Circular supply chain management for the wind energy industry

Conceptional ideas towards more circularity

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1. Introduction

Trends such as globalization and customers' requirements for individuality have led and still lead to an increase in complexity (Khan/Yu 2019). Recent events (e.g. Covid-19, Suez Canal blockage) have shown how fragile supply chains can be as assumptions for the design and management of supply chains become negated (Bocconi University et al. 2021; Khan/Yu 2019). Thus, supply chains have to be designed and managed to handle complexity and uncertainties. In addition, governments progressively announce aspired system changes towards more sustainability (e.g. European Green Deal) and are anchoring this into legislation such as the European Climate Law (Regulation (EU) 2021/1119 of the European Parliament and of the Council, 2021).

To meet the resulting requirements for supply chains, aspects that promote resilience are often highlighted (Christopher/Peck 2004). In this context, the concept of a circular economy (CE) recently gains attention as it could contribute to building a sustainable and resilient system (Bocconi University et al. 2021; Chaouni Benabdellah et al. 2021; Ellen MacArthur Foundation 2019b; Negri et al. 2021). The evolving research stream, circular supply chain management (CSCM), intends to embed the concept of a CE into the supply chain management (SCM) (Farooque et al. 2019). The tasks are assigned to design, plan and manage as well as execute material, information and financial flows within a supply chain (The Supply Chain Council 2012).

The German wind energy industry is a well-suited application for further investigations on CSCM as the country has an established wind energy industry, a long track record of installed wind turbines and aspires to further increase the share of installed turbines. Ambitious expansion targets of the government and new regulation will eventually promote the scale up of the wind energy industry (Sozialdemokratische Partei Deutschland et al. 2021). Hence, it is meaningful to learn from historical projects and shift towards a circular system prior to a possibly increased path-dependency. In addition, the wind energy industry and the concept of a CE are major contributors towards reaching the climate goals (Ellen MacArthur Foundation 2019b; European Commission 2019). However, with lifespans of roughly 20-30 years a high turnover ratio of materials in comparison to other energy

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sources exists. Switching to a circular supply chain and herewith implementing new business models could strengthen material availability and economic profitability as Germany is limited in raw material sources (Alves Dias et al. 2020; Velenturf 2021). For example, supply chain managers could reduce dependencies from scarce raw materials by using secondary materials that could be sourced following a multi-source procurement strategy (Wannenwetsch 2014). In conclusion, CSCM should consider circular strategies for the existing portfolio of turbines as well as for the newly to be installed plants.

According to Kramer/Schmidt (in press), research on CSCM for the wind energy industry is still rare. Therefore, the aim of this paper is to outline ideas to facilitate an efficient design of a circular wind energy industry in Germany. Questions from a SCM perspective are outlined that need to be answered to enable a circular supply chain. The paper is divided into seven sections. The subsequent section defines CE and CSCM, followed by section three that presents the current state of the art. The fourth section provides an overview of the current portfolio of wind turbines in Germany and roughly sketches potential future developments. In the fifth section the methodology for answering the research question 'What is required for a CSCM in the wind energy industry in Germany?' is presented that is applied in the sixth section. Thus, the organization, products and processes level for CSCM in the German wind energy industry and its belonging tasks are presented. The last section summarizes the main findings.

2. Definition of Circular Economy and Circular Supply Chain Management

For CE a multitude of definitions exist and a consensus has not yet been established (Alhawari et al. 2021; Kirchherr et al. 2017). Kirchherr et al. (2017) analysed 114 different definitions and consolidated them to a comprehensive definition that is used in this paper: "*A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations*" (Kirchherr et al. 2017). Another widespread definition is given by the Ellen MacArthur Foundation. According to the foundation, the definition of CE bases on the following aspects, that are also reflected in the above definition by Kirchherr at al. (2017): First, the system changing character of the CE concept that foresees to "*decouple economic growth from the consumption of finite resources*" (Ellen MacArthur Foundation 2019). Secondly, maintaining the highest possible value in its cascading nature – use less by designing out waste and pollution, prolong the use of materials and products and regenerate natural systems. The herewith often stated strategies are also called R-principles. There are several

R-principles, with Kirchherr et al. (2017), for example, highlighting four principles: Reduce, Reuse, Recycle and Recover. And finally, to overall contribute to a sustainable development (Ellen MacArthur Foundation 2019b).

For CSCM, researchers have developed a variety of different conceptions (Alhawari et al. 2021; Corvellec et al. 2021; Kirchherr et al. 2017; Lengyel et al. 2021). In this context, Lengyel et al. (2021) argue that the CE concept is not yet fully integrated into SCM. They also state that existing literature not always considers the three dimensions of sustainable development as part of CSCM. Farooque et al. (2019) add, that next to the sustainable dimensions, a regenerative dimension should be part of CSCM. They conclude with the following definition: "*Circular supply chain management is the integration of circular thinking into the management of the supply chain and its surrounding industrial and natural ecosystems. It systematically restores technical materials and regenerates biological materials toward a zero-waste vision through system-wide innovation in business models and supply chain functions from product/service design to end-of-life and waste management, involving all stakeholder in a product/service lifecycle including parts/product manufacturers, service providers, consumers, and users*" (Farooque et al. 2019). This paper considers the holistic definition of CE by Kirchherr et al. (2017) and considers, like Farooque et al. (2019), CSCM as a multi-level and multi-objective system that embeds the circular thinking into SCM.

3. State of the Art

The research focus of this paper is at the intersection of SCM, CE and wind energy. To frame the research, a search within article title, abstract and keywords at Scopus on 21 April 2022 was conducted. The results are shown in *Figure 1* and *Figure 2*. *Figure* 1 displays the total number of publications on CE, SCM and wind energy as well as at their intersections.

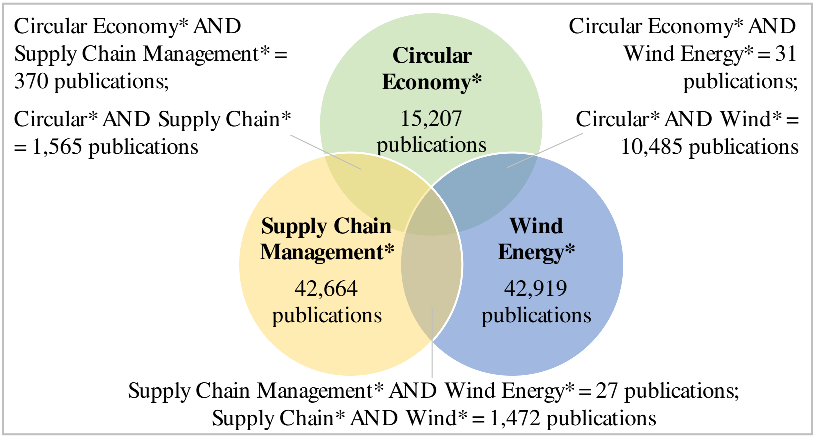

Figure 1: Scopus-listed publications about SCM, CE, wind energy and their intersections in total

The research field wind energy has, out of the three research fields, the longest track record with its first publication in 1961 and an exponential increase in publications since 2002 that led to a total of 42,919 publications. SCM counts 42,664 publications with its first publication in 1982 and an exponential growth from 2000-2010, followed by a decline until 2015 and since then, again, a rise is registered. The field CE with 15,207 publications is a relatively young research field with its first record in 2001 and an exponential growth since 2016. The intersections between the research fields show significantly less publications. For example, even as the number of CSCM publications has increased in the last years, based on the total number it is still a niche research field in relation to CE. Looking at the intersection of all three research fields and thus the research focus of this paper, the number of publications is marginal as outlined in *Figure 2*.

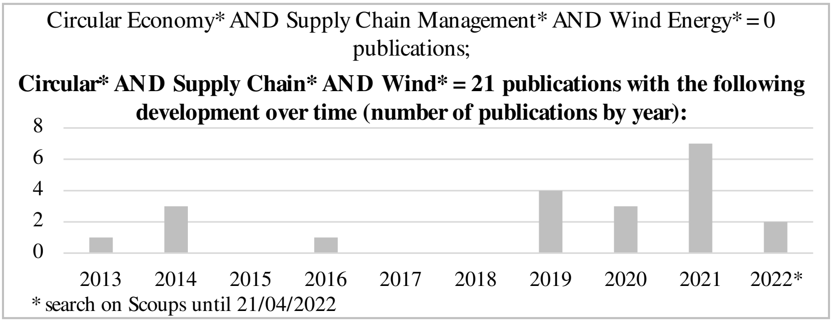

Figure 2: Scopus-listed publications on CSCM in the wind energy industry per year

The Scopus search with 21 publications in total underpins that the wind energy supply chain from the perspective of the CE has been rarely investigated. The first publication is listed in 2013, however, continuous releases are observed only since 2019. None of these publications presents an overview of the CSCM for the wind energy industry in general or in Germany. Instead, for instance, a strategic roadmap within the composites supply chain (Koumoulos et al. 2019), an exploratory study on closing the supply chain of critical materials (Lapko et al. 2019) and the second use of wind blades (Nagle et al. 2022) have been investigated.

Next to the 21 publications at the intersections of the three research fields and contrary to the non-existence of a systematic CSCM overview in the wind energy industry, CE research with a linkage to the wind energy industry exist. For example, Velenturf (2021) presents the state of the art and develops a framework for the offshore wind energy industry. This eventually could also be applied to the onshore wind energy industry. She does not reflect on CSCM or SCM and instead proposes 18 strategies from the CE perspective which are subdivided in narrowing (e.g. design to use less material), slowing (e.g. use products for as long as possible), closing (e.g. establish reverse material flow cycles) and integrating (e.g. minimize landfill sites and restore areas). Moreover, with a focus on circular business models, Mendoza et al. (2022) evaluate 14 circular business models that are implemented in the wind energy industry. The strategies are clustered into (i) dematerialization, (ii) circular production and distribution, (iii) collaborative consumption, (iv) circular sourcing, (v) long life and (vi) next life.

Next to CE research in the wind energy industry, scientific literature on general frameworks and archetypes for CSCM exist. Batista et al. (2018) develop a circular supply chain archetype based on a content-based literature review. They divide between primary, recovered and secondary material flows within a closed-loop and open-loop design. Farooque et al. (2019) highlight in their work the influence of a circular thinking within product/service design, procurement, production, logistics, consumption, end-of-life (EoL) and waste management. Further they outline supporting business models and the role of technology. González-Sánchez et al. (2020) propose a conceptual framework from a strategic management theory perspective consisting of the four dimensions (i) relational, (ii) technological, (iii) environment as well as (iv) logistics and organizational. Amongst others, they highlight that the concepts of reverse logistics, industrial symbiosis and circular business models facilitate economically and environmentally sustainable circular supply chains. They further add, that the use of smart technologies (e.g. big data analytics), collaboration within the supply chain network as well as designing new legislative, fiscal and cultural frameworks are of relevance. Montag et al. (2021) present a circular supply chain maturity framework. During the conceptualization process they frame the three dimensions organization (strategic), products (tactical) and processes (operational) with their sub dimensions. These dimensions are set to contribute to a sustainable development and should in total facilitate a holistic system thinking. The organizational level consists of management as well as information and technologies, enabling the paradigm shift. The products level with a focus on retaining the highest possible value has the three sub-dimensions, beginning-of-life (BoL), middle-of-life (MoL) and EoL. The processes dimension has the phases of an extended SCOR-model (plan, source, make, deliver, use, return, recover and enable) as sub dimensions. In this operational level, the R-principles as well as the differentiation between restorative and regenerative cycles are found.

In conclusion, none of the stated research has systematically outlined how a multi-level, multi-objective CSCM for the German wind energy industry could look like. This paper aims at making a first contribution to close this research gap. The objective is to provide an overview of key CSCM tasks from an organization, products and processes level for the German wind energy industry. Thus, a linkage of existing literature on CSCM in general and research on CE in the wind energy is provided. Questions to be answered are outlined that add to a potential research agenda for a circular German wind energy industry.

4. Wind Energy Industry in Germany

The wind energy industry consists of several supply chains offering products and services related to materials, components and wind turbines. According to a circular thinking, the wind turbines should be kept as their highest possible value prior handling single components or materials. Thus, this paper focuses as a starting point on wind turbines and provides in this section an overview of the wind turbines in Germany. In Germany a publicly available register of energy plants, the Marktdatenstammregister (MaStR), exists that forms the basis for describing the wind energy market (Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen 2022). Plants with commission between 01.11.1983 to 25.04.2022 are considered in this contribution.

As of 25.04.2022, 33,149 wind turbines are registered in Germany, of which 95.4% are onshore turbines and 4.6% offshore plants. The first onshore plant was commissioned in 1983 with the youngest plant being commissioned in 2022. The offshore wind energy market is not as mature with its first plant being commissioned in Germany in 2009. The last plant was commissioned in 2020, thus from 2020 to 25.04.2022 no further installation process was ended. However, planned offshore and onshore wind turbines are already registered. The geographical allocation of all registered plants shows a dominance in the North of Germany and less presence in the South. The highest share of registered plants can be found in the postal code region 2 (27.3%), followed by the region 1 (17.4%) and 3 (16.1%). The least turbines are registered in the postal code area 8 (1.3%), followed by the region 7 (2.2%) and 6 (2.6%).

For logistics, procurement and manufacturing capacity planning the number of plants is of interest. *Figure 3* shows the number of plants per year being planned, in operation, temporarily or permanently decommissioned.

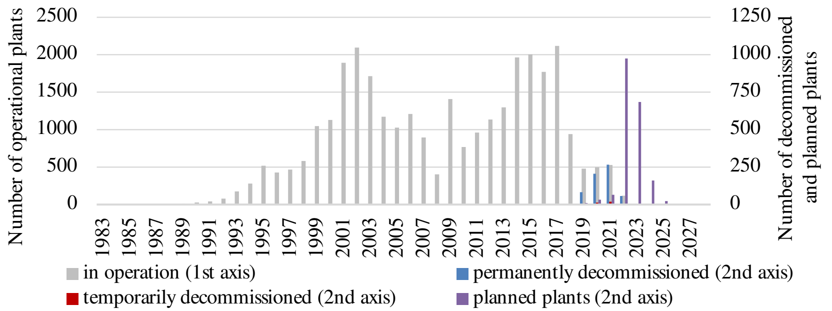

Figure 3: yearly number of planned, operational and decommissioned wind turbines

The current portfolio of registered wind turbines in Germany consists of mainly operational plants (92.1%). The average age of the operational plants is 13.6 years. However, 27.0% of all operational plants are equal or older than 20 years. The

30,545 operational wind turbines represent an installed capacity of 64,098.2 MW, leading to an average size of 2.1 MW per wind turbine. When looking at the development over time of all registered plants, technological progress has led to an increase in MW per wind turbine. For instance, in 2001 the average net installed capacity was 1.3 MW, rose to 2.1 MW in 2011 and equalled to 3.6 MW in 2021. The Compound Annual Growth Rate (CAGR) of the time window from 2001 to 2021 measures 5.1%. The higher installed capacity per plant is achieved by building higher and larger plants (Hau 2013; Lee/Zhao 2022). Especially, the increase of offshore wind energy with its typically higher capacity per plant in comparison to onshore wind energy could explain this development (Poulsen/Lema 2017).

Plants that are at present shut down or decommissioned permanently are with 0.1% and 1.9% a negligible portion. The net capacity of temporarily decommissioned plants equals to 35.6 MW and of permanently decommissioned plants to 640.3 MW. The first plant was decommissioned in 2009, however, until 2019 only sporadically eight further plants followed. In 2019, 83 plants were decommissioned, in 2020 206 plants, in 2021 266 plants and in the commenced year 2022 so far 57 plants. The average age of all decommissioned plants accounts to 20 years, varying between less than a year to up to 33 years. Originally, it was expected that most plants will be decommissioned by the end of their 20 years lasting feed-in-tariff (Zotz et al. 2019). Nevertheless, many plants that are older than 20 years and do not profit from a feed-in-tariff anymore are still in operation. The expected lifetime of a plant is dependent on several factors. Amongst others the technical conditions of the installed components, the expected energy spot price development, the operational expenditures (OPEX) and the pricing level for turbines and components on a secondary market could influence the decision of an operator to extend the lifetime or to decommission a plant. Considering an expected lifetime of a plant with roughly 20-30 years, the number of plants that reach their EoL will increase over the next years.

Currently, 5.9% of the registered plants are in a planning process, which corresponds to a net capacity of 8,952.3 MW. However, the registration in the MaStR is only in specific cases mandatory for planned plants. Thus, the 1,956 registered plants that are planned and expected to be commissioned between 2019 and 2040 are not a complete picture of the expected development. The majority (84.9%) of those plants are planned for 2022 and 2023. Why 107 plants with planned commission between 2019-2021 are not in operation yet, is not stated in the MaStR. Next to the planned turbines according to the MaStR, the German Federal Network Agency publishes historical and upcoming tendering processes. Depending on the duration of the approval and installation process, the plants can get finally commissioned. In addition, different scenarios on the long-term expansion targets of wind energy plants in Germany exist. For example, the current coalition agreement foresees to expand offshore wind energy to a capacity of at least 30 GW until 2030, 40 GW until 2035 and 70 GW until 2045 (Sozialdemokratische Partei

Deutschland et al. 2021). The agreement does not state specific targets for onshore wind. Following the targets that are mentioned in §4 in the law for the expansion of renewable energies (Erneuerbare-Energien-Gesetz – EEG 2021), an increase of 62 GW onshore capacity until 2023 with reaching 71 GW in 2030 is targeted (Gesetz für den Ausbau erneuerbarer Energien, 2021). Also taking the disassemble of old wind turbines into account, a massive expansion of the wind energy industry is envisaged.

In summary, the wind energy industry is important for securing energy supply in Germany against the background of the energy transition and current geopolitical developments. In the future, there will be an increasing demand for wind energy plants (Gesetz für den Ausbau erneuerbarer Energien, 2021; Sozialdemokratische Partei Deutschland et al. 2021). Different materials are required for the construction of these plants, and in this context global competition for raw materials is expected to increase in many areas (Bobba et al. 2020; Lee/Zhao 2022). In order to make the supply chain more resilient, the establishment of a CSCM in the wind energy industry is crucial for success. In view of the future growth of the wind energy industry, it is now the right time to develop the supply chain in a future-oriented way and not to have to rebuild it later in a more time- and cost-intensive way. Therefore, potential opportunities and requirements for becoming more circular should be investigated. This paper is intended to contribute to this by identifying open questions for the design of a CSCM for the wind energy industry. Hence, this paper deals with the research question 'What is required for a CSCM in the wind energy industry in Germany?'.

5. Methodology

Practical implications from a CSCM perspective should be highlighted in this section by following the structure of existing frameworks. A CSCM should enable a holistic system thinking with a positive effect on economic, ecological, social and regenerate objectives (Farooque et al. 2019; Lengyel et al. 2021; Mendoza et al. 2022). The proposed methodology is to be applied to the wind energy industry in Germany.

The CSCM multi-level framework by Montag et al. (2021) functions as a foundation as they embed key facets of a CE into SCM. For this work, the framework is adapted for the wind energy supply chain by reflecting the work by Velenturf (2021). *Figure 4* presents the methodology for this contribution.

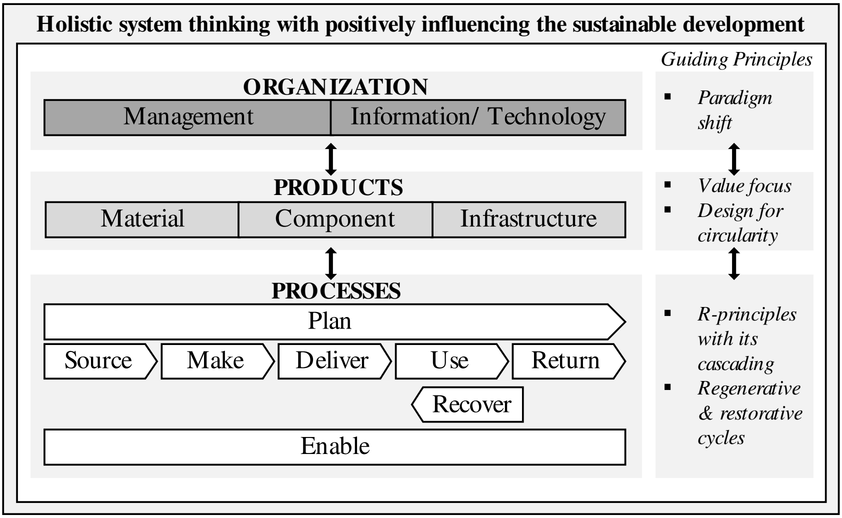

Figure 4: research methodology of this paper (based on Montag et al. 2021; Vegter et al. 2020; Velenturf 2021)

The presented research methodology consists of the three levels organization, products and processes. The organization level with its sub dimensions management and information/technology aims at enabling the paradigm shift in the wind energy industry (Montag et al. 2021). In line with Velenturf (2021), the different products to be considered are raw materials, components and infrastructure. The products are to be designed that they are capable to foster a circular thinking across all life phases, thus BoL, MoL and EoL, and therefore enable the creation, retention and extension of value. Looking at the process level, the supply chain processes must be designed and managed to comply with the R-principles and enable the distinction of regenerative and restorative cycles. The extended SCOR-model by Vegter et al. (2020) describes the different processes of the supply chains in alignment with CE thinking. Vegter et al. (2020) distinguish between the processes Plan, Source, Make, Deliver, Use, Return, Recover, and Enable. In comparison to the original SCOR-model (The Supply Chain Council 2012), the processes Use and Recover are main processes and not part of the other processes (e.g. recycling and remanufacturing being part of the process Make). However, Vegter et al. (2020) argue that extracting Use and Recover as further processes, would promote the CE thinking.

6. Circular Supply Chain Management for the Wind Energy Industry

Following section 5, the sub-sections outline the organization, products and processes level of a CSCM for the wind energy industry in Germany. The section 6 bases on literature research, discussions with experts from wind turbine manufacturers and a recycling company of wind turbines and the experience of the authors.

6.1. Organization Level

For facilitating a CSCM for the German wind energy industry the management as well as the information systems and (digital) technology need to enable a paradigm shift. From a management perspective, there are three main tasks (Montag et al. 2021; Sehnem et al. 2019; Velenturf 2021; Yadav et al. 2020):

- Describing and understanding the logistics network and the stakeholders in the wind energy industry.
- Deriving a vision of CSCM as well as defining a comprehensive target system.
- Obtaining requirements regarding the legal and competitive framework conditions.

The first step is to identify the relevant stakeholders of a circular wind energy industry in Germany. In the wind energy industry, the stakeholders are different in terms of their specialization of skills in comparison to other industries such as the automotive industry. Considering the manufacturing process of wind turbines, a wide variety of suppliers of raw materials and semi-finished products appear alongside the often globally active wind turbine manufacturers, similar to other production networks. But when it comes to installing, maintaining or deinstalling the wind turbines, special skills and technical equipment of regionally acting companies become apparent (Lee/Zhao 2022). This applies to the transport of the components as well as to the (de)installation of the turbines, e.g. offshore with special vessels. During the operation of the turbines, maintenance, repair and overhaul (MRO) services are provided by specially trained companies, for example, due to the work at high altitudes (Poulsen/Lema 2017). At the end of a turbine's life cycle, the turbine must be dismantled and components remanufactured or refurbished or materials recycled to return to the material cycles in an environmentally friendly way (Nachhaltiger Rückbau, Demontage, Recycling und Verwertung von Windenergieanlagen, 2020; Velenturf 2021). The interaction of different players (wind turbine manufacturers, suppliers of raw materials and semi-finished products, specialized installation companies and MRO service providers, dismantling, remanufacturing and recycling companies, port operators, freight forwarders, shipping companies, energy suppliers, etc.) is to be systematically described and the economic and logistical relationships and interdependencies between these companies are to be worked out in order to obtain a comprehensive picture of the wind energy industry in Germany. In addition, critical supply chain components are to be identified that may have an impact on the design of products in the future. For example, the need for sourcing secondary materials or designing the product differently to reduce dependencies on rare earths materials such as neodymium and dysprosium is discussed in literature (Bonfante et al. 2021).

To establish and operationalize the idea of a CSCM in the long term, the individual companies must develop a vision of the circular supply chain for themselves. This vision must be coordinated with the partners in the supply chain in order to avoid the formation of sub-optima. This also includes, for example, the establishment of a target system in order to measure the effects on economic, ecological, social and regenerative goals of the companies and to be able to derive improvements based on this. In conclusion, the stakeholder networks should be transformed from an association of loosely cooperating companies to a symbiotic network of companies acting in a coordinated manner with similar visions.

On this basis, meta-requirements are to be derived which the individual companies cannot directly influence and which work towards the creation of suitable framework conditions. Here, for example, the adaptation of laws and guidelines at the federal level but also at the European level should be considered, since the German wind energy industry is networked with other European countries and is part of the European electricity market. For instance, the European and German carbon emission trading, the German EEG 2021 (Gesetz für den Ausbau erneuerbarer Energien, 2021), the German law for CE (Kreislaufwirtschaftsgesetz) or more specifically the German DIN Spec 4866 on decommissioning and recycling of wind turbines triggers requirements for the German wind energy industry (Gesetz für den Ausbau erneuerbarer Energien, 2021; Die Bundesregierung 2020; Nachhaltiger Rückbau, Demontage, Recycling und Verwertung von Windenergieanlagen, 2020).

In the area of information systems and (digital) technology, a platform must be created that first increases transparency in the wind energy industry (Bundesverband WindEnergie e.V. 2019; Gebhardt et al. 2021; Mendoza et al. 2022; Velenturf 2021). This transparency relates on the one hand to the quantities of components and building units in different value creation stages (raw materials, semi-finished products, plants in operation with assumed residual lifetimes, deinstalled plants, deconstructed semi-finished products, remanufactured semi-finished products, recycled materials) and on the other hand to the available capacity of the individual stakeholders in the German wind energy industry. To develop such an information platform, the relevant data and information must be determined and a data model must be designed. Moreover, a business model and the operator for the platform should be set. Further, the way in which data is processed and transferred (including the definition of access rights) must be defined as well as incentives for stakeholders to share data. The last point in particular presents a challenge (Colicchia et al. 2019). For example, barriers to sharing sensitive data (e.g., material composition of the blades) are to be expected. Nevertheless, also initiatives like a digital product pass (Sozialdemokratische Partei Deutschland et al. 2021) could be applied to the wind turbines as well and could, for example, ease the work for remanufacturing and recycling companies. In addition, as mentioned in section 4, a register of all energy plants in Germany with master data (e.g. on location, installed capacity, operator, date of installation and decommissioning, technical data) already exists (Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen 2022). Next to the information to be provided by the stakeholders and the existing market register, big data analytics and the use of natural language processing (NLP) could enhance market transparency (Mendoza et al. 2022). For example Ertek et al. (2017) use NLP to identify wind turbine accidents. With increased transparency, analyses of the past developments as well as forecasts can be made, enabling data-based logistical planning and control of the network and each organization (Gebhardt et al. 2021). For instance, the risk of a bullwhip effect could be reduced if the required demand by each supply chain participant is shared throughout the supply chain (Gebhardt et al. 2021; Sahu et al. 2021). Moreover, process modelling could support the establishment of clean production, logistic and operation strategies (Mendoza et al. 2022). For example, the installation of sensors and the implementation of a predictive maintenance strategy could improve the availability of the components by reducing the downtime (Dulman/Gupta 2018). Along with the management activities it supports a shift towards a circular supply chain (Ellen MacArthur Foundation 2019b; Gebhardt et al. 2021).

6.2. Products Level

The products level focuses on creation, retention and extension of the value through the design for circularity (Montag et al. 2021). Thus, the aim is to design out waste and pollution (Ellen MacArthur Foundation 2019b). Only through an adequate product design, the R-principles can be followed on the processes level (Ellen MacArthur Foundation 2013; Montag et al. 2021). The turbine's or components' designs are typically not specifically adapted for countries such as Germany. Instead, the design reflects different wind and location conditions, e.g. a different foundation for offshore wind near the coast is needed as in deep waters or on land (Hau 2013).

Depending on the aggregation level, the view on onshore and offshore wind energy can be divided into materials, components and infrastructure. Concrete, steel, electronical components (with its rare earth materials neodymium and dysprosium), copper, aluminium, polyvinyl chloride (PVC), operating fluids, composites (glass-fibre reinforced plastic (GFRP) and carbon-fibre reinforced plastic (CFRP) are used materials (Bundesverband WindEnergie e.V. 2019; Lee/Zhao 2022). The key components are the foundation, tower, rotor blades, rotor hub, nacelle, generator, gear-box and grid connection technology (Hau 2013; Lee/Zhao 2022). And the infrastructure view reflects on the installed wind turbine with its grid and road connection (Velenturf 2021).

From a CE point of view, dematerialization of the products should be aimed for. Furthermore, no hazardous and only regenerative or restorative materials should be used. Thus, it should be aimed for a design that allows the distinction between biological/regenerative and technical cycles (Ellen MacArthur Foundation 2019b). A wind turbine enables to produce power from regenerative sources, however the construction of a wind turbine is mainly based on finite materials. As such, the Ellen MacArthur Foundation (2019b) argues that products, components and materials should be recovered and restored trough applying CE strategies, known as R-principles. Hence, wind turbine components should be designed in a way that efficient and effective maintenance, repairment, reuse, repurpose, refurbishment, remanufacturing, disassembly and regeneration is possible (Velenturf 2021). In this context, applying a modular design for components (e.g. to enable the upgradeability) and turbines (e.g. to enable the replacement of components) represents a promising approach. Modularity also qualifies for increasing the durability of the turbine and its components (Bundesverband WindEnergie e.V. 2019; Velenturf 2021). In addition, adequate quality measures for materials and production processes are to be considered. In this matter, it should also be highlighted that the continuous increase of installed capacity per turbine in Germany and associated increase of most components' size, calls for research on how to upgrade old components. With this, the attractiveness for reusing components might increase.

Further, the product design for recycling should ease a recycling in the highest possible quality. For instance, there are dependencies on rare earth materials that are used in permanent magnets for generators (Alves Dias et al. 2020). Those should ideally be replaced by alternative materials when installing new plants and be recycled out of existing plants. Another example are multi-layer composites (GFRP and CFRP) that are used for rotor blades. Composite structures complicate the realization of restorative strategies (e.g. recycling in a high quality) (Beauson et al. 2022). Thus, research is needed to find alternatives.

In relation to Germany, it should be stressed that currently only 10% of the dismantled wind turbines in Germany are put to secondary use. Further, almost 90% of the dismantled components of a wind turbine, based on the total mass, are fed into an orderly recycling process. However, often downgraded recycling takes place and mostly only the metals are being recycled for their original purpose. The demand for secondary raw materials is currently too low and characterized by reservations also due to the quality losses of the recycled material (Bundesverband WindEnergie e.V. 2019).

As the minimum effort, there is a need for aiming to avoid a design that leads to landfill or downgraded recycling (e.g. for most compound structures the case). Beyond, a product design that for example allows the integration of by-products from the industry or other industries has a positive contribution to achieve restorative cycles (Ellen MacArthur Foundation 2019b).

6.3. Processes Level

The processes level aims at implementing and executing the R-principles. As shown in *Figure 4* the processes need to be structured for different products (materials, components and the wind turbine itself). In addition, processes should differ between restorative and regenerative cycles and should aim for dematerialization. As stated above, this can only take place if the products are accordingly designed. In this relation, the choice of adequate business models is of importance. These are implemented on the process level, based on the foundation set in the organization and products level. For example, offering services instead of products requires the development of digital capabilities, a change of the pricing strategy and a transformation of the relationships with customers (Mendoza et al. 2022). For the processes level, the challenges and the questions to be answered for the different levels of investigation (material, component, wind turbine) can be identified using the extended SCOR model by Vegter et al (2020).

The Plan process foresees the product and supply chain design for the wind energy industry. In addition, the planning of the source, make, deliver, use, return and recover process is part of the Plan process. Within the Source process the procurement of raw materials, semi-finished and finished materials, components and turbines from primary as well as secondary sources takes place. The Make process comprises of the production of the components that are then delivered to the site. At the location of the wind turbine, the assembly and installation of the wind turbine occurs. In the Use process, the operation of the turbine alongside the according MRO of the installed components is in focus. As an additional approach to extend the lifetime of a turbine, components can be reused, repurposed, refurbished and remanufactured (Velenturf 2021). Those processes are part of the Recover process (Vegter et al. 2020). In some cases, this can take place at the location of the turbine and components do not have to be disassembled and returned. The Return processes describe the activities associated with the reverse flow of the wind turbines and its components. Thus, the identification of products to be returned and the decision on the decommission approach for the wind turbine as well as the disassemble strategy for the components is necessary. Further, scheduling and performing the return and finally the receipt of the returned products are part of the Return process (The Supply Chain Council 2012; Velenturf 2021). Part of the Recovery process for the materials, is the recycling, alternatively the energy recovery or the landfill to be avoided (Vegter et al. 2020; Velenturf 2021). The Enable process describes the activities related to SCM, for example performance management, data management and resource management (The Supply Chain Council 2012).

For the processes outlined, specific questions arise that need to be answered for an efficient CSCM. In this paper, questions that occur in the Plan process will be addressed in an exemplary manner. In the area of planning, the prerequisites for efficient CSCM must be created, mainly the following tasks emerge:

- Forecasting future installation and decommissioning quantities
- Design of the network depending on a previously defined target system
- Long-term planning of the capacities of the individual stakeholders of the network and also of the inventories.

First, the expected demand of wind turbines in their different life-phases is decisive. To the best of the authors' knowledge, no reliable quantity structure is available today for future installation and decommissioning quantities for wind turbines in Germany. This is an important requirement for the various stakeholders to be able to increase or reduce their capacities in a targeted manner, which sometimes entails very long lead times depending on the stakeholder (e.g. ships for installation of offshore wind turbines) (Mendoza et al. 2022; Sultan et al. 2018). The starting point for such a forecast model is the current information on plants in operation, which can be taken from the in section 4 mentioned market register, as well as the development targets of the German government with regard to the energy volumes to be generated from wind energy in the future. Based on this, influencing variables on the quantity structure to be developed need to be identified. These can be for example the following variables:

- development of MW output per turbine,
- development of land availability for the installation of wind turbines onshore and offshore,
- estimated lifetimes of wind turbines possibly depending on manufacturer, operating site, plant capacity and efficiency.

Scientific work can deal with the creation of such a dynamic model, e.g. using data-based models for forecasting and scenario analyses of the German wind energy industry. It should be considered, that a transformation to a CE will lead to a different timed allocation of demand. For instance, prolonging the lifetime of a wind turbine will lead to a later demand for decommissioning capacities.

Based on these forecasts, the circular supply chain network (production, logistics, MRO, dismantling, reprocessing, etc.) can be designed. The quantity structure resulting from the dynamic forecast model has a significant influence as well as the design of the products (e.g. which wind turbine manufacturer can actually refurbish and reuse which components). Depending on these factors, different network structures can be considered for the individual components (Sultan et al. 2018). For certain components, it may be possible to establish hubs from which the manufacturers can obtain returned components, which may already have been remanufactured to a certain extent. Furthermore, the optimal cascade of CE strategies for the German wind energy industry – in theory reduce, reuse, recycle and recover

– needs to be empirically investigated regarding the achievement of social, economic and ecological objectives (Corvellec et al. 2021; Sahu et al. 2021; Schröder et al. 2019). For example, decommissioning and transporting a German wind turbine to a country on a different continent (e.g. to India) might be less attractive than using local recycling capacities. Therefore, an optimal scenario of a circular German wind energy network looks differently when based on existing capabilities or potential future resources in Germany.

Based on the forecast model and the network design, models are required for the long-term planning of the capacities of the individual stakeholders of the network as well as the inventories at the different stages of the value chain. Hence, capacities such as human resources, fleet size or logistical, production and remanufacturing sites are to be planned. Exemplary questions to be answered in this context are:

- Which capacities will be required in the future at which point in time for the different life phases of wind turbines? What technological capabilities are required?
- Which stocks and strategies can be used for components in order to be able to balance capacity and load in the network?

For the efficient implementation of the core processes according to Vegter et al. (2020), by the various stakeholders in the wind energy industry (with its different materials, components and turbine types), there are questions related to the technical design of the processes as well as the development and implementation of problem-specific planning and control approaches for the individual core processes. Current research is already addressing some of those questions.

7. Conclusion

This paper structures the circular wind energy supply chain in Germany according to its organization, products and processes level. The aim was to contribute to the research question 'What is required for a CSCM in the wind energy industry in Germany?'. Thus, it provided an overview of tasks and related research questions. This paper represents a starting point and needs to be underpinned with further expert interviews, surveys, market data analytics and scientific research. Nevertheless, as a sustainable transformation of the economic system is urgent, the discussion on a suitable design of a circular supply chain for the German wind energy industry should start now. When developing the associated CSCM, strategies for the existing portfolio as well as for the portfolio to be developed should be reflected.

For future research, modelling demand and capacities of different stakeholders and the entire supply chain under complex dependencies is key. Thus, scenario analyses reflecting the actual and planned geographical allocation of turbines as well as stakeholder capacities (e.g. remanufacturing sites) under different CE maturity degrees should be developed. Additionally, first ideas on designing a circular wind energy network were presented in this paper. An interesting research field might also be the mapping of material flows across different supply chains. If the necessary data basis exists, artificial intelligence methods could support to analyse similarities between supply chains and to indicate synergy effects (Ellen MacArthur Foundation 2019a). This contribution focused on wind turbines located in Germany, however, for compiling the application of restorative strategies across the entire lifecycle of a wind turbine, also synergies with other countries could be meaningful.

It should also be stressed, that the theoretical concept of CE and CSCM is still evolving and further practical evaluations are needed (Corvellec et al. 2021; Sahu et al. 2021; Schröder et al. 2019). For example, it still needs to be empirical validated if CE contributes to more sustainability and resilience in the wind energy supply chains. In this context, also the different product and process design strategies need to be evaluated on their contribution towards becoming more circular. Even as the CE concept is seen as promising, implementing the idea of CE across entire supply chains or ecosystems remains a major challenge (Corvellec et al. 2021; Kirchherr et al. 2018; Lopes de Sousa Jabbour et al. 2018). In this context, for example, digital technologies and strategic cooperation could help to ease the implementation (Gebhardt et al. 2021; Kirchherr et al. 2018).

In conclusion, as the achievement of a CE foresees a system change an evolvement of different disciplines is necessary. The provided ideas form a starting point for future discussions and should encourage researchers and practitioners to join those discussions.

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