain	Manufacturing chain	Deployment chain				Re-Deployment

quay access on site near Nantong in the Jiangsu province for offshore wind module production (towers, monopiles, transition pieces, etc.). At this manufacturing site, ZPMC also constructs wind turbine installation vessels specialized for the Chinese inter-tidal and offshore markets. Finally, ZPMC houses their logistics/shipping joint-venture with Longyuan division of the China 'big 5' utility, Guodian.

Cable production is an area that may occasionally be overlooked. However, the production of both export and array/infield cables has sometimes been faced with bottlenecks and logistically, so has the area of cable laying. As a consequence of cable laying vessel supply shortages, the DONG Energy/Siemens Wind Power joint-venture firm, A2Sea, acquired cable laying specialist firm CT Offshore which has now been fully integrated into A2Sea. Possibly the most infamous case of cable laying delays is the situation for the offshore wind farms in Germany [91]. According to Feld [114], severe shortages in trained offshore wind cable laying vessel personnel is a bottleneck and overall threat to the industry as a whole.

3.3.3. Supply chain readiness: Logistics in Europe and China

In Table 4 below, the supply chain readiness has been depicted in summary form as a result of our cross-case analysis work. Focus has been put on those supply chains which our research indicates to have had the largest impact on the levelized cost of energy (supply chains II, III, IV, V, and VI) from a logistics perspective [127–130]. Our cost focus areas are based on the European case study with the world's leading offshore wind farm developer and operator [93]. A score from 0 to 3 has been applied in terms of supply/demand for shipping and logistics service offerings within Europe (depicted as 'EU') and China (depicted as 'PRC') as follows:

- 0 indicates that supply seems to be non-existing and that this factor *blocks* offshore wind diffusion
- 1 indicates a supply constraint with a *negative impact* on offshore wind diffusion
- 2 indicates supply/demand balance with a positive yet *limited impact* on offshore wind diffusion
- 3 indicates sufficient supply with a *positive impact* on offshore wind diffusion

A traffic light colour coding has been applied in Table 4 as well in order to make the findings more clear (0 and 1 marked as red, 2 marked as yellow, and 3 marked as green).

4. Addressing supply chain constraints

In Section 3, we unveiled the logistics and shipping constraints of the supply chain gradually through our inter-regional case study. We detailed the life-cycle phases including the major sub-supply chains and argued why they are distinctively different from a logistics perspective. We concluded with a logistics readiness assessment where we contrasted Europe with China along a 4-dimensional scale focused on offshore wind energy diffusion. In the following subsections, we will discuss how to alleviate these constraints.

4.1. How the supply chain constraints may be alleviated – construction logistics

When we review the CapEx findings of Table 4 above (supply chains II and III), EU based developers will mainly need to be able to deal with the logistical challenges associated with transporting, lifting, and installing a new generation of jacket foundations which are now being constructed. As offshore wind farms move further offshore and into deeper waters, jacket foundations will replace the previously used monopile/transition piece foundation type [131]. Similarly, the EU developers and governments will also need to better deal with the logistical challenges associated with both offshore sub-stations and export cables. In terms of offshore sub-stations, DONG Energy's order of 5 locally made UK offshore wind farm substations[10] for their UK pipeline of offshore wind farms is a good example of how market leading DONG Energy starts to industrialize and modularize the supply chain while simultaneously creating jobs locally in the markets they serve. However, the logistical infrastructure needs to follow: With some 60–70% of wind farm life-cycle cost related to upfront CapEx [121], accurate planning and forecasting processes including logistics have proven to be crucial for European developers in terms of pay-back and profitability of the offshore wind farms. This directly affects the ability on the part of the developers to secure adequate offshore wind farm project financing [121,132]. The wind farm construction process has undergone several stages of development and improvement in Europe over the past 20+ years since the first Bonus (now Siemens Wind Power) wind turbines were installed offshore in Vindeby, Denmark. Although much more advanced ashore, in the ports, and offshore today compared to 1991, 2005, or even 2010, the installation & commissioning process is far from being considered to be in a mature or steady-state condition as evidenced by new construction transportation

[10] Announced during the UK offshore wind conference in Glasgow, Scotland during June 2014

Table 4
Offshore wind supply chain readiness with focus on shipping and logistics in Europe and China.

	0	1	2	3
Supply chain #II - Inbound to manufacturing				
Nacelle				EU, PRC
Tower				EU, PRC
Blades/hub				EU, PRC
Wind turbine foundation monopile/transition piece		PRC	EU	
Wind turbine foundation jacket	PRC	EU		
Onshore sub-station/booster station			PRC	EU
Offshore sub-station/booster station		PRC	EU	
Offshore sub-station foundation		PRC		EU
Export cables	PRC			EU
Array/infield cables		PRC		EU
Supply chain #III – Installation and commissioning				
Onshore sub-station/booster station			PRC	EU
Offshore sub-station/booster station	PRC	EU		
Export cables	PRC	EU		
Array/infield cables		PRC	EU	
Wind turbine/offshore sub-station foundations		PRC	EU	
Wind turbine generator		PRC	EU	
Supply chain #IV – Preventive operations & maintenance				
Preventive/planned (wind turbine generator)		PRC	EU	
Return flow (reverse supply chain)		PRC	EU	
Supply chain #V - Unscheduled maintenance				
Unscheduled/Break-down (wind turbine generator)	PRC	EU		
Supply chain #VI – Contingency maintenance				
Contingency (entire offshore wind farm)	PRC	EU		

concepts introduced for safety purposes using roll-on/roll-off vessels to minimize vertical lifts, for example [133]. *Our research indicates* that the European supply chain is largely ready to match the future market requirements but that the area of logistics is suffering for a single reason: No binding legislation about offshore wind exists in Europe beyond 2020. It follows that because offshore wind is not yet competitive in its own right compared to other electricity generation e.g. levelized cost of energy of nuclear or coal generated energy, none of the supply chain lead firms seem willing to enter into the necessary and binding long-term agreements with the shipping and logistics industry firms that would enable these firms to invest in the necessary infrastructure, assets, and personnel necessary to support the planned diffusion in the "home market" of Europe. To alleviate this challenge, *our recommendation is* that the EU considers implementing binding legislative offshore wind energy targets by member country up to 2030.

Conversely for the offshore wind CapEx in China, strong logistical capabilities only exist in relation to the manufacturing the wind turbine itself as well as onshore sub-stations. For the remaining logistical needs, assets, and infrastructure, the Chinese supply chain faces a steep logistical learning curve [64,65]. *Our research indicates* that China's formidable roster of ultra-large state-owned conglomerates - led by the 'big 5' utilities and supplemented by the massive supply of state-owned and private Chinese firms - are of course theoretically capable of leading China down the path of massive and rapid offshore wind diffusion as politically desired. Our research also suggests that the 12th Five Year Plan mandate for China to focus on indigenous innovation had caused some degree of isolated Chinese sub-optimization. This has occurred in many areas including the Balance of Plant supply chain itself which is not yet fully developed in China and also within the critical diffusion area of offshore wind shipping and logistics. This sub-optimization is both costly and time consuming for China. To alleviate this challenge, *our recommendation is* that China considers implementing legislation that supports Chinese firms in embracing European experience, know-how, and skills. The authors believe that this is the only option to jointly create the necessary Chinese offshore wind logistics infrastructure with suitable assets, trained personnel, and the right competencies for China's very special logistical conditions. These special conditions include inter-tidal zones and the – for China as a whole – critical main rivers, the Yellow River, the Yangtze River, and the Pearl River, with river delta offshore wind construction location opportunities being exploited.

4.2. How the supply chain constraints may be alleviated – operations logistics

When we consider the OpEx findings summarized in Table 4 above (supply chains IV, V, and VI), EU based operators are gaining traction when it comes to preventive maintenance logistics (supply chain IV) with the exception of the reverse supply chain for the return flow. Academia is supporting this with relevant research as outlined above [82,83,110]. Europe is just now getting enough streamlined information in terms of operational "big data" type data sets for offshore wind farms and this is crucial to measuring performance, comparing wind turbines, and working with the OEMs to improve performance quality in different kinds of weather and wind conditions at sea [113]. *Our research indicates* that EU operators still need to deal more appropriately with the logistical challenges pertaining to unscheduled maintenance challenges for individual wind turbine positions (supply chain V) and with logistics contingency plans (supply chain VI) when the entire offshore wind farm shuts down (supply chain VI). *It is our assessment* that during 2017, the operational European offshore wind farm install base will reach a point of critical mass at least for leading operator DONG Energy as well as other prominent operators E.On, RWE, and Vattenfall. This critical mass milestone will most likely enable these operators to individually create a level of industrialization, a degree of operational synergies, and produce some economies of scale across their respective portfolios of operating offshore wind farms. A considerable challenge does, however, exist for smaller offshore wind operators because their OpEx cost base will remain relatively stabile as they have fewer options to make improvements within a small portfolio. To alleviate this challenge, *our recommendation* is again for EU to implement binding legislative targets and speed up diffusion up to 2030 by when offshore wind should be a viable stand-alone energy form also compared to other energy forms from a levelized cost of energy perspective due to the industry's on-going drive for cost savings. Only with a much larger and blended portfolio of "old 2010s" and "newer 2020s" offshore wind farms may proper OpEx critical mass be obtained across Europe.

In China, it has long been suspected that onshore wind farm operators have faced challenges from an O & M perspective. However, as many challenges derived from the Chinese wind turbine OEM industry, the actual O & M challenges faced have not been shared openly outside China so far. Basic challenges with bearings, yaw gears, and gearboxes produced in the localized Chinese onshore supply chain are now being shared publicly due to the extent and severity of the challenges faced [134]. This has implications for the offshore aspirations of the Chinese wind industry. In the 1990s when Europe started the offshore wind journey, many technological 'teething problems' were faced with e.g. corrosion, rust, and other issues as Europe essentially moved onshore technology into the salty waters offshore using onshore personnel to do so. With this 25-year track-record, Europe has learned that all operations offshore are much more expensive than similar operations carried out ashore. Therefore, some of the basic challenges with the onshore wind turbine generator technology could advantageously be sorted out with support from European firms and academia before China executes a revolutionarily paced push of onshore technology into the offshore sphere.

5. Conclusion

The main question addressed in this article is provided in the title: *Is the supply chain ready for the green transformation*? Our analysis of the supply chain readiness was presented by using our case studies focusing on the logistics and shipping aspects of the overall offshore wind supply chain. Due to the global plans for offshore wind diffusion, we chose to contrast Europe with Asia because the Americas development is still at an early stage. Within Asia, we opted to focus on the fastest maturing market which is China although our case study is pan-Asian in nature. By drawing on prior research that broke down the wind farm life-cycle into phases, we introduced seven sub-supply chains and this allowed analysis of the logistical readiness of the supply chain broken down into different segments. These sub-supply chains were reviewed with an objective of how to alleviate the constraints. This was done in several steps based on our 5 research questions and this concluding section summarizes and brings together the key insights.

We first analyzed the current situation through a set of questions pertaining to how *ready the supply chain is* for the exponential expansion of offshore wind in the energy system. This included our review of the *key barriers, bottlenecks, and constraints*. Through our case study, we subsequently analyzed and highligted the *differences between Europe and China* as the largest markets in this regard.

The second set of questions looked at the situation in the future. Here, we first analyzed how the diffusion challenges can be *addressed with new solutions*. And finally, we looked at *where the solutions will come from*.

The research presented in this article provides grounding for directing the effforts in the drive to expand offshore wind. The efforts should involve government policy and research efforts, corporate investment, as well as collaboration in knowledge transfer. Our overall answer in terms of supply chain readiness for the green transformation is: When analyzing the logistics part of the global supply chain for offshore wind, the supply chain is *not ready*.

Based on current scenarios for 2050, wind energy could make up as much as 25–30% of global electricity consumption by then [36]. *Our empirical data gathering efforts* [11] *indicate* that the Chinese offshore wind operations & maintenance set-up is quite rudimentary compared to Europe when it comes to ports, vessels, tools, personnel, and skills. This may have less impact in moderate wind speed areas visited in the Jiangsu Province of China: However, when provinces like Fujian and Guangdong start to execute their extensive plans to add wind capacity, the typhoons and higher wind speeds resemble conditions similar to the North Sea in Europe. It is our assessment that China will need to carefully study the European operations & maintenance experiences for both onshore and offshore wind. The Chinese onshore diffusion has exceeded all targets set by the Chinese government since the 2006 implementation of the Renewable Energy Law [89]. This rapid diffusion comes with clear and present operations & maintenance quality challenges. These already existing onshore operations & maintenance challenges could be exacerbated further for offshore wind at a much higher cost for China. To alleviate this sizable conundrum for China, *our recommendation* is to openly collaborate and innovate together with especially European counterparts both at government level, at academia level, and at firm level.

It seems clear from our contextual research and empirical data gathering efforts that the wind industry is very much an industry which has been created largely by governments [6,24]. The drivers seem to be two-fold: To meet a political demand for both abating the emission of greenhouse gasses whilst at the same time driving a geopolitical agenda.

The geopolitical agenda in Europe seems to try to avoid dependence on Russia and simultaneously try to prevent the oil and gas rich countries, especially in the Middle East, from amassing an even more disproportionate amount of wealth than what has already happened [135]. With that being said, different EU regions and countries have very different drivers to promote offshore wind with Denmark taking on an early-mover role mainly for historical reasons [12] and because changing Danish coalition governments have shared both greenhouse gas emission and political drivers as outlined above. In other European countries, such as UK [19] and France, the key driver has been the EU 20-20-20 binding renewable energy targets. In Germany, wind energy has flourished simply because German firms are traditionally involved in many aspects of wind turbine and Balance of Plant production related to engineering and mechanical parts in general.

According to the last Five Year Plans of China, the key driver of offshore wind diffusion seems to be the Central Government's wish to

[11] Offshore wind farm site visits in China's Jiangsu Province conducted on July 29, 2015 and October 23, 2015

fight the ever worsening pollution by building power plants in the available space in the oceans near the big consumption centers of the large cities mainly on the East Coast. Compared to onshore wind turbine projects, offshore wind farms are a lot more difficult as well as costly to plan, finance, manufacture, install, commission, connect to the grid, operate, and de-commission. Therefore, global learning, collaboration, and innovation are even more important factors for offshore wind than for onshore wind going forward. Europe has learned offshore wind farm life-cycle management 'the hard way' since the Vindeby offshore farm was first erected in 1991. Our case study in Asia reveals that whereas the global wind industry is acutely aware of the upcoming rush for offshore wind installations in China - based on the Beijing decree for the offshore wind 2014 Feed-In Tariff - many Chinese developers and wind turbine manufacturers have seemingly almost exclusively had a 'fully installed wind turbine price' focus as selection criteria in the early years of onshore wind development in China. Other critical onshore wind success criteria such as connecting the wind turbines to the grid, how to ensure a steady 20–25 year phase of operations, and the de-commissioning of the wind turbines do not seem to have received the same proactive attention levels in China so far. This is being seen now as onshore wind turbines are starting to incur considerable operations and maintenance costs for Chinese wind farm operators to maintain. Early-movers from Europe who set up in China as sub-suppliers to the growing onshore wind turbine OEM industry got somewhat caught off-guard by the subsequently introduced local content requirements [89,136,137]. *Our research findings indicate* that European firms are hoping that the on-going onshore wind price/quality debate in China may generate a renewed offshore wind momentum for knowledge transfer from Europe to China with a main focus on quality.

Central to this continuous knowledge transfer is that the offshore wind industry in Europe may continue to develop and evolve. For logistics, this requires a long-term investment horizon in terms of key infrastructure, assets, equipment, personnel, and skills. Binding EU legislation up to at least 2030 is a must to create the right investment climate.

Our recommendations are two-fold and split by geography: In Europe, binding national targets across EU countries are necessary in order for the sizable and long-term logistics investments to be made by the private sector. The EU and national governments should also further invest in research to address technological development in identified supply chain bottlenecks and address them with tailored engineering education programs focused on offshore installation and maintenance, logistics being one such area. Additionally, there is a need for creative initiatives aimed at supporting EU-China collaboration in terms of research and establishment of collaborative business models. In China, the very ambitious offshore diffusion could be very costly and prolonged unless collaboration with Europe is embraced in an open manner to build on the learning from the rapid onshore wind diffusion in China. Chinese offshore wind constituencies ought to openly collaborate and jointly innovate with especially European counterparts both at government level, academia level, and at firm level. *Our research indicates* that if offshore wind diffusion will indeed happen, as evidenced by political ambitions globally, governments must provide the right settings for the supply chain to be flexible and adaptive.

And this is also true within the field of logistics.

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