End-Of-Life Wind Turbines in the EU: 
An Estimation of the NdFeB-Magnets 
and Containing Rare Earth Elements 
in the Anthropogenic Stock 
of Germany and Denmark

Uttjänta vindturbiner i EU: En uppskattning av tillgången på sällsynta jordartsmetaller i NdFeB-magneter i vindturbinsbeståndet i Tyskland och Danmark

Lisa Welzel
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Abstract

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Securing rare earth elements (REE) for a stable supply require sustainable management strategies in Europe due to a missing local primary production and a dependence on China as the main producer of REE. These elements, like neodymium (Nd) and dysprosium (Dy), are contained in permanent magnets (PM) (mostly NdFeB-magnets) in wind turbines. Addressing the question whether PM-material, Nd- and Dy-contents from wind turbines could help to meet future demands of REE in Europe while reducing simultaneously the import dependence, the purpose of the present work was to analyze the urban mining opportunities, recovery - and recycling potentials for REE from end-of-life (EoL) wind turbines. This thesis aimed to identify current and upcoming stocks as well as material flows of the PM and their containing REE in the wind energy sector. Two European countries, Germany and Denmark, were chosen as case studies to be compared based on created future scenarios and the modeling of the theoretical recycling potential of Nd and Dy in both countries. It could have been identified that the German anthropogenic stock contains greater amounts of NdFeB-magnets and REE compared to the Danish stock. Overall it could be concluded that the countries’ demand could partly be met by using secondary Nd and Dy from the EoL-wind turbines. Although future scenarios were used, the results realistically illustrate the German and Danish anthropogenic stock until 2035 by relying on data of already installed turbines up to 2018, which makes an evaluation of capacities and EoL-turbines, which need to be decommissioned by 2035, achievable. The provided information is valuable for further investigations regarding recovery strategies, feasibility analysis, and future decision-making processes.

Key words: rare earth elements, neodymium, dysprosium, wind turbines, permanent magnets, recycling, recovery, closing the loop, urban mining, sustainability

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Lisa Welzel

För att säkra tillgången på jordartsmetaller (REE) i Europa krävs hållbara beslutsstrategier. Detta på grund av avsaknaden av en inhemsk primärproduktion samt ett beroende av Kina som en huvudproducent av REE. Jordartsmetaller som neodymium (Nd) och dysprosium (Dy), finns kvar i permanenta magneter (PM) (mestadels NdFeB-magneter) i vindturbiner. För att ta itu med frågan om huruvida Nd- och Dy-innehållet i PM-material, från vindturbiner skulle kunna bidra till att uppfylla framtida efterfrågan på REE i Europa samtidigt som importberoendet skulle minsas, var syftet med detta arbete att analysera möjligheterna till urban utvinning, återvinning och materialutnyttjande av REE från vindturbiner i uttjänt tillstånd (EoL). Syftet med denna uppsats var att identifiera nuvarande och kommande tillgångar samt materialflöden av PM och därav följande REE inom vindkraftsektorn. Två europeiska länder, Tyskland och Danmark, valdes ut som fallstudier och jämfördes i framtida scenarier och modellering av Nd- och Dy-teoretiska återvinningspotential i båda länderna. Det kunde konstateras att det tyska antropogena beståndet innehåller större mängder NdFeB-magneter och REE än det danska beståndet. Sammanfattningsvis kan man dra slutsatsen att ländernas efterfrågan delvis kunde tillgododosa genom att man använde sekundär Nd och Dy från EoL-vindturbiner. Även om framtidens scenarier användes illustreras resultatet på ett realistiskt sätt det det antropogena lagret i Tyskland och Danmark fram till 2035 genom att man förlitar sig på uppgifter om redan installerade turbiner fram till 2018, vilket gör det möjligt att göra en utvärdering av kapaciteten och antal EoL-turbiner, som måste avvecklas senast 2035. Informationen är värdefull för ytterligare utredningar om återvinningsstrategier, genomförbarhetsanalys och framtidens beslutsprocesser.

Nyckelord: sällsynta jordartsmetaller, neodymium, dysprosium, vindturbiner, permanenta magneter, återvinning, cirkulärt system, hållbarhet

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5 Analysis ........................................................................................................................................ 46
  5.1 Germany ................................................................................................................................... 46
  5.1.1 Business-As-Usual ............................................................................................................... 46
  5.1.2 GreenEe ................................................................................................................................. 52
  5.2 Denmark .................................................................................................................................. 55
  5.2.1 Hydrogen ............................................................................................................................... 55
  5.2.2 Bio+ ...................................................................................................................................... 60
  5.3 Nd and Dy contents in the anthropogenic stock ....................................................................... 64
  5.3.1 Germany ............................................................................................................................... 64
  5.3.2 Denmark ............................................................................................................................... 68
6 Discussion ....................................................................................................................................... 71
  6.1 RQ1: Future differences in the German and Danish wind energy market ......................... 71
  6.2 RQ2.1 & RQ2.2: By which extend can recovered REE-amounts from PM of wind turbines support the countries’ demand? ................................................................. 72
  6.2.1 Germany’s theoretical recycling potential and demands in future .................................... 73
  6.2.2 Denmark’s theoretical recycling potential and demands in future .................................... 74
  6.2.3 Implications for the EU ....................................................................................................... 75
  6.2.4 A generalized discussion .................................................................................................... 76
7 Conclusion ...................................................................................................................................... 78
Acknowledgement .......................................................................................................................... 80
References .......................................................................................................................................... 81
Appendix 1: Comparison of different turbine concepts and their efficiencies ....................... 90
Appendix 2: Gross newly build capacities [MW] in Germany from 2001-2018 ................... 91
Appendix 3: Gross new-built capacities [MW] in Denmark from 2000-2018 ....................... 93
Appendix 4: Cumulative capacity in GER (GreenEe-scenario) ............................................... 95
Appendix 5: Gross new-installed capacity in Denmark (Bio+) ............................................... 96
Appendix 6: Yearly element input to the anthropogenic stock (all scenarios) ..................... 97
List of abbreviations

a  Year
B  Boron
Ce  Cerium
CO₂  Carbon dioxide
CRM  Critical raw materials
CS  Constant-speed (wind turbine)
DD  Direct drive synchronous generator without a permanent magnet
DD-PM  Direct drive-permanent-magnet-generator
DEA  Danish energy agency
DFIG  Doubly-fed induction generator
DK  Denmark
Dy  Dysprosium
EESG  Electrically excited synchronous generator
EoL  End-of-life
Er  Erbium
EVM  Electric vehicle motors
Eu  Europium
EU  European Union
Fe  Iron
Gd  Gadolinium
GDP  Gross domestic product
GER  Germany
GHG  Greenhouse gas
GW  Giga Watt
IEA  International Energy Agency
IG  Induction generator
HREE  Heavy rare earth elements
HTS  High temperature superconductors
MFA  Material flow analysis
La  Lanthanum
LREE  Light rare earth elements
Lu  Lutetium
MW  Megawatt
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Term</th>
</tr>
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<tbody>
<tr>
<td>Nd</td>
<td>Neodymium</td>
</tr>
<tr>
<td>NdFeB</td>
<td>Neodymium, iron, boron (magnet)</td>
</tr>
<tr>
<td>PJ</td>
<td>Petajoule</td>
</tr>
<tr>
<td>PM</td>
<td>Permanent magnet (NdFeB-magnets considered only)</td>
</tr>
<tr>
<td>Pr</td>
<td>Praseodymium</td>
</tr>
<tr>
<td>REO</td>
<td>Rare earth oxide</td>
</tr>
<tr>
<td>RE</td>
<td>Rare Earths</td>
</tr>
<tr>
<td>REE</td>
<td>Rare Earth Elements</td>
</tr>
<tr>
<td>REM</td>
<td>Rare Earth Metals</td>
</tr>
<tr>
<td>RQ</td>
<td>Research question</td>
</tr>
<tr>
<td>Sc</td>
<td>Scandium</td>
</tr>
<tr>
<td>SDG</td>
<td>Sustainable Development Goal</td>
</tr>
<tr>
<td>SG</td>
<td>Synchronous generator</td>
</tr>
<tr>
<td>SG-PM</td>
<td>Synchronous generator with permanent magnet</td>
</tr>
<tr>
<td>Sm</td>
<td>Samarium</td>
</tr>
<tr>
<td>t</td>
<td>Metric ton; 1,000 kg</td>
</tr>
<tr>
<td>Tb</td>
<td>Terbium</td>
</tr>
<tr>
<td>TWh</td>
<td>Terawatt-hour</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
</tr>
<tr>
<td>Y</td>
<td>Yttrium</td>
</tr>
<tr>
<td>Yb</td>
<td>Ytterbium</td>
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</tbody>
</table>
List of tables

Tab. 1: Average weights of permanent magnets for different wind turbines technologies .................................................17
Tab. 2: Shares of elements in permanent magnets used in wind turbines .................................................................17
Tab. 3: PM-weights in kg/MW that were chosen according to estimations for onshore and offshore operating turbine concepts in the future ..................................................................................................................................................30
Tab. 4: Development of PM-weights over time in kg/MW ..............................................................................................31
Tab. 5: Development of REE-shares in permanent magnets applied in wind turbines ...................................................32
Tab. 6: Germany’s total installed gross new-built capacities onshore and offshore before the year 2000 ........................................................................................................................................................................39
Tab. 7: Denmark’s total installed gross new-built capacities onshore and offshore before the year 2000 ........................................................................................................................................................................39
Tab. 8: German set goals of gross new-build capacity for the wind energy market ......................................................41
Tab. 9: German set goals of gross new-build capacity for the wind energy market as well as calculated and estimated data for forecast scenario until 2050 ........................................................................................................................................41
Tab. 10: Applied percentages for different turbine technologies over time ....................................................................41
Tab. 11: Provided information for calculated wind energy targets used as background information in the report of Günther et al. (2017) ......................................................................................................................................43
Tab. 12: Installed capacity in MW by 2050 ......................................................................................................................44
List of figures

Fig. 1: Development of installed wind turbine capacity [MW] in Germany .........................6
Fig. 2: Development of yearly repowered and decommissioned capacity onshore in Germany 6
Fig. 3: Share of turbine concepts in yearly new commissioned capacities ..........................7
Fig. 4: Age distribution of decommissioned wind turbines in 2018 ..................................8
Fig. 5: Danish wind energy sector development from 2009-2018 ......................................10
Fig. 6: Visualizes simplified the composition of a horizontal-axis-type wind turbine ..........14
Fig. 7: Schematic categorization of available wind turbine technologies ............................15
Fig. 8: Calculated averages (2010-2014) of countries and shares in supplying Europe’s CRM 19
Fig. 9: Development of rare earth element applications over time ....................................20
Fig. 10: Reported data and average estimates for REE resources [kt] for each rare earth  element ............................................................................................................................22
Fig. 11: Representation of the distribution function using Weibull-parameter ....................34
Fig. 12: Schematic visualization of the calculation model, using Umberto ..........................36
Fig. 13: The scenario funnel ................................................................................................37
Fig. 14: Aggregated input flows in kW entering the German anthropogenic stock,  differentiated between 4 turbine concepts that are available onshore and offshore (BAU scenario) .........................................................................................................................47
Fig. 15: Disaggregated input flows of NdFeB-material [kg] to the German anthropogenic stock, differentiated between PM-containing turbine technologies (BAU scenario) ........48
Fig. 16: Aggregated output flows in kW entering the German anthropogenic stock,  differentiated between 4 turbine concepts that are available onshore and offshore (BAU scenario) .........................................................................................................................49
Fig. 17: Disaggregated output flows of NdFeB-material [kg] from the German anthropogenic stock, differentiated between PM-containing turbine technologies (BAU scenario) ........50
Fig. 18: German BAU scenario and its cumulative capacity in kW distinguished by various turbine technologies with and without a built-in PM onshore and offshore (BAU scenario) ...51
Fig. 19: Disaggregated input of NdFeB-material [kg] to the German wind energy stock  distinguished by PM-containing turbine technologies (BAU scenario) .........................................................................................................................51
Fig. 20: PM-material [kg] incoming to the German anthropogenic stock in form of new commissioned wind turbines (GreenEe scenario) ....................................................................52
Fig. 21: Aggregated output flow [kW] from the German anthropogenic stock distinguishing 4 turbine concepts that are available onshore and offshore (GreenEe scenario) ............53
Fig. 22: PM-material [kg] that becomes available in the German anthropogenic stock in form of decommissioned wind turbines, according to the GreenEe scenario ...........................................53

Fig. 23: PM-material [kg] accumulated in the German anthropogenic stock in form of operating wind turbines, according to the GreenEe scenario .................................................................54

Fig. 24: Input flow [kW] of new capacity to the Danish wind energy sector distinguished by two turbine technologies using a PM and the rest that is using no NdFeB-magnet (Hydrogen scenario) .........................................................................................................................56

Fig. 25: PM-material [kg] incoming to the Danish anthropogenic stock in form of new-commissioned wind turbines (Hydrogen scenario) ..........................................................................................................................57

Fig. 26: Danish decommissioned capacities [kW] over time (Hydrogen scenario) .................................58

Fig. 27: PM-material [kg] that becomes available in the Danish anthropogenic stock by the decommissioning of wind turbines (Hydrogen scenario) ........................................................................58

Fig. 28: Danish Hydrogen scenario and its cumulative capacity in kW, differentiated between various turbine technologies with and without a built-in PM onshore and offshore (Hydrogen scenario) ..................................................................................................................59

Fig. 29: PM-material [kg] accumulated in the Danish anthropogenic stock in form of operating wind turbines (Hydrogen scenario) ........................................................................................................59

Fig. 30: PM-material [kg] incoming to the Danish anthropogenic stock in form of new-commissioned wind turbines (Bio+) .................................................................................................................60

Fig. 31: Danish decommissioned capacities [kW] over time, distinguished by various turbine concepts estimated (Bio+) .................................................................................................................61

Fig. 32: PM-material [kg] that becomes available in the Danish anthropogenic stock in form of decommissioned wind turbines (Bio+) ........................................................................................................62

Fig. 33: PM-material [kg] accumulated in the Danish anthropogenic stock bound in wind turbines (Bio+) .................................................................................................................................63

Fig. 34: Nd and Dy-amounts [kg] that become available in the German anthropogenic stock due to decommissioning of wind turbines (BAU scenario) .................................................................66

Fig. 35: Nd and Dy-amounts [kg] that become available in the German anthropogenic stock due to decommissioning of wind turbines (GreenEe scenario) .................................................................66

Fig. 36: Accumulated Nd and Dy amounts [kg] in the German anthropogenic stock bound in different wind turbine concepts located onshore and offshore (BAU) .............................................................67

Fig. 37: Accumulated Nd and Dy amounts [kg] in the German anthropogenic stock bound in different wind turbine concepts located onshore and offshore (GreenEe) .................................67
Fig. 38: Nd and Dy-amounts [kg] that become available in the Danish anthropogenic stock due to decommissioning of wind turbines, according to the Hydrogen scenario..........................69

Fig. 39: Nd and Dy-amounts [kg] that become available in the Danish anthropogenic stock due to deconstruction of wind turbines (Bio+)........................................................................................................69

Fig. 40: Accumulated Nd and Dy amounts [kg] in the Danish anthropogenic stock bound in different wind turbine concepts located onshore and offshore (Hydrogen)........................................70

Fig. 41: Accumulated Nd and Dy amounts [kg] in the Danish anthropogenic stock bound in different wind turbine concepts located onshore and offshore (Bio+)............................................70
1 Introduction

The Earth is facing social, environmental and economic challenges. Therefore, in 2012 17 Sustainable Development Goals (SDG) were defined as global priorities and future ambitions for governments, businesses and the civil society (UN, 2019). These goals seek global efforts to realize a more sustainable future.

Already in the last decades, approaches of tackling climate change, factors of cost-efficiency and sustainability issues led to changes in the energy production of many countries. Additionally, in order to combat climate change and its impacts (SDG 13) and to assure access to reliable, affordable and sustainable energy for all (SDG 7) (UN, 2019), the EU decided to cut carbon dioxide emissions. Therefore, the member states are focusing on less greenhouse-gas-emitting techniques, especially in the energy-producing industry. Renewable energy sources, like wind energy, should help to meet the electricity demand and make it possible for countries to reduce the energy production from greenhouse-gas-intensive methods, like the burning of fossil fuels and coal. Generally, a worldwide consensus exists that wind energy can play an important role in securing electricity production in a more sustainable way (Wagner & Mathur, 2018). However, to make a growth of the wind energy sector possible, an extension of the turbine network and the grid connections is necessary. Not only the already installed capacity but also the upcoming growth of this market is connected to great material flows and, increasing demands for primary raw materials and secondary resources. Therefore, it is important to analyze how wind turbines as a great and long-lasting stock of materials, develop over time and how they could be used at the end of their service-lifetime to meet material demands in the future, especially those of rare earth elements (REE). In the following the focus lies on the REE which are applied in permanent magnets used in some wind turbine technologies. Although there are turbines and generator systems available that do not require a permanent magnet (PM), there are some technologies, like direct-drive configurations or synchronous generators that use a permanent magnet. These magnets, mostly neodymium-iron-boron (NdFeB) magnets, contain various rare earth elements like neodymium, dysprosium, and partly terbium and praseodymium. Due to very unique material characteristics of the rare earths, the PM is of superior magnetic strength and made improvements of efficiency, reliability and weight reductions of the magnet and generator in general possible (Weng & Mudd, 2017). However, rare earth elements are considered to be critical raw materials for the EU. This
stems from their economic importance and their supply risk due to Europe’s dependence on China as the global main producer of REE which can result in export-restrictions or price fluctuations. Since there is no primary or secondary production of REE in Europe but an economic interest in these elements, closing the material loop is not only of economic interest but also helps to implement a circular economy approach. Furthermore, because a sustainable and efficient usage of natural resources is a key driver in today’s world, the motivation for this thesis is to estimate the amount of rare earths that are already built-in in commissioned wind turbines.

1.1 The switch to wind energy
Electricity production is one of the major points on countries’ political agenda of today’s world. There are very different techniques to produce energy. So far, the biggest share in the world’s energy production has electricity from petroleum, solid fuels, like coal, and gas (European Commission, 2018). The fact of approaching ‘peak oil’ while many countries are dependent on oil and imports, plays a great role in shifting to renewable energy. Moreover, renewable energy can lead to greater independence in the energy-producing sector of each country and can, therefore, lead to a higher security of supply (Meyer, 2007). Additionally, in 2014 it was calculated that the cost for onshore wind energy production is cheaper compared to energy from coal or nuclear fission when taking all external costs of storage or health effects into account (Ecofys, 2014). Lastly, greenhouse gas emissions which are causing global warming are emitted to a big extend by the energy-producing sector, for instance, by burning fossil fuels and coal. Despite the fact that nuclear power has good results with respect to emitting low greenhouse gas concentrations, people are very critical against it due to its inherent problems of storage and nuclear disasters. Therefore, Germany and Denmark decided on a future energy supply without nuclear power. For that reason, renewable energies should help to meet the goals set by the EU for its countries in order to reduce greenhouse gas emissions (Meyer, 2007) while still covering the energy demand of citizens and the industry.

Some background information about why the electricity market is changing so slowly, although there were calls for change decades ago, and why a sustainable energy production development, which requires planning horizons of more than 40 years, was not started earlier, can be found in the work of Meyer (2007).

Nevertheless, a global trend can be observed that wind energy will play an important role in ensuring electricity production in a more sustainable way.
1.2 Aim of this study

In Germany analysis studies for identifying the future demand of neodymium and dysprosium were previously conducted, for example, by Brumme (2014) and the Wuppertal Institut (2014). For Denmark, Habib et al. (2014) identified stocks and flows of Nd and Dy respectively several applications until 2035. The theoretical recycling potential of PM from different applications for the whole EU was analyzed, for instance, by Elwert et al. (2017) and Ciacci et al. (2019).

The goal of this study is, generally, to contribute more in-depth information of the German and Danish anthropogenic stock and to analyze the upcoming rare-earth-containing secondary material from permanent magnets of end-of-life turbines. The question is if it is possible to reduce Europe’s dependence on REE-imports and to minimize the balance problem. Moreover, currently existing challenges for REE-recovery and recycling are discussed. For these purposes, Germany and Denmark were chosen to be compared. Germany is of interest since it has the biggest share of wind turbines in Europe. Moreover it decided on a future with no energy production from coal and nuclear fission so that energy demand has to be covered by other energy sources, for instance by wind energy. In contrast, Denmark is the pioneer in wind energy since the 1970s and had already in 1995 the second-highest number of installed wind turbines possessing a lot of experience in this sector.

In collaboration with the German Environment Agency (Umweltbundesamt) the present work was composed to answer the following research questions (RQ):

**RQ1:** How do the German and Danish wind market expansions differ possibly from each other in the future?

**RQ2.1:** Is it possible that rare earth elements recovered from PM-recycling can help to meet the future demand of rare earths and magnetic material, using NdFeB-magnets from wind turbines as an example?

**RQ2.2:** If RQ2.1 applies, to which extent could the upcoming secondary rare earth material be integrated in future supplies?

To answer these questions, the following pages introduce the topic of wind energy and its importance in the future. Subsequently, developments of policies and the wind energy market in Germany and Denmark are described. Afterwards, it will be explained why rare earth elements and their application as permanent magnets are of interest for Europe, as well as for the wind en-
ergy sector, and why the target of recovering and recycling these elements is currently challenging to reach. In order to estimate the Nd and Dy content in the anthropogenic stock of both countries and to estimate the theoretical recycling potential of NdFeB-magnets, the REE-material flows and stocks are modeled for both countries separately. For defining and estimating the wind energy sector from the past until 2050, politically set goals, trends and forecast scenarios are used. Furthermore, different turbine technologies, as well as differences in offshore and onshore locations, operating lifespan, and technology improvements over time, are considered. For the calculations and modeling, the computer program Umberto® and the information system Dy-MAS are used. Lastly, the results of the analyses are presented and discussed before this thesis closes with a conclusion summarizing the most important findings. In the following chapters, the installed wind turbine capacities and politically set goals in Germany and Denmark will be described.
2 Overview of wind power expansion in Germany and Denmark

Firstly, it has to be mentioned that Denmark is of smaller geographical size (43,000 km²) with less inhabitants (roughly 5.7 million) (Danish Energy Agency, 2016) compared to Germany with an area of 357,000 km² and 83.5 million inhabitants. Consequently, the demand of energy and its general electricity consumption in both countries vary widely, which results in greater wind energy capacities for Germany than for Denmark. More detailed information for the countries are explained below.

2.1 Germany

2.1.1 Status Quo

Fig. 1 is a simplified representation of Germany’s installed capacity development of wind turbines on- and offshore over the last decades. It can be seen, that a continuous growth occurred. The year 2019 describes the new construction of wind turbines for the first months and is not representative for the whole year 2019.

To give a more detailed example, in 2018 743 wind turbines were built with a gross new-build capacity of 2,402 MW. This number corresponds to 55% less new-built capacity compared to 2017. In 2018, onshore turbines with a total of 249 MW were decommissioned. Repowered turbines are generally recorded and registered simply as new-built turbines. How repowering and decommissioning of onshore wind turbines evolved over time can be seen in Fig. 2 (Deutsche WindGuard, 2018).
Furthermore, the shares of wind turbine technologies and generator concepts were analyzed and used in this work (see Fig. 3) (Rohrig, 2018; Fraunhofer IEE, 2018b). In the early stages of wind turbine technology, the market was dominated by constant-speed wind turbines (CS), whereas today speed-variable concepts and direct-drive (DD) wind turbines are most common. One major turbine manufacturer started already in 1993 to produce DD SG converters (Zimmermann et al., 2013). However, many producers provided the doubly-fed induction
generator (DFIG) from the past until today. Before 2010, DD-PMSG can be seen as negligible for Germany’s wind energy market (Zimmermann et al., 2013) and shares of built-in permanent magnets are currently decreasing (Fraunhofer IEE, 2018b)

In 2018, the shares were as followed: Direct drive turbines with a permanent magnet (DD-PMSG) were 3.58 % while permanently excited synchronous generators with a gearbox (PMSG) had 15.52 % of all commissioned turbines in 2018. Gearless DD turbines not permanently excited had 52.65 %, DFIG 17.90 %, IG 8.22 %, and electrically excited synchronous generators had 1.72 % of the total installed capacity in 2018 (Fraunhofer IEE, 2018b).

![Fig. 3 Share of turbine concepts in yearly new commissioned capacities (slightly changed after Fraunhofer IEE, 2018b)]

The age distribution of German onshore EoL-wind turbines from 2018 can be seen in Fig. 4. In total, 142 turbines (367 turbines in 2017) with a total capacity of 188 MW (473 MW in 2017) were decommissioned or deconstructed. Although, according to the German law, wind turbines are approved for 20 years, around 90 % of the decommissioned turbines in 2017 and 2018 did not reach the end of their approved service-lifetime of 20 years. The average EoL-turbine in 2018 was 17.7 years old with a capacity of 1.33 MW (Fraunhofer IEE, 2018c).

End of 2018, 4,600 German wind turbines exceeded the lifetime of 20 years. These represent 15.4 % of the total installed turbines, but only 4.1 % of total installed capacity (473 kW). Until the end of August 2014, no decommissioned turbine was registered, which can lead to a slightly too high number of still operating turbines (Fraunhofer IEE, 2018a)
2.1.2 History

In the mid-1970s, when the oil crisis and coal scarcity favored the construction of new nuclear reactors and opponents of nuclear power became more popular, the wind energy became increasingly important. However, during this period the wind energy did not supply energy but was still in the testing phase (Ohlhorst et al., 2008). Renewable energy got even more acceptance after the Chernobyl disaster in 1986 and the first non-binding suggestions of the Intergovernmental Panel on Climate Change (IPCC) in 1990 put renewables for climate protection reasons in the center (Bechberger et al., 2008). Furthermore, after the nuclear disaster of Fukushima in 2011, German citizens were more aware of the threat of nuclear power, so that this event is for many people the starting point of the German Energiewende with the aim of climate protection. Nevertheless, shutting down nuclear power plants in Germany after 2011 led to compensating the lack of produced nuclear energy with burning coal.

While in Denmark the first offshore wind turbines were rotating in 1991, it took 18 more years in Germany for commissioning offshore turbines. In 2009, three testing turbines were installed in the wind farm Alpha Ventus.

2.1.3 Energy policies

The initializing-phase in the late 80s was supported in 1991 by the Electricity-Feed-In-Act (Stromeinspeisungsgesetz), which helped the German wind energy sector to develop. One key
element was the financial refund to wind turbine owners whose electricity generated by wind turbines entered the electricity network (Ohlhorst et al., 2008).

In 2000, the new Renewable-Energy-Sources-Act (EEG) was put into force, which led in the following years to reduced turbine construction due to adaption in the regulation. Aims were formulated, that 35% of the electricity demand should be met by renewable energy sources by 2020. By 2050, 80% of the energy demand should be met by renewables (IEA, 2012). Furthermore, the EEG regulates a priority in grid connection and electricity supply for renewable energy plants.

In 2014, a new element was added: mandatory direct marketing with market premium, which replaced the fixed reimbursement and should help integrating renewable energy to the market. By directly managing and marketing the electricity the energy plant is generating market premiums and subsidies became possible (IEA, 2015).

Another EEG update in 2017 introduced public tender procedures to introduce a market-orientated price-finding mechanism. In order to be approved, projects have to bid for remuneration in public auction. The announcement of changes in the EEG by 2014 and 2017 led to peaks of wind turbine installation. In 2013 and 2016 wind energy projects applied for approval before regulation changes were put into force, that turbines would be treated and handled also in future according to EEG-status at the time of approval. The commissioning and installations occurred mostly in the following year, which resulted in high installation rate in 2014 and 2017. In the following years, these levels could not be reached.
2.2 Denmark

2.2.1 Status Quo
In order to describe the Danish wind energy sector during recent years, Fig. 5 visualizes new-installed capacities per year offshore and onshore. The diagram begins in 2009 after the wind energy sector started to grow again. The graphs represent the cumulative installed capacities for both onshore and offshore wind energy as well as the totally installed wind capacity. While in 2017 no offshore wind turbines were installed, in 2018 437 MW were commissioned offshore and 220 MW of land-based turbines.

![Fig. 5 Danish wind energy sector development from 2009-2018. Newly commissioned capacities according to the left y-axis, while cumulative and total installed capacities use the right axis (after Wind Denmark, 2018)](image)

2.2.2 History
Besides the USA, Denmark was the first country in the world using wind energy for electricity production (Mez & Meyer, 2008). Poul la Cour created 1891 the first Danish wind turbine (Meyer, 1995) and provided later on commercialized technologies to the Danish wind energy sector (Meyer, 2007). Already in 1908, 72 turbines and by 1931 around 30,000 turbines supplied (rural) areas with electricity (Mez & Meyer, 2008; Tranæs, 1997).

However, governmental and public interest in wind energy decreased over decades, but the debate about introducing nuclear power on a large scale as well as the oil and energy crisis of 1973, lead to the wish of independence from oil and other raw material imports (Tranæs, 1997). In 1985 the Danish parliament decided to plan a future energy supply without nuclear power and renewable energies got back in the center of attention in Denmark (Meyer, 2007).
In 1990 and 1996, new energy policies were decided in order to create more sustainable energy systems, to promote renewable energy production as well as to reduce greenhouse gas emissions (Meyer, 2007). Denmark became the pioneer in wind energy development in Europe with a strong (exporting) wind energy industry with manufacturers, like Siemens, Vestas, and Bonus situated in Denmark (IRENA, 2013).

### 2.2.3 Energy policies

To support the growth of the wind energy sector, the Danish government subsidized the construction and commissioning of new turbines and partly reimbursed the price of the turbines. Therefore, to invest and share wind turbines for their private energy demand, individuals grouped together to local wind cooperatives, which was later rewarded by tax incentives (IRENA, 2013). With increasing economic stability, the subsidies were gradually reduced during the 1980s and extinguished completely in 1989 after total subsidy investments of roughly 280 million Danish Krones (~38 million Euro) and installed rated wind power of 300 MW (Meyer, 2007). Additionally, taxes on oil and coal were put into force to help the wind energy to compete. The globally first wind farm on the ocean (offshore) was operating since 1991 in the Danish sea-site.

In the 1990s, a fixed feed-in tariff was introduced, which decoupled the price for purchasing electricity from prevailing electricity rates and favored electricity production from wind (IRENA, 2013). The social acceptance for wind power was very high because most of the Danish wind turbines were in possession of private citizens and neighborhood cooperatives (Meyer, 2007) and the feed-in-tariff led to a growth of the wind energy sector from 1994 until 2002. Nevertheless, with the switch in the Danish government in 2001 the ending of the fixed-feed-in-tariff was decided and resulted in hardly new commissioned wind turbines and a stagnated wind turbine industry until 2008 (IRENA, 2013). After 2001, the highest contribution to increase the land-based (onshore) installed capacity was by re-powering and replacing existing turbines with wind turbines of greater capacity using the same location, rather than using new sites (Meyer, 2004). The wind energy market started to grow again in 2009 after newly decided European long-term goals promoting energy from renewable sources (Lund et al., 2009; IRENA, 2013).

Until 2020, the National Renewable Energy Action Plan (NREAP) from 2009 determined that 30% of final energy consumption should be generated from renewable energy sources (IEA, 2013).
The Danish Energy Strategy 2050 from 2011 aims to reach by 2050 100% independence from fossil fuel in the Danish energy mix. In order to achieve a energy supply from exclusively renewable energy sources, Denmark expects wind energy to provide 40% of the total electricity demand, with shares of biomass and biogas. This goes along with a growth of the wind manufacturing market as well as increasing capacities of offshore operating wind turbines (IEA & IRENA, 2011).

All in all, research, subsidies and economic support schemes, as well as local involvement and ownership led to a successful integration of wind energy in Denmark since the 1980s (Meyer, 2007).

After giving an overview of the development of the German and Danish wind energy market, it is relevant for the generic aim of this work to evaluate various possible conditions for the future. By doing so, the theoretical recycling potential of REE from wind turbines’ NdFeB-magnets can be estimated for GER and DK. Moreover, of interest is how these countries differ from each other regarding politically set targets, chosen turbine technologies, and the extend of PM in upcoming commissioned wind turbines. Therefore, this work aims to answer the following research question: *How do the German and Danish wind market expansions differ possibly from each other in the future?* (RQ1)
3 Theoretical background

3.1 Construction parts of wind turbines

3.1.1 Wind turbine technologies

The following section should give a brief overview of the technological background of wind turbines, but it will be restricted to the relevant information which is necessary to understand the following chapters and analyses that have been done in this thesis.

Generally, it is possible to classify wind power technologies according to their structural shape, size, or tower concepts (Hennicke & Bodach, 2010). Today, a horizontal axis wind turbine with three blades is most commonly built and which will be considered only while mentioning wind turbines in the following.

During the last decade, the discussion arose whether REE are a limiting factor for the wind energy sector in the future. This implied that wind energy converters are always produced with REE or have a built-in permanent magnet, which is not the case. In fact, permanent-magnet-based generators are an option out of many other available technologies (compare Fig. 6) (Zepf, 2013). A more detailed explanation can be found below.

Beforehand, Fig. 6 shows schematically the composition of the nacelle as the part where the machinery and compartments for energy up-taking and conversion are located. For this thesis, the generator, which can be found in the back of the nacelle, is of greatest interest. Its function is to convert mechanical energy which is derived from the blade rotation to electrical energy (Joselin Herbert et al., 2007).
Fig. 6 Visualizes simplified the composition of a horizontal-axis-type wind turbine (after: Mahmoud & Xia, 2012)

Generally, onshore- and offshore turbines are very similar and vary only slightly from each other with respect to technology and materials. An offshore turbine of the same capacity as a land-based turbine uses mainly more bulk material, like iron, concrete, and gravel for a stronger foundation of the turbine and robustness of the tower (Kleijn & van der Voet, 2010). Critical material requirements are not affected by the turbine’s location since for on- and offshore turbines the same generator concepts are available (Brumme, 2014).

Fig. 7 visualizes a categorization of available wind turbine technologies to identify the different generator concepts that will be of interest later on for the REE flows and stock analysis.

Only wind turbines were considered that are feeding electricity into the grid. Wind turbines today are mostly driven by aerodynamic lift due to better efficiency (Ackermann & Söder, 2002; Brumme, 2014). The next distinction was made according to the orientation of the spin axis, of which the horizontal-axis-type the today’s commonly produced turbine represents (Hau, 2008). Generally, wind turbines are designed for greatest efficiency at certain ranges of wind speeds or even one specific wind speed. Therefore, they have to be slowed down by the limiting process, called power control, in case of too fast wind speed in order to prevent efficiency losses and damages. Depending on the power control technique that is used, the generator is chosen accordingly (Brumme, 2014).

Doubly-fed induction generators (DFIG) can handle different rotational speed in combination with a gearbox. It is robust, available at relatively low costs, and the generator can be
lighter and smaller compared to the synchronous generator. Therefore, DFIG are used quite often (Brumme, 2014) with mostly around 30% of new-installed onshore turbines in Germany between 2010 and today (Fraunhofer IEE, 2018b).

As well as DFIG, also synchronous generators could handle variable rotational speed and made a gearbox optional and direct-drive turbines possible. The synchronous generators have greater complexity and are more costly whereas they make it possible to offer good efficiencies at different wind speeds due to their variable rotational speed (Ackermann & Söder, 2002; Brumme, 2014). In order to create a magnetic field, synchronous generators can be either permanently - or separately excited. While a separately excited magnetic field often works with an electromagnet, the permanent excitation uses a permanent magnet, today mostly made out of neodymium-iron-boron (NdFeB-magnet) (Hau, 2008). The advantages of using these permanent magnets are weight reductions, high efficiency, less required maintenance, and no need for external power supply. However, the materials for NdFeB-magnets, especially the built-in REE, Nd and Dy, are expensive and considered as critical raw materials for Europe. Nevertheless, separately or electrically excited generators have exactly the oppositional advantages and disadvantages (Hau, 2008; Brumme, 2014).

Permanent generators offer yield advantages and better efficiencies at various wind speeds compared to DFIG (Kurronen et al., 2010) (see Appendix 1). By now in Europe, mostly permanently excited direct-drive turbines are commissioned (Glöser-Chahoud et al., 2016).

![Diagram of wind turbine technologies](image)

**Fig. 7** Schematic categorization of available wind turbine technologies (after Brumme, 2014; Ackermann & Söder, 2002)
3.1.2 Permanent magnets

Permanent magnets are one of the major applications for REE, especially samarium, neodymium, terbium and dysprosium. Of the global REE production in 2010, roughly 20% were used for permanent magnets (Humphries, 2013).

The historical and technological development of rare-earth-magnets started in the 1960s with the invention of samarium-cobalt (SmCo) magnets which replaced the conventional aluminum-nickel-cobalt (AlNiCo) magnets (Gutfleisch et al., 2011). AlNiCo-magnets have a significantly lower magnetic strength and are therefore not equally good as permanent magnets. However, SmCo-magnets need samarium, a rare earth element, which is only available in very little quantities and is therefore connected to higher prices and not suitable for large-scale application (Glöser-Chahoud et al., 2016).

In the 1980s, neodymium-iron-boron (NdFeB) magnets were invented as the strongest permanent magnets available until today (ERECON, 2014) and got commercialized to minimize the reliance on cobalt, to reduce weights and improve fuel efficiencies. Besides their superior magnetic strength, coercive force properties and a very high induction, NdFeB-magnets have the best strength–to–weight ratio and led to size and weight reductions and fuel efficiency improvements in the industry (Ciacci et al., 2019). NdFeB-magnets, find application in different electronic products, like in hard-disk-drives (HDD) or speakers as well as in electric vehicles or in wind turbines (Zepf, 2013).

In comparison to conventional magnets used for the same application, permanent magnets are lighter and made the development of larger and lighter wind turbines possible with increasing efficiency, better reliability and, therefore, fewer maintenance efforts.

Because NdFeB magnets are of greater relevance than SmCo-magnets, only NdFeB-magnets will be considered as permanent magnets in the following.

Generally, no differences between onshore and offshore permanently-excited turbines exist with respect to the built-in PM. However, the NdFeB-magnets can vary in size and strength according to the turbine technology they are applied in. A direct-drive (DD) turbine, for example, requires a PM of 650 kg/MW because the magnet is located directly behind the rotor blades and has to be bigger compared to PM in permanently-excited synchronous generator (SG-PM) turbines. Furthermore, to achieve best efficiencies with various wind speeds, the turbine has to rotate accordingly fast, so that, amongst others, synchronous generators with a high-speed gear or middle-speed gear can be differentiated. Respectively, simplified PM-weights can be found in Tab. 1 (after Wuppertal Institut, 2014).
Tab. 1 Average weights of permanent magnets for different wind turbines technologies (after Wuppertal Institut, 2014)

<table>
<thead>
<tr>
<th>Generator class</th>
<th>PM weight [kg/MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gearless (DD)</td>
<td>650</td>
</tr>
<tr>
<td>Middle-speed gear</td>
<td>160</td>
</tr>
<tr>
<td>High-speed gear</td>
<td>80</td>
</tr>
</tbody>
</table>

*Note: DD = direct drive.*

Generally, NdFeB-magnets consist of roughly 67% iron, 1% boron and 32% of a total REE amount (Elwert et al., 2017). Permanent magnets for wind turbine application contain besides Nd also low but important amounts of other REE, like dysprosium (Dy), praseodymium (Pr), and terbium (Tb). In Tab.2, the composition and shares of the compounds can be found.

Dy is added to achieve a better stability of the magnet at high temperatures, but because Dy is a HREE it is not as available as the LREE Nd and Pr and is much more expensive (DERA, 2018). Additionally, praseodymium (Pr) can work as Nd-substitute up to a certain percentage to lower the neodymium content while still achieving comparable properties of the magnet (Elwert et al., 2017). Nevertheless, the more Pr is used, the greater are the losses in quality.

Moreover, terbium (Tb) might be present to a very little extend to preserve the magnetic strength at high temperature, just like Dy, but is rarely applied due to its high price (Janssen et al., 2012; Elwert et al., 2017).

Tab. 2: Shares of elements in permanent magnets used in wind turbines (after: Wuppertal Institut, 2014)

<table>
<thead>
<tr>
<th></th>
<th>Nd</th>
<th>Dy</th>
<th>Fe</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>[%]</td>
<td>31</td>
<td>2.3</td>
<td>65.7</td>
<td>1</td>
</tr>
</tbody>
</table>

3.2 Metal supply for wind technology

In order to construct the wind turbines and permanent magnets, resources and raw materials are needed.

They can be subcategorized in abiotic and biotic resources, where biotic raw materials “are materials which are derived from renewable biological resources that are of organic origin but not of fossil origin” (European Commission, 2014). As abiotic raw materials, metallic ores or metals as well as industrial minerals are considered (European Commission, 2014).
3.2.1 Concept of criticality

All countries around the world depend on resources. Raw materials are elementary for economies, employment, and growth. Criticality analyses are conducted to identify future demand, supply, appropriate actions, and raw material policies to secure these materials in the future. In order to secure the needed resources and to keep the European GDP high, the European Commission (EC) launched in 2008 the Raw Material Initiative. In 2010, the first list of identified critical metals was published which was extended in 2014 and 2017 of several raw materials (European Commission, 2014). For the EU, raw materials are considered to be critical when they are of high economic importance but underlie a certain supply risk. One of the biggest impacts on the supply risk is considered to be the primary supply from countries with poor governance since this can lead to supply interruptions due to political instability and unrests. The supply risk gets lower the better secondary resources and full substitution options are available according to price and functionality (European Commission, 2014). It has to be kept in mind, that several approaches are available to analyze the criticality and the results of various studies can differ due to the country of study, its economy and required imports. Habib & Wenzel (2016) were criticizing, for instance, static supply risk calculations that are often used but which does not consider changes in geological reserve estimates and – locations over time.

REE are on the European criticality list since they are becoming increasingly important for Europe while the primary production is concentrated mainly in China which showed its position on the REE-market by export restrictions in 2010. Although there are many countries providing important shares of EU’s critical raw materials (CRM), China is the principal supplier of CRM, especially of REE (Alves Dias et al., 2018) (compare Fig. 8).
3.2.2 Rare Earth Elements

The rare earth elements (REE), also called rare earth metals (REM) or rare earths (RE), are according to the International Union of Pure and Applied Chemistry (IUPAC), a group of 17 elements, consisting of 15 so-called lanthanoids as well as the elements scandium and yttrium (Zepf, 2013).

Rare earths are usually distinguished as either light rare earth elements (LREE) or heavy rare earth elements (HREE). This grouping is variously defined by several authors using different approaches. The U.S. Geological Survey defines this classification of REE as division according to the elements’ electron shell configuration. Therefore, the elements from lanthanum (La) to gadolinium (Gd) are forming the LREE, whereas elements in the periodic table from terbium to lutetium are considered as the HREE (Cordier, 2009).

For this thesis, the rare earth elements neodymium (Nd), dysprosium (Dy), terbium (Tb) and praseodymium (Pr) are in the focus due to their usage in permanent magnets for wind turbines. Nd and Pr are LREE, while Dy and Tb are HREE. HREE are considered as the most critical REE due to their high economic importance but greater scarcity compared to LREE (Wall, 2013).

The long history of discovering the rare earths started with Arrhenius in 1787 in Ytterby, Sweden.
The word ‘earth’ was used as a common denomination in the 19th century to reference oxidic materials, often metal oxides, for instance, for an element compound with oxygen (Zepf, 2013).

The term “rare” is explained differently by several authors. While Klinger (2015) described it by the former belief that the discovered elements can only by sourced in Ytterby, Reiners (2001) suggested that ‘rare’ was used in the late 15th century onwards to describe “strange, extraordinary, astonishing” things (Zepf, 2013).

It is import to underline the great variety of diversity and at the same time similarity of rare earth elements. While, for instance, similar densities can cause problems during separation steps, the similar atomic structures and states can result in very unique behavior. Therefore, REE are useful for a broad range of applications. As an example, REE like Dy, Nd, Gd, Er, and Sm show beneficial properties for magnet production (Zepf, 2013) (compare Fig. 9).

**Fig. 9** Development of rare earth element applications over time (from Zepf, 2013)
A few years ago, around 270 minerals were known to contain REE in their chemical formula and crystal structure.

They occur in silicates, carbonates, oxides, phosphates, and oxysalts, as well as in sulfates. Furthermore, REE are hosted by so-called ion-adsorption clays (Chakhmouradian & Wall, 2012). Accordingly, to the high REE-containing number of minerals, different geological processes and ages can lead to RE concentrations in minerals. Nevertheless, despite the cast number of REE-bearing minerals, it is difficult to find minable grades (USGS, 2018) and extracting and processing steps of REE deposits have to be adapted to each deposit. Great natural REE deposits could be found in the U.S., Brazil, and Australia.

There are several tables and analyses available to describe the rare earth elements’ abundance in the Earth’s crust. Due to variable approaches, geographical sample areas, and assumptions, no uniform abundance list can be shown Zepf (2013).

Another issue worth mentioning is the ‘balance problem’ in REE minerals and production. Rare earth elements occur in variable ratios in ores and mineral, which reflect the natural abundance of the elements (Binnemans et al., 2013). Global REE ores are dominated by LREE compared to HREE, with a predominant average ratio of light rare earth element oxides to heavy rare earth element oxides of 13:1 (compare also Fig. 10). HREE are considered as the most critical REE due to their economic importance and upcoming increasing demand in the future. At the same time, HREE are of greater scarcity compared to LREE (Wall, 2013) and REE mines might oversupply LREE, while not meeting the demand for certain needed HREE (Weng & Mudd, 2017).
Fig. 10 Reported data and average estimates for REE resources [kt] for each rare earth element (from Weng et al., 2015).

From 1980 on, China became the dominant producer REE with roughly 50 % of globally proven REE reserves (Wall, 2013), provided 2017 about 80 % of the world’s REE production (Reichl & Schatz, 2019) and has the unique position to operate the whole production chain from the ore to separated REE metals (Elwert et al., 2017).

What are the factors that are holding back a non-Chinese primary production of REE? Although there are REE deposits, like in Norra Kärr (Sweden) or Kvanefjeld (Greenland), potentially worth mining, there are other problems. China has great expertise to separate the very similar elements compared to Europe. Furthermore, the REE-market was instable with prices fluctuating, so that investments and mining ventures were not feasible from time to time. Moreover, REE deposits often contain thorium and uranium which can cause the generation of radioactive waste during extraction and processing. Treating these wastes can cause problems and fulfilling European standards can lead to higher costs and make the prices potentially uncompetitive. The last major aspect is the social negative ‘Not-in-my-backyard’ (NIMBY) attitude towards mining, as it was the case in Norra Kärr, Sweden.
3.2.3 Secondary raw materials' supply potentials

According to their winning and production process, materials can be distinguished between primary – and secondary resources. Primary resources are extracted from ore deposits, whereas secondary materials have (non-) mineral-based wastes as an extraction source (Ladenberger et al., 2018).

Due to the growing demand for resources, the increasing exploitation and decreasing ore grades, combined with the environmental and legislative regulations for mining activities, it becomes necessary to start implementing a more sustainable economy. One approach is the circular economy, which focuses on keeping the value of materials and products for as long as possible in the economy by re-using and recycling products and materials (European Commission, 2015). However, there is no uniform definition available yet.

Generally, identifying the potential secondary sources, estimating the present and upcoming stocks as well as recovery and recycling techniques, are key components for a more sustainable material handling. Moreover, the dynamics of material stocks, their dependency on geographic location, and life spans of the goods have to be considered (Müller et al., 2007).

Besides the ambition to close the loop, using secondary REE-sources could also support more independence of Europe from ERR-imports and could help to tackle the balance problem which is caused by the fact of different abundances of REE in ore deposits as well as unequal demand for single rare earths. However, due to financial and economic purposes shortages and oversupplies should be minimized by keeping supply and demand of single REE equal. Since this cannot be achieved via primary production, REE-recovery and recycling could be beneficial from this perspective and, additionally, no radioactive wastes occur and REE-concentrates would be less complex (Binnemans et al., 2013).
3.2.4 Urban mining and the anthropogenic stock

After the extraction from the Earth’s crust or their natural environment, raw materials remain in the anthroposphere. This can be described as the human environment where daily life happens as well as technical and biological processes (Baccini & Bader, 1996; Müller & Lehmann, 2017).

Most metal- and mineral-based materials and products that do not serve as energy source remain for years or decades in the anthroposphere, leading to a continuous growth of the anthropogenic stock (Gerst & Graedel, 2008) which is estimated to contain globally equal amounts of natural resources as still present in Earth’s crust deposits (Nakamura & Halada, 2015).

Since not every country is able to mine and produce primary resources required for the economy by itself and raw material supply chains are transnational in today's globalized economy, economic dependencies are the result. This dependency could be reduced by identifying already imported natural resources that are stored in a country’s anthropogenic stock, trying to recover these materials and to make use of them again. Moreover, reusing resources could eventually lead to less environmental impacts.

Goods that are considered as waste or are at the end of their service-lifetime are either upgraded and reused or compositional materials are extracted by recycling techniques. With respect to REE, the recycling of secondary resources can be differentiated between (I) the direct recycling using REE scrap and residues from pre-consumer manufacturing (Jones et al., 2011), (II) urban mining of End-of-Life (EoL) products with mostly a complex material-mixture (Schüler et al., 2011), (III) landfill mining using industrial and urban REE–containing waste residues (Jones et al., 2013).

Although, urban mining is getting (politically) more attention and acceptance, there are still challenges to be overcome, which are “substance and product diversity, rapid technology cycles, international trade flows, dissipation contamination and downcycling in processing and usage” (Müller et al., 2016).

All in all, sourcing REE via urban mining from the anthropogenic stock, especially from permanent magnets used in wind turbines, is an important tool to potentially meet the future demand for certain REE, like Nd and Dy.
3.2.4.1 German and Danish demand and stock

In 2014, global NdFeB-magnet production were 127,000 tons with 88 % (112,000 tons) coming from China (ReportLinker, 2018; Müller, 2019). Germany imported 2015 9,371 tons PM (UN Comtrade, 2019), however, no differentiation between various kinds of permanent magnets is possible. Nevertheless, Müller (2019) estimated that 8,000 tons of imported permanent magnets were NdFeB-magnets. However, these amounts cannot be considered to be available for a future circular economy due to the export of goods containing the imported PM-material (Müller, 2019). Reimer et al. (2018) identified for Germany a PM-usage and final amount remaining in Germany, after excluding exports, of 1,570 tons and a stock of NdFeB-magnets in 2015 of roughly 10,500 tons (Müller, 2019).

For the case of Europe, Ciacci et al. (2019) analyzed in their work a cumulative Nd in-use stock for Europe of roughly 14,300 t Nd and an average of about 28 g Nd per capita. For Denmark and the Netherlands, a higher in-use stock per capita could be identified possibly due to great installed wind power capacities in both countries, which covers in DK roughly 40% of the country’s electricity demand. In 2012, roughly 1 % (~283 t Nd) of global Nd primary production was imported to DK, either as magnets or magnet alloy, for further production of end-use goods, like wind turbines, or as final products including NdFeB-magnets, like electric equipment. The wind energy market used 46 % of the imported Nd in 2012, of which 80% was applied in prototypes and testing turbines, 11 % have been exported as manufactured wind turbines, and 9 % were installed in wind turbines connected to the Danish electricity grid. Therefore, after excluding, for example, exports, the in-use stock of Nd from PM was in 2012 1424 t in DK, with 38 % (~541 t) used in the wind energy sector (Habib et al., 2014). In Danish waste flows in 2012, roughly 3 t, mostly of electrical equipment, could be identified. For dysprosium, an import of about 17.34 t (representing 1 % of global primary production) was estimated as well as a total in-use stock of 97 t, with 38 % (~37 t) that have been installed in wind turbines. In 2012, 1.95 t Dy were exported in products and left the Danish system, and only 0.21 t Dy were recognized in the Danish waste streams, mostly due to IT-applications.

All in all, Nd and Dy recognized in waste flows are low compared to imported amounts. This is mainly due to long service-lifetimes of products of 12 to 25 years. It can be stated, that neither Nd nor Dy was recovered to any extend in 2012 because of too various sizes, compositions and applications of PM. Furthermore, the non-existence of a commercial-scale tech-
nology to recover the REE leads to the fact that these critical materials are in the end not more than impurities in the Danish waste system while extracting other (Habib et al., 2014).

The highest REE recovery potential from NdFeB-magnets in DK in 2012 could be identified to be 3 t Nd and 0.2 t Dy, being equivalent amounts of Nd and Dy as in five 3 MW direct-drive turbines (Habib et al., 2014).

Besides calculation for the year 2012, Habib et al. (2014) made estimations until 2035 for the Nd and Dy demand and flows in Denmark. For 2035, both element imports are expected to be three times higher than in 2012, with roughly 943 t Nd and more than 52 t Dy. The greatest growth rate could be identified for the wind energy sector impacting the REE-demand.

Based on the previously given information it can be concluded that PM in wind turbines are an important application and, similarly, offer a potential secondary source for the REE. In this regard, this work deals with the following research questions:

Is it possible that rare earth elements recovered from PM-recycling can help to meet the future demand of rare earths and magnetic material, using NdFeB-magnets from wind turbines as an example? (RQ2.1)

If RQ2.1 applies, to which extent could the upcoming secondary rare earth material be integrated in future supplies? (RQ2.2)

In the following sub-chapter of the theoretical background the focus lies on the barriers that hinder currently a REE-recovery and recycling in Europe.

3.2.5 Problems in REE recovery and recycling

Since there is no mining and refining of rare earths in Denmark, Germany or elsewhere in Europe, the recovery of REE from secondary sources could reduce the dependence on imports and could help to tackle the balance problem of rare earths (Binnemans et al., 2013). However, so far no recovery or recycling of rare earths is happening in Europe, although there are REE amounts in the German and Danish waste streams, as stated above, that could potentially be recovered. Generally, it has to be mentioned that the great variety of PM-applications lead to extremely varying sizes of the magnets and different alloys and elements are added to the (surrounding of the) magnet in order to achieve the required properties for the various products. Therefore, a unique recycling strategy for all NdFeB-magnets becomes nearly impossi-
ble. Moreover, there are several other reasons that hinder a REE recycling in Europe, as stated in the following.

The first step and equally the first problem in the recycling chain of these magnets is to identify upcoming EoL-PM-material, which would require information about quantity and quality of up-coming REE-containing EoL- or waste material, e.g. from small electronic goods in households or from wind turbines (Graedel et al., 2011; Lixandru et al., 2017). Moreover, information about the secondary market and sales of already used wind turbines from Germany to other countries should be collected to know the amounts of exported PM-material, and eventually establish a collection of these magnets from other (European) countries, too. The next step is to manage the collection and logistics. When decommissioning a wind turbine, it has to be decided whether the extraction of the magnet should occur directly at the wind turbine site with demagnetization at the site, too, due to transportation problems of these strong magnets, or if the whole nacelle or separated magnet can be transported to a facility for appropriate treatment. Compared to other electronic equipment that uses a build-in PM of smaller sizes, the advantage of NdFeB-magnets from wind turbines is their compact great size with relatively high REE-contents. It seems more efficient to recover these resources than those of thousand computers and phones (Habib et al., 2014). Elwert et al. (2017) found out that there is currently some extraction of PM from various applications and partly some collection of post-production wastes in Europe. The calculated amount of currently around 150 t is then leaving Europe and is exported to China and Japan for recycling purposes. This is due to the fact, that there is no primary production and refining in Europe and appropriate treatment plants are not available in Europe that could be used for REE-recycling, although in theory and on lab-scale very different recycling technologies are available. So far, the estimated amounts of REE from EoL-applications were considered to be too less for implementing a recovery and recycling infrastructure with appropriate expertise and machinery in Germany and Denmark. Additionally, secondary REE-production has to compete with the primary production quality- and financial-wise. According to this, Elwert et al. (2017) found out that the low traded amounts of REE-containing PM, compared to the higher theoretical potential, indicate the rarely economic feasibility of the whole REE-recycling chain. This depends, for instance, on the market prices for Nd and Dy and the price for REE-containing scrap material.
Due to the scope of this thesis, there will be no detailed explanation of recycling methodologies and technologies that are currently known. However, it should be mentioned shortly that the possibility exists to directly reuse the PM. It can be a cost-effective method to recycling NdFeB-magnets and is known to be feasible especially for large magnets, like present in wind turbines or electric vehicle motors (EVM). With this process, energy-intensive production steps for completely new magnets could be avoided (Högberg et al., 2016). Due to the fact, that PM in wind turbines and EVM are in-use for a long time and are currently not available, a planning and collection of information would be necessary to be able to use this source later on. Furthermore, these applications are of increasing importance which could influence the economic feasibility of recovery techniques as well.

It can be concluded that even with new results from research no tremendous progress and development in the PM-recycling and REE-recovery in Europe can be expected in the next years due to many impacting factors. For further details on technical possibilities of recovery and refining REE from NdFeB-magnets, for example, the research projects MORE and SEMAREC can be mentioned.
4 Methodology

On the following pages, the methodical approach of this work is clarified. In this regard, the basics behind modeling a future scenario as well as the way how wind turbines’ life expectancy was considered by using the Weibull-distribution are explained. Moreover, the computer program, Umberto, and the information system, DyMAS, used for calculating and modeling purposes, will be described. Furthermore the assumptions made for the forecast scenarios and the used data for these are addressed in detail.

Because of the explorative proceeding of the present work a method that functions likewise explorative had to be chosen. Thus, to answer the research questions a case study was conducted. In doing so, the theoretical recycling potential of NdFeB-magnets from wind turbines should be estimated. In this regard, Germany and Denmark were chosen to be compared for following reasons. Both countries were analyzed separately. While Germany has the biggest share of wind turbines in Europe and probably will rely more heavily on wind energy in the future, Denmark is the pioneer in wind energy since the 1970s and already had the second-highest number of installed wind turbines possessing a lot of experience in this sector in 1995. Thus, both countries were found to be appropriate cases for the present study. According to literature and German approval regulations, wind turbines have a service-lifetime of roughly 20 years. In order to consider the long lifetimes of wind turbines and to be able to make estimations on a appropriate time horizon, the timeframe of analysis was set started in 2000 until 2050.

To be able to estimate and to compare the German and Danish stock of neodymium and dysprosium as well as the NdFeB-material in the future, scenarios were used, which are described more in detail in the following. For the modeling and estimating to create the mentioned scenarios, the PC program Umberto® and the information system DyMAS (Dynamic Modeling of Anthropogenic Stocks) were used (see chapter 4.3). In the end, the collected and created data were analyzed with Microsoft Excel® with the help of Pivot charts and -diagrams.

4.1 Assumptions for analysis

In order to set up the future scenarios, some assumptions were made for simplicity reasons, which are described in the following. Firstly, it was assumed that there will be no significant changes of the population size in GER and DK until the end of the forecast, so that society and industry would require comparable energy demands like today. In general, despite the fact
that research and technology will progress, for example, regarding new sources of energy production or existing turbine technologies, these developments were not considered in this work. The currently existing wind turbine concepts were assumed to be the best choices available on the market until 2050.

As stated in chapter 3.1.2, no differences between onshore and offshore permanently-excited turbines exist with respect to the built-in PM in general. However, the NdFeB-magnet can vary in size and weight according to the turbine concept they are applied in (Tab. 1, chapter 3.1.2). Janssen et al. (2012) and the Wuppertal Institut (2014) estimated for the future, that the greatest share of new-build wind turbines offshore will be asynchronous generators followed by permanently excited middle-speed turbines. Moreover, in comparison to other permanently excited turbines, high-speed wind turbines were assumed to have the greatest share onshore from today until 2050 (Wuppertal Institut, 2014). For simplifying reasons, 160 kg/MW PM-material were used for calculations and modeling purposes while considering offshore turbines with a permanent magnet as well as 80 kg/MW for onshore turbines (see Tab. 3).

**Tab. 3** PM-weights in kg/MW that were chosen according to estimations for onshore and offshore operating turbine concepts in the future

<table>
<thead>
<tr>
<th></th>
<th>Onshore DD-PM</th>
<th>Onshore SG-PM</th>
<th>Offshore DD-PM</th>
<th>Offshore SG-PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>[kg/MW]</td>
<td>650</td>
<td>80</td>
<td>650</td>
<td>160</td>
</tr>
</tbody>
</table>

*Note. DD = direct drive, SG = synchronous generator.*

Moreover, due to the fact that researchers and the industry aim to reduce the size, weight and content of critical raw materials of permanent magnets for efficiency and economic purposes, these developments have to be considered for further analyses. Therefore, the assumption was made that the magnet size will continuously be reduced from 2030 on (compare Tab. 4).
Tab. 4 Development of PM-weights over time in kg/MW

<table>
<thead>
<tr>
<th>Generator class</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
<th>2035</th>
<th>2040</th>
<th>2045</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gearless (DD)</td>
<td>650</td>
<td>650</td>
<td>644</td>
<td>612</td>
<td>582</td>
<td>553</td>
<td>526</td>
</tr>
<tr>
<td>Middle-speed gear</td>
<td>160</td>
<td>160</td>
<td>158</td>
<td>75</td>
<td>72</td>
<td>68</td>
<td>65</td>
</tr>
<tr>
<td>High-speed gear</td>
<td>80</td>
<td>80</td>
<td>79</td>
<td>151</td>
<td>143</td>
<td>136</td>
<td>130</td>
</tr>
</tbody>
</table>

Note. DD = direct drive.

Furthermore, estimations regarding the magnet compounds were made. Firstly, simplified NdFeB-magnet compositions were taken into consideration for calculation and modeling purposes, focusing on Nd and Dy as rare earth elements. In contrast to this, Pr and Tb are minor constituents of PM and are already considered as substitutes for Nd and Dy. Additionally, they are mixed to very variably extend to the magnet. For that reason, Tb and Pr were not considered in the analysis. Secondly, the Wuppertal Institut (2014) compared several studies on permanent magnet compounds and calculated the currently available average composition of PM as shown in Tab. 5 (today). It was assumed that Nd and Dy contents in PM will reduce after 2030. Oriented on the Wuppertal Institut report (2014), REE-reductions in PM were calculated until 2040, while considering the magnet size to be constant over time. Respectively, the iron contents were assumed to increase, accordingly, to achieve the constant PM-weight of 650, 160, or 80 kg/MW, as stated above. The percentages and shares of single elements as constituents of PM were then applied to the different PM-weights per turbine concept. As an example, it was assumed that a PM contains 25% Nd in 2030. Considering a DD-PM onshore turbine, which requires a NdFeB-magnet-weight of 650 kg/MW, the 25% Nd result in 162.5 kg Nd in this kind of wind turbine (compare Tab. 5).
Tab. 5 Development of REE-shares in permanent magnets applied in wind turbines (oriented on Wuppertal Institut, 2014)

<table>
<thead>
<tr>
<th></th>
<th>today [kg/MW]</th>
<th>2030 [kg/MW]</th>
<th>2040 [kg/MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>Onshore DD-PM</td>
<td>Onshore SG-PM</td>
</tr>
<tr>
<td>Nd</td>
<td>31</td>
<td>201.5</td>
<td>24.8</td>
</tr>
<tr>
<td>Dy</td>
<td>2.3</td>
<td>14.95</td>
<td>1.84</td>
</tr>
<tr>
<td>Fe</td>
<td>65.7</td>
<td>427.05</td>
<td>52.56</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>6.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Nd</td>
<td>25</td>
<td>162.5</td>
<td>20</td>
</tr>
<tr>
<td>Dy</td>
<td>1.8</td>
<td>11.7</td>
<td>1.44</td>
</tr>
<tr>
<td>Fe</td>
<td>72.2</td>
<td>469.3</td>
<td>57.76</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>6.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Nd</td>
<td>20</td>
<td>130</td>
<td>16</td>
</tr>
<tr>
<td>Dy</td>
<td>1.8</td>
<td>11.7</td>
<td>1.44</td>
</tr>
<tr>
<td>Fe</td>
<td>77.4</td>
<td>503.1</td>
<td>61.92</td>
</tr>
<tr>
<td>B</td>
<td>0.8</td>
<td>5.2</td>
<td>0.64</td>
</tr>
</tbody>
</table>

Note: DD = direct drive, SG = synchronous generator.

After giving the required background information for the made assumptions in this work, the next chapter introduces the probability distribution used to statistically model and include the life spans of the wind turbines in the forecast scenarios.
4.2 Weibull distribution

Although new commissioned turbines get approval for 20 years of service-lifetime in Germany and most research use this age as life expectancy for wind turbines, for this work a different approach was used. Due to the steady progress in wind turbine technology, for instance regarding efficiency, capacity, and turbine height, many turbines do not reach the age of 20. Instead, they are often deconstructed beforehand, so that the wind turbine location can be used for a new and better turbine, which replaces the old turbine. This process is called repowering. According to that, the Weibull-distribution was applied for the following calculations to represent the life spans of wind turbines, in order to make a more realistic age distribution of turbines possible.

The Weibull-parameter $\lambda$, as scale parameter, makes it possible to stretch or squeeze the distribution function. It describes the rate of failure and loss being calculated as one, divided by the characteristic life span. The shape parameter, k or $\alpha$, allows to vary the shape of the distribution (NIST/SEMATECH, 2013). In Fig. 1, two different Weibull-distribution functions are visualized, both times with a maximum loss rate after 18 years (Fig. 1 a) and b): $\lambda = 18$). With respect to the example of wind turbines ages, Fig. 11 a) uses, additionally, the Weibull-parameter $k = 9$, which represents a flatter (black) curve and, therefore, a wider range of EoL-ages at which turbines are decommissioned. In diagram b) $k = 18$ and describes that EoL-turbines have a higher probability, compared to a) $k=9$, to be around 18 years old at the time of decommissioning. While looking at the black graph, which can be found in both diagrams a) and b), the first decommissioning-rates of wind turbines are represented in the beginning. The peak, however, shows the age at which turbines are deconstructed with the highest probability. The decommissioning time is influenced by production failures and technological breakdowns. Over time, more turbines are deconstructed for repowering purposes, whereas the rest of the turbines last until the end of approval time. With respect to the present work, the Weibull-distribution and -parameters aimed to smooth the capacity and material outflows from the anthropogenic stock. This means, that a commissioned capacity is not exactly decommissioned, for example, 18 years later, but rather a more realistic decommissioning rate before and after these 18 years due to technical failures or repowering projects can be achieved.
4.3 Dynamic Modeling of Anthropogenic Stocks (DyMAS)

In order to estimate the NdFeB-magnet-material as well as Nd and Dy contents from wind turbines in the anthropogenic stock, the computer program Umberto and the information system DyMAS were used. DyMAS (Dynamic Modelling of Anthropogenic Stocks) is the result of a project named KartAL II conducted by the German Environment Agency (compare Hedemann et al., 2017). The dynamic calculation model makes it possible to analyze the anthropogenic stock of a country according to the information that is implemented in the knowledge base. The knowledge base is a database where stocks and flows of long-lasting goods and their components are described. It includes both master data and variable data, which are described separately. Master data characterize goods and materials by units, properties and hierarchies. For the creation of materials’ and goods’ hierarchies, product and industrial classifications are used (Hedemann et al., 2017). With this information, stock-related material and good categories are determined. On the other hand, variable data include information about flows and stocks of chosen goods and their respective material compounds. Moreover, variable data need a specific point in time as a reference. The main goal of most analyses is the estimation of future developments of secondary raw material which is build-in in durable goods. One way to estimate those developments is the creation of material flow networks. Such networks aim for flexible and transparent modeling while illustrating material transformations as well as places that link hold stocks and link processes. In Fig. 12, the calculation model as a material flow network is schematically visualized, using the standard software Umberto. Functional parameters are shown in green, while the rest are mass flows.
The black frame represents the scope of this thesis. That means, that exports, recovery processes and production were not in the scope of this thesis and were, therefore, not modeled. P1, for instance, is used to describe the anthropogenic stock by considering the central goods store as well as the synthesis processes, the connected analysis and the removal of goods at their EoL. The goods store holds information about the material stock accumulated in the anthropogenic stock. Furthermore, the synthesis and analysis processes use the in- and output flows from the central goods store to calculate material flows.

Based on the properties of the stocks, the end of service-lifetime is calculated for the goods and outgoing flows are generated by the program. The web interface of the DyMAS-system is the connection between the calculation model and the knowledge base. The required information can be imported to Umberto as calculation model and future forecasts for materials’ and goods’ flows and stocks can be calculated, including the removal of stock at EoL-spans of goods. For the analysis of the results, Sankey-diagrams can be used directly or exports of the raw data can be generated and analyzed via Microsoft’s Excel (Hedemann et al., 2017). All in all, DyMAS makes it possible to differentiate on a product – and a material level and at the same time allows the connection and dependence of materials and goods. Therefore, DyMAS can be used as estimation and projections tool for urban mining possibilities (Müller et al., 2016). The made estimations in form of modeled future scenarios are described in detail in the next chapter.
4.4 Building explorative scenarios for the future

In order to get information of possible stocks and flows of NdFeB-magnets and build-in Nd and Dy contents, the present work made future estimations about the wind energy sector and its installed capacities in the upcoming years and decades in Germany and Denmark. For the creation of the forecast scenarios, existing scenarios, conducted by research institutes or energy agencies, were partly used. The generated scenarios differ, for example, regarding the expansion of wind turbine concepts in onshore and offshore locations. Moreover, the growth of the installed capacities per country as well as NdFeB-magnet-weight and -composition were considered.

Due to the fact that Germany and Denmark do not have explicitly formulated and politically set goals for the energy-producing sector for the next decades, it was necessary to rely on existing methods, techniques and data to make predictions, as realistic as possible, for the future. For that reason, trend analyses for shorter timeframes as well as scenario analysis for longer timeframes were applied in this work. The scenario analysis is a tool of futurology research to consider and compare possible variations in the development of a specific object of investigation (Kosow & Gaßner, 2008a), such as the wind turbine market. Explorative sce-
narios as chosen for this study depict possible future outcomes without necessarily giving them any probability.

Many authors define a scenario as a representation of a possible future situation including the steps of development leading to this situation (Kosow & Gaßner, 2008a). It is important to mention that scenarios are not capable to predict, but rather to explore possible future situations. Therefore, most relevant “is not what will happen but what might happen and how people could act to encourage or counteract particular events and trends” (UNEP, 2002). Keeping this in mind the following applies to the construction of scenarios: the more time passes from today \(t_0\) to a specific point in the future \(t_s\), the more possibilities can emerge and, therefore, influence the future situation or the development of an object of investigation. Thus, with a bigger time interval, the number of possible development scenarios increases. Fig. 13 visualizes this idea of a scenario construction. It is shown, that similar developments \((a_1, b_1, c_1\) vs. \(a_2, b_2, c_2)\) can be summarized to various scenarios, marked here as \(S1\) and \(S2\), making distinctions possible (Kosow & Gaßner, 2008b).

![Fig. 13 The scenario funnel, \(t= time\) (after Kosow & Gaßner, 2008b; von Reibnitz, 1992)](image)

Turning now to the created future scenarios, the used political goals for the wind energy sector per country and the made assumptions are described in the following. For both countries and the different forecast scenarios, a gross new-build capacity per year was mostly not available at politically set goals or other reports, so that estimations for future wind energy capacities had to be done. Besides the gross new-build capacity it was necessary to assume how the available turbine technologies and their shares in the wind energy market will develop over time.
Based on a current trend and interviews with colleagues from the German Environment Agency, it seems that new-installed onshore turbines will be steadily using less turbine concepts with a permanent magnet in the future. This stems from the fact, that the REE market and its prices can change quickly and a future stable supply might not be guaranteed. Onshore turbines are, furthermore, more easily accessible for maintenance and repairing purposes, although turbines using a PM would still operate with better efficiencies. On the other hand, new-commissioned offshore turbines are assumed to focus continuously more on turbine technologies with a PM due to harsh conditions on the sea which make a robust turbine necessary. Moreover, the turbine needs to be reliable because it cannot be accessed and repaired anytime, due to weather changes and great waves for workers’ safety reasons, and high efficiencies are required to make use of the strong wind. Both described assumptions are represented in the estimated shares of turbine concepts applied in each scenario for GER and DK, mentioned below as ‘Mix’.

For Germany, both onshore and offshore turbines were differentiated between four concepts: DD-PM (permanently excited direct drive turbine), SG-PM (turbine with permanently excited synchronous generator), DD (direct-drive turbines without a PM), and others (summarizes different turbine concepts like induction – and synchronous generator that are indirectly driven without a built-in PM). These differentiations were possible because of the existing statistics that showed clearly which turbine and generator concepts were used for newly-commissioned onshore turbines (Fraunhofer IEE, 2018b). These shares in percentages were then calculated with the gross new-built capacity which was installed per year in the past.

This kind of information was not available for Denmark. Therefore, the register of commissioned and decommissioned turbines in Denmark, which included partly the manufacturing company and the turbine model, was used to check which of these commissioned turbine models use a permanent-magnet-based technology. Due to the scope of this thesis and not available information, for Danish forecast scenarios only three turbine concepts were differentiated. For onshore and offshore this distinction was: DD-PM, SG-PM, and others. ‘Others’ describes turbine concepts that do not require a built-in PM. Therefore, the summarized turbines would not have had any influence on answering the research questions with respect to estimating NdFeB-, Nd-, and Dy-contents in the Danish anthropogenic stock.

For both countries, the analysis was done from the year 2000 until 2050. Because in Germany and Denmark wind turbines were operating already before 2000, the inventory and begin stock before 2000 were included in the calculations. Tab. 6 (GER) and Tab. 7 (DK)
show the turbine technologies which were differentiated in the forecast scenarios in this work and their cumulated gross capacity for Germany. Besides two future scenarios that were chosen to estimate the expansion of the wind energy sector from 2019 on, additionally, the recent years of investment (2000-2018) regarding gross new-build capacities and operating turbine concepts were calculated. By doing so, the currently exiting wind turbine capacities, built-in PM-amounts, as well as future estimations were possible.

Tab. 6 Germany’s total installed gross new-built capacities onshore and offshore before the year 2000, based on own research and calculations according to reports like (Rohrig, 2018; Deutsche WindGuard, 2018)

<table>
<thead>
<tr>
<th></th>
<th>Onshore</th>
<th>Offshore</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DD-PM</td>
<td>SG-PM</td>
</tr>
<tr>
<td>MW</td>
<td>13.5</td>
<td>42.67</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Tab. 7: Denmark’s total installed gross new-built capacities onshore and offshore before the year 2000, based on own research and calculations according to the Danish register of existing and decommissioned wind turbines in Denmark (Danish Energy Agency, 2019)

<table>
<thead>
<tr>
<th></th>
<th>Onshore</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DD-PM</td>
</tr>
<tr>
<td>MW</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

The primary focus in the analyses of this work lies on input flows of PM- and REE-amounts and to the Danish anthropogenic stock in form of new-commissioned turbines. But also output flows of these materials by decommissioning wind turbines were analyzed. Outflowing contents, generally, describe the amounts of material that become available in the anthropogenic stock for recovery and recycling due to the deconstruction of wind turbines. Furthermore, the generated stock per country should be described according to the different
modeled scenarios. At the same time, newly-installed and decommissioned capacities were additionally taken into account.

In the following the four created future scenarios, two per country, for both Germany and Denmark are presented.

4.4.1 Germany
In the following, the two future scenarios used for modeling the stocks and flows of wind energy capacities and the material-contents in the anthropogenic stock are described. In Appendix 2, the gross new-commissioned capacities for GER from 2000 to 2018 can be found.

4.4.1.1 Business-As-Usual
The Business-As-Usual (BAU) scenario with the above as ‘Mix’ described estimated development of turbine concepts was set as the basic scenario, which seems most realistic according to current politically set goals in Germany for the wind energy sector. In the BAU-scenario, no outstanding changes in technology, policies, and economics are assumed. Everything remains very similar to what is known and done today.

As set in the Renewable Energy Sources Act (EEG) from 2017 and described in chapter 2.1.3 about Germany’s energy policies from 2020 on, a new gross construction per year of 2.9 GW will be approved in Germany (compare IEA, 2016). The gross new-build capacity goals for onshore and offshore wind energy the German government agreed to are summarized in Tab. 8. While a yearly commissioning rate of 2.9 GW/a was decided for onshore wind energy, longer timeframes were set for offshore turbines in order to realize the new installation of 3.1 GW between 2015 and 2025, and additional 4.2 GW between 2026 and 2030. Due to the fact that the set goals do not exceed 2030 for offshore wind energy, assumptions had to be made, which are compiled in Tab. 9.

Further parameters were set as the following: The Weibull-parameters were applied with \( \lambda=1/18 \) and \( k=9 \) and a gradual development of turbine concept shares as presented in Tab. 10. The begin stock before 2000 got slightly different applying Weibull-parameters with \( \lambda=1/19 \) and \( k=7 \), due to the fact that turbines that were commissioned before 2000 were treated as turbines operating since 01.01.2000. Because of a regulation that was put in force end of the 90s, it was possible to operate a turbine longer than 20 years which impacts the average year of the turbines. The data for the begin stock of accumulated gross installed capacities are described in Tab. 6 (chapter 4.4).
Tab. 8 German set goals of gross new-build capacity for the wind energy market

<table>
<thead>
<tr>
<th></th>
<th>until 2019</th>
<th>2020 (-2050)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onshore</td>
<td>2.8 GW/a</td>
<td>2.9 GW/a</td>
</tr>
<tr>
<td>Offshore</td>
<td>3.1 GW</td>
<td>4.2 GW</td>
</tr>
</tbody>
</table>

Tab. 9 German set goals of gross new-build capacity for the wind energy market as well as calculated and estimated data for forecast scenario until 2050

<table>
<thead>
<tr>
<th></th>
<th>until 2019</th>
<th>2020-2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onshore</td>
<td>2.8 GW/a</td>
<td></td>
</tr>
<tr>
<td>Offshore</td>
<td>2.2 GW already installed</td>
<td>4.2 GW</td>
</tr>
<tr>
<td></td>
<td>880 MW total; 125.7 MW/a</td>
<td>840 MW/a</td>
</tr>
</tbody>
</table>

Tab. 10 Applied percentages for different turbine technologies over time

<table>
<thead>
<tr>
<th></th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onshore DD-PM</td>
<td>1.9</td>
<td>0.2</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Onshore SG-PM</td>
<td>14.8</td>
<td>11.4</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Onshore DD</td>
<td>52.0</td>
<td>54.8</td>
<td>60.6</td>
<td>60.6</td>
</tr>
<tr>
<td>Onshore others</td>
<td>31.3</td>
<td>33.7</td>
<td>39.4</td>
<td>39.4</td>
</tr>
<tr>
<td>Offshore DD-PM</td>
<td>22.6</td>
<td>25.0</td>
<td>51.5</td>
<td>37.9</td>
</tr>
<tr>
<td>Offshore SG-PM</td>
<td>41.1</td>
<td>56.3</td>
<td>32.3</td>
<td>56.0</td>
</tr>
<tr>
<td>Offshore DD</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Offshore others</td>
<td>36.3</td>
<td>18.7</td>
<td>16.2</td>
<td>6.1</td>
</tr>
</tbody>
</table>
4.4.1.2 GreenEe

The GreenEe-scenario stands for “Germany – resource efficient and greenhouse gas neutral-energy efficiency” and is part of the project “Greenhouse gas neutral Germany 2050” of the German Environment Agency. It aims to show an ambitious and energy-efficient way to achieve the transformation to greenhouse gas (GHG) neutrality while preserving and treating resources sustainably (Günther et al., 2017). Furthermore, the development of GHG emissions and required raw materials until 2050 were calculated in this scenario. The central assumptions of this scenario are that in 2050 the energy supply will be completely based on renewable energy sources. The German population is estimated to be relatively similar like today, but stable and with a constant development. However, changes were assumed in the transportation sector, which will use fuels from renewable energies more intensively over time (Günther et al., 2017). The scenario aims to achieve a reduction of GHG emissions of 60 % until 2030, 80 % in 2040, and 95 % until 2050 compared with 1990. Moreover, primary raw material demand should be diminished by 60 % compared to the usage in 2010.

For the wind energy sector, the following described targets were defined in order to make the previously defined goals achievable. Günther et al. (2017) calculated that for reaching the aims set for 2030, 90 GW onshore capacity has to be installed. Ideally, this could have been reached when the gross new-build capacity of 2015 with 3.7 GW would have been steadily increased by 115 MW/a, so that in 2030 new turbine installations of 5.5 GW/a gross could have been built, which results in an average of 3 GW/a net-build.

However, the renewable energy regulation from 2017 limits the gross new-build onshore turbines to 2.8 GW/a in 2017 and 2018, and from 2019 onwards to 2.9 GW/a (BMWI, 2017). Compared with the optimum-case, a backlog demand exists, because in 2020 a gross new commission rate of 4.3 GW/a should have been reached. Thus, there are 1.4 GW/a too less to reach the set capacity of 90 GW onshore in 2030. Therefore, from 2020 to 2030 the gross new-build capacity has to be increased from 2.9 GW/a to more than twice, namely 8 GW/a. From 2030 until 2050, 5.5 GW/a gross new-built onshore capacity was calculated and used.

Since it was not possible to get information from the report or the authors personally about their calculated offshore capacities until 2050, assumptions were made based on Tab. 11, provided by co-authors of Günther et al. (2017), and set to 1600 MW/a between 2019 and 2050.
Tab. 11 Provided information for calculated wind energy targets used as background information in the report of Günther et al. (2017)

<table>
<thead>
<tr>
<th></th>
<th>Onshore</th>
<th></th>
<th>Offshore</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2030</td>
<td>2040</td>
<td>2050</td>
<td>2030</td>
</tr>
<tr>
<td>GW</td>
<td>83.45</td>
<td>107.73</td>
<td>127.42</td>
<td>15.57</td>
</tr>
<tr>
<td>TWh</td>
<td>200.45</td>
<td>326.54</td>
<td>414.15</td>
<td>71.34</td>
</tr>
</tbody>
</table>

4.4.2 Denmark

As it was described previously for Germany, the Danish installed capacity before 2000 was calculated and considered in the modeling. Furthermore in Appendix 3, the gross new-commissioned capacities for GER from 2000 to 2018 can be found.

In order to compare different energy transition scenarios, to identify potential challenges in achieving an energy system independent from fossil fuels until 2050, and to meet the goal of fossil fuels independence in the electricity and heating sector by 2035, the Danish Energy Agency published the report “Energiscenerier frem mod 2020, 2035 og 2050” (ENS, 2014). The scenarios presented in this publication do not describe future projections, but rather identify current challenges for certain development paths. For this thesis two scenarios from ENS (2014) were chosen, which will be described in the following.

The hydrogen scenario aimed to simulate very little bioenergy consumption (>200 PJ). This results in a high hydrogen usage and the greatest wind deployment, compared to the other future scenarios, with 17,500 MW installed capacity offshore and 3,500 MW onshore (see Tab. 12).

In the Bio+ scenario, a fuel-based system as known today was used, but natural gas and oil were replaced with bioenergy. Hydrogen was not considered in this scenario and electricity from wind gets the lowest share compared to other scenarios with 2,500 MW offshore and 3,500 MW onshore, to meet roughly 50 percent of Denmark’s electricity demand (Agora Energiewende & DTU Management Engineering, 2015).
Tab. 12 Installed capacity in MW by 2050 (according to Agora Energiewende & DTU Management Engineering, 2015; ENS, 2014)

<table>
<thead>
<tr>
<th>scenario</th>
<th>Bio+</th>
<th>Hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>offshore wind</td>
<td>2,500</td>
<td>17,500</td>
</tr>
<tr>
<td>onshore wind</td>
<td>3,500</td>
<td>3,500</td>
</tr>
<tr>
<td>solar PV</td>
<td>1000</td>
<td>2000</td>
</tr>
<tr>
<td>gas turbines</td>
<td>400</td>
<td>4,600</td>
</tr>
<tr>
<td>CHP biomass</td>
<td>2,400</td>
<td>0</td>
</tr>
<tr>
<td>CHP coal</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>fuel cells</td>
<td>0</td>
<td>500</td>
</tr>
</tbody>
</table>

As already mentioned, only three turbine technologies were differentiated for Danish forecast scenarios, not four as in the case of Germany. Others than that, same assumptions were made according to the reducing magnet weight [kg/MW] from 2030 on.

4.4.2.1 Hydrogen

The Hydrogen scenario was set as the Danish basic scenario to allow a better comparison with the results of other scenarios.

In order to reach the 3.5 GW onshore by 2050 (Hydrogen- and Bio+ scenario), it was estimated that more than 3.5 GW gross new-built turbines have to be installed, because within 31 years (2019-2050) turbines will have to be replaced at their EoL. Therefore, 5 GW gross new-built turbines were set between 2019 and 2050, which results in roughly 161.3 MW/a. Moreover, 17.5 GW offshore by 2050 were calculated to be expected. The already existing 1.7 GW capacity offshore will need to be repowered or replaced as well as partly the turbines commissioned between 2019 and 2050 until reaching the goal of 17.5 GW. Accordingly, it was assumed that 25 GW have to be gross new-commissioned between 2019 and 2050, which results in roughly 806.5 MW/a.

4.4.2.2 Bio+

In general, for the Bio+ scenario a way lower cumulative capacity in the wind energy sector was calculated by 2050. As well as in the Hydrogen scenario, 3.5 GW onshore capacity by 2050 were estimated. It was expected that gross new-built turbines of 5 GW have to be installed between 2019 and 2050, which results in roughly 161.3 MW/a. This is due to the fact
that within these 31 years (2019-2050) turbines will reach their EoL and have to be decommissioned. Moreover, 5 GW gross new-built capacity offshore were set (2019-2050) in order to reach 2.5 GW installed capacity by 2050, resulting in roughly 1613 MW in one decade. These gross inputs range in total between 250 MW and 450 MW per year.
5 Analysis

In the following, the modeled results based on the previously described estimations in the future scenarios will be described. A differentiation was made between German and Danish results, which will be firstly analyzed for the total NdFeB-material and installed capacities, whereas afterwards, the results for Nd- and Dy-contents in the anthropogenic stock per country will be evaluated.

5.1 Germany

5.1.1 Business-As-Usual

In Fig. 14, the input flows of new installed capacities in kW are visualized per year. The newly commissioned turbines were differentiated between the four generator concepts: Direct drive (DD) and indirectly driven turbines (others) both available with and without PM (DD-PM; SG-PM) onshore and offshore. The greatest peaks in 2014, 2016 and 2017 are the results of changes in the EEG, the German Renewable Energy Sources Act. From 2014 on, EEG charges needed to be paid and operators of renewable energy plants had to market their generated electricity directly. Furthermore, the path was cleared for tendering and auctions for wind turbine approvals with EEG-changes in 2017. Because renewable energy plant operators wanted to get approval for their wind turbines before these changes were put into force, in order to achieve a treatment of the turbines according to the EEG-regulations in the year of granting permission, peaks in wind turbine approval occurred in 2013 and 2015/2016. Since it takes some time to finally commission turbines, most of them were installed in the following year, respectively 2014, 2016/2017 and eventually some in 2018, although the regulation already changed at this point.

Generally, it can be seen in Fig. 14 that the 2,900,000 kW/a (2.9 GW/a) onshore gross new-build capacity builds the base for the German wind energy sector until 2050. The assumed trend is that permanently excited onshore turbines will hold a small share in the new-installations in the next decade. Between 2019 and 2025 it can be seen, that there is nearly no new-commissioning of offshore turbines. This is the result of the politically set goal of installing 3.1 GW between 2015 and 2025. Between 2015 and 2018 turbines with a total of 2.2 GW started to operate, which leaves for the years until 2025 a total of 880,000 kW or ~125,700 kW/a. Therefore, it does not matter to which extend permanently excited turbines
are installed compared to non-PM-using turbines when there is such a low commissioning-rate. However, after 2026 more offshore turbines should start operating and as estimated in the ‘Mix’ market shares of turbine technologies, turbines using a PM are most common (compare orange and light blue categories). Between 2026 and 2030, 4.2 GW should be installed and it was estimated that after seven years of low commissioning rate, governmental institutions, operators and the industry will need some time to refocus on the new task again. Accordingly, a gradually growth of installed capacities per year was estimated, leaving a great share of the 4.2 GW to be commissioned until 2030. After that, relatively stable new-installations rates onshore and offshore are visible.

The following diagram (Fig. 15) shows the PM-material input in kg to the German anthropogenic stock. It can be seen, that in the past Germany’s wind energy sector relied on permanently excited turbines to different extends. In 2010, firstly 25,000 kg/a NdFeB-material were entering the anthropogenic stock, were increasing until the EEG-change in 2014 and decreasing due to less installations in general. In 2018 a peak in new-installed-capacities can be identified which leads to a corresponding input of PM-material to the anthropogenic stock due to changes of the EEG by 2017. In 2018, roughly 540 t of NdFeB-material were build-in in new-
commissioned wind turbines. From 2019 on the ‘Mix’ market shares with a growth of permanently-excited turbines installed offshore were estimated, while, similarly, a steady phase out of permanently-excited onshore turbines was assumed. However, the new-commissioning rate is greater for onshore locations than offshore, which leads, consequently, to the fact that onshore input-flows of PM are greater between 2019 and 2025, although a decreasing input-trend can be observed with ~75 t (2019) to 50 t (2025) (Fig. 15). In the contrary, 25 t total PM-input in form of offshore turbines can be identified 2019 and by 2025 40 t.

As described above, the steadily increase in the years before 2030 and the peak in 2030 itself result from the aim of installing 4.2 GW (2026-2030). Moreover, a slowly increasing commissioning rate per year was estimated, leaving a great share of the 4.2 GW to be commissioned until 2030, which results in great PM-inputs of roughly 460 tons (t) offshore and more than 30 t onshore.

Although after 2030 similar shares for DD-PM-turbine concept as well as for SG-PM-turbines were estimated, the input-flow of NdFeB-material to the German wind energy stock is greater for DD-PM because more magnet material is required for that technology compared to permanently-excited synchronous generators.

![Disaggregated input flows of NdFeB-material [kg] to the German anthropogenic stock, differentiated between PM-containing turbine technologies (BAU scenario)](image)

**Fig. 15** Disaggregated input flows of NdFeB-material [kg] to the German anthropogenic stock, differentiated between PM-containing turbine technologies (BAU scenario)

The output flows of EoL-turbines in kW (compare Fig. 16) show which capacities will be decommissioned over time. Influencing factors are the set Weibull-parameters to describe the
turbines’ lifetime. The first smaller peak around 2021 is the result of the new installations from the years 2000 until 2004 roughly. The maximum output flow of roughly 3.8 GW in 2034 is, in contrast to this, the consequence of the vast amount of approved and commissioned turbines between 2014 and 2017, which are reaching their end of service time and have to be repowered or decommissioned.

Similar trends and developments can be found with respect to the output-flows of NdFeB-material from the German anthropogenic stock (see Fig. 17). The major difference between the decommissioned capacities (Fig 16) and the PM-amounts accessible due to deconstructing EoL-turbines (Fig. 17) is that the first smaller peak around 2020 in the decommissioned capacities (Fig. 16) is not appearing in Fig. 17 due to negligible amounts of permanently-excited wind turbines installed before 2010. From 2017 on, the PM-amount that would potentially be Available at EoL-turbines for recovery and recycling purposes is slowly increasing. The first peak of high amounts of accessible PM-material can be identified 2036, 18 years after the great NdFeB input flow from 2018 and in the previous years (compare Fig. 17), resulting in 210 t NdFeB-material. The highest PM-content outflowing from the anthropogenic stock can be identified in 2048 with 240 t.

![Figure 16](image.png)

**Fig. 16** Aggregated output flows in kW entering the German anthropogenic stock, differentiated between 4 turbine concepts that are available onshore and offshore (BAU scenario)
Generally, it can be seen, that a future path according to the BAU-scenario would lead to an accumulated installed capacity of 60 GW until 2050. However, this capacity is reached already in 2030, whereas afterwards no growth but rather a stagnation of the operating capacity occurs (compare Fig. 18). This is due to the fact that new-commissioned turbines will need to compensate EoL-turbines, which have to be decommissioned, so, that no further expansion of the wind energy sector can be achieved. Corresponding to this, an increase of PM-material in the German anthropogenic stock can only be identified until 2030, while afterwards a relatively stable NdFeB-amount if more or less 3,000 tons is bound in German wind turbines (see Fig. 19).
Fig. 18 German BAU scenario and its cumulative capacity in kW distinguished by various turbine technologies with and without a built-in PM onshore and offshore (BAU scenario)

Fig. 19 Disaggregated input of NdFeB-material [kg] to the German wind energy stock distinguished by PM-containing turbine technologies (BAU scenario)
5.1.2 GreenEe

The gross new-build input flow capacity between 2020 and 2030 is in total 9.6 GW/a, with 8 GW/a onshore capacity and 1.6 GW/a offshore. 2030 until 2050, the input flow is decreasing to totally 7.1 GW/a, with 5.5 GW/a gross new-commissioned onshore capacity and 1.6 GW/a offshore. The shares of operating turbine concepts in future were estimated according to the ‘Mix’ assumption with greater amounts of permanently exited turbines in offshore regions compared to onshore installed turbines. Accordingly, the NdFeB-material input flows to the German anthropogenic stock build-in in wind turbines is decreasing for onshore turbines (Fig. 20). The general trend of decreasing PM-input flows results, additionally, from the reducing PM-weights after 2030 (compare Tab. 4, chapter 5).

![yearly NdFeB-magnet input to anthropogenic stock](image)

**Fig. 20** PM-material [kg] incoming to the German anthropogenic stock in form of new-commissioned wind turbines (GreenEe scenario)

In Fig. 21 the corresponding decommissioned capacities in kW per year are illustrated. Compared to the deconstructions in the BAU scenario, it can be recognized that the first smaller peak around 2020 occurred in both scenarios for the same reason as mentioned before in chapter 5.1.1. After a steady increase of capacities that need to be uninstalled, the greatest decommissioning rate per year starts after 2039 with roughly 8 GW onshore and 1.6 GW offshore. These results are corresponding to the new-installed capacities from 2020 on. According to that, until 2040 a continuous expansion of PM-material up to nearly 800 t can be recog-
nized, which is becoming available in the anthropogenic stock due to turbines’ deconstruction (see Fig. 22).

**Fig. 21** Aggregated output flow [kW] from the German anthropogenic stock distinguishing 4 turbine concepts that are available onshore and offshore (GreenEe scenario)

**Fig. 22** PM-material [kg] that becomes available in the German anthropogenic stock in form of decommissioned wind turbines, according to the GreenEe scenario
The German anthropogenic stock and its accumulated NdFeB-amounts in the wind energy sector are modeled in Fig. 23. The respective development of the cumulative installed capacity in the analyzed period can be found in Appendix 4. It can be observed, that the greatest PM-amounts in the German anthropogenic stock come from offshore located DD-PM turbines. This is, however, not necessarily only because of chosen market shares for the different turbine technologies but also due to the enormous PM-weight of 650 kg/MW in direct drive turbines. In this scenario a peak in accumulated NdFeB-material from wind turbines is reached in 2037 with a stock of roughly 13,000 t. In 2030, 10,000 t could be reached for the first time. However, of this total PM-material iron has the greatest part in composition, while REE are in total only 31 %. Therefore, 13,000 t NdFeB-material results in roughly 4,300 t REE-amount totally.

It can be concluded, that the GreenEe scenario is a very optimistic scenario compared to the BAU scenario. Despite the question how realistic it is to reach these targets from a current point of view, it is a good way to show a potential future path. Moreover, it shows how decisions in favor or against relying on permanently excited turbines in general can impact the amount of NdFeB-magnets in the German anthropogenic stock.

![Fig. 23 PM-material [kg] accumulated in the German anthropogenic stock in form of operating wind turbines, according to the GreenEe scenario](image-url)
5.2 Denmark

5.2.1 Hydrogen

Fig. 24 visualizes the input of new capacity to the Danish wind energy sector per year. It can be observed that the gross new-build capacity but also the chosen turbine technologies are varying a lot between 2000 and 2018. Therefore, the estimated development of the Danish wind energy market looks very optimistic from a current point of view. Since in the scenarios of the Danish Energy Agency only the estimated capacities operating by 2050 were mentioned, assumptions had to be made regarding the question how the market shares of turbine technologies on- and offshore will develop over time. Because no information or trends were available for Denmark, it was guessed that market shares of PM-using-technologies will evolve similar like in Germany, so that greater amounts of NdFeB-magnets can be forecasted in offshore turbines. Additionally, according to the ‘Mix’ market shares, onshore turbine technologies were considered to use continuously less permanent magnets. The general trend of an increasing new-installation rate in total per year after 2019 can be observed and is the result of the start of modeling and projection. However, this growth stops and evolves to a downwards trend after 2040 when the decommissioned capacities are greater than the new installations. This high peak as well as the minimum-peak in 2030 is the result of assumed installation trends per year. It was expected that a steady increase (2030-2040) in turbine-installations is more realistic than a constant new-installation rate between these years. This can be best observed in the category of ‘Onshore others’. However, after 2040 a further increase of new-installations per year would have led to too many newly-commissioned capacities, so that a lower installation-rate until 2050 was assumed, which leads to the decreasing trend of kW per year.

Generally, it can be seen that in this scenario the offshore operating turbines are the leading part of the Danish wind energy in future. More in detail, permanently excited offshore turbines hold a great share in commissioned capacities although they were not considered to be the most important technologies for the Danish wind energy sector in the future. Nevertheless, it has to be mentioned that until today nearly no permanently-excited offshore turbines on the Danish sea were installed. So it remains questionable how strong Denmark will rely in general on PM-using turbine technologies in offshore locations.

Similarly, the NdFeB-material input flow to the Danish anthropogenic stock is dominated by the offshore turbines, while onshore turbine technologies do rely steadily less on perma-
nent magnets in this scenario (see Fig. 25). Furthermore, it can be recognized that before 2030 rising PM-material input flows were identified, whereas after 2030 decreasing NdFeB-amounts enter the anthropogenic stock. This is, firstly, due to the previously mentioned fact of the constantly increasing assumed installation-rate per year with a decreasing growth after 2040. But, secondly, the PM-weights were estimated to be reduced after 2030 which impacts the build-in amounts of NdFeB-magnets in wind turbines additionally. In 2030, nearly 160 t inflowing NdFeB-material can be expected to enter the anthropogenic stock, and by 2050 around 175 t in total.

Fig. 24 Input flow [kW] of new capacity to the Danish wind energy sector distinguished by two turbine technologies using a PM and the rest that is using no NdFeB-magnet (Hydrogen scenario)
Looking at Fig. 26, the turbines that need to be repowered or decommissioned are visualized. During the last years until today (after 2017), a great amount of Danish wind turbines reach their end-of-service time, commissioned around 2000 when permanently excited turbines were not common (compare pink and light-red categories). The second lower peak between 2027 and 2032 that describes higher decommissioning rates is the result from the installation-period 2009 until 2013 of which the turbines start reaching their EoL after 2027.

Due to the missing build-in NdFeB-magnet in the deconstructed turbines, this peak cannot be seen in Fig. 27. Fig. 27 represents the PM-material that becomes shortly available in the anthropogenic stock due to decommissioning of turbines, before this material is leaving the system due to exports or losses in waste streams. Others than that, the output flows of NdFeB-material after 2026 (Fig. 27) are respective to the decommissioned capacities in Denmark (Fig. 26).
Fig. 26 Danish decommissioned capacities [kW] over time (Hydrogen scenario)

Fig. 27 PM-material [kg] that becomes available in the Danish anthropogenic stock by the decommissioning of wind turbines (Hydrogen scenario)
In Fig. 28, the cumulative installed capacity over time is illustrated. With the set target of 17.5 GW offshore and 3.5 GW onshore, Denmark would achieve a continuous growth of its wind energy market and could reach capacities around six times higher compared to 2002. The exact 21 GW as forecasted were not reached in this scenarios because of made assumptions and too less estimated decommission-rates during this period.

By comparing these trends with the aggregated PM-stocks in Denmark (Fig. 29), the same tendencies can be observed according to the estimated market shares of permanently excited turbine technologies.

![accumulated stock of installed capacities](image)

**Fig. 28** Danish Hydrogen scenario and its cumulative capacity in kW, differentiated between various turbine technologies with and without a built-in PM onshore and offshore (Hydrogen scenario)
5.2.2 Bio+

Looking at Fig. 30, which illustrates the inflowing PM-material to the Danish anthropogenic stock, it can be observed that despite increasing shares of permanently excited turbine technologies offshore (compare red and dark blue sections) the PM-inputs are decreasing steadily in total. One reason is the general diminishing PM-weight after 2030. The second reason is the assumption that onshore turbines are expected to rely steadily less on PM, so that a leading part of the Danish wind energy market in this scenario is declining. In Appendix 5 the gross new-commissioned capacities [kW] can be found for a better traceability of the results of Fig. 30. Whereas in 2019 in the beginning of the projections 70 t NdFeB-input-material could be expected, it would be roughly 45 t entering the Danish anthropogenic stock in form of wind turbines in 2050.
Comparing the decommissioned capacities from the Hydrogen scenario with the Bio+ scenario, the same peaks after 2017 and from 2027 on can be identified for the same reasons as stated above in chapter 5.2.1. However, in the Hydrogen scenario a tendency of increasing output-rate per year could be observed while this is not the case for the Bio+ scenario. In the latter case, a decreasing decommissioning-rate per year can be seen after 2037 (see Fig. 31). By then, most of the turbines installed before 2019 reached already their EoL. Moreover, from 2037 on, corresponding to the decreasing gross new-installations in this scenario, the decommissioning-rates diminish accordingly. This trend can be determined in the PM-output-flows from the Danish anthropogenic stock as well (Fig. 32).
Fig. 31 Danish decommissioned capacities [kW] over time, distinguished by various turbine concepts estimated (Bio+)

Fig. 32 PM-material [kg] that becomes available in the Danish anthropogenic stock in form of decommissioned wind turbines (Bio+)
In the Danish anthropogenic stock, PM-contents from the wind energy sector accumulate as shown in Fig. 33. Already since 2012, a slower but steady growth of permanently excited turbines can be identified, whereas the expansion became greater in 2018. Moreover this trend continues with the assumption made in this scenario for the following years. Although offshore turbines were considered to contain on a long-term more regularly NdFeB-magnets, the Danish stock contains great amounts of PM due to commissioned onshore turbines. This occurs because of permanently excited onshore turbines installed after 2014 (compare Fig. 24 2014-2018 or respective PM-amounts in Fig. 30) which reach their EoL around 2032, where a corresponding decrease in the diagramm can be observed. Besides this, DD-PM turbines located offshore are the greatest source of NdFeB-magnets in the Danish stock. This is not necessarily because of greater installed capacities but due to higher PM-weights needed for this turbine technology with 650 kg/MW.

![accumulated stock of NdFeB-material](image)

**Fig. 33** PM-material [kg] accumulated in the Danish anthropogenic stock bound in wind turbines (Bio+)

After presenting these very different forecast scenarios for Denmark, it can generally be concluded that it cannot be said which path Denmark needs to focus on while considering the Danish electricity demand. This is due to the fact that each scenario offers various alternatives.
for the energy production besides the wind energy, so that the goal of a 100 %-fossil-fuel-free Denmark still can be reached.

In both scenarios, nearly the first time greater PM-outflows could be observed is in 2031. From this time on NdFeB-magnet amounts can be estimated with roughly 20 t with increasing contents in the upcoming years. However, iron has the greatest share of this PM-amount, while REE are only about 31 %, which are respectively roughly 6.2 t REE-content in total.

5.3 Nd and Dy contents in the anthropogenic stock

The previously described scenarios are used in the following again with the difference of the described good. This time, not the total magnet material but each element as component to build the NdFeB-magnet was considered separately, with a focus on neodymium and dysprosium as rare earth elements. In the following, when REE is mentioned, only Nd and Dy are considered. The total REE-input flows to the countries’ anthropogenic stock can be found in Appendix 6. But, generally, these input flows are corresponding to the total NdFeB-material inputs described in the respective scenario in chapters 5.1 and 5.2.

5.3.1 Germany

In the following, both German forecast scenarios, BAU and GreenEe, should be taken into account for evaluation of accumulated Nd and Dy contents in the anthropogenic stock as well as available REE-amounts from decommissioned wind turbines in the future. Only Nd and Dy are taken into consideration while using the term REE-amount at this point.

The output-flows of Nd and Dy from the German anthropogenic stock can be found for the BAU scenario in Fig. 34 and in Fig. 35 for the GreenEe scenario. A comparison shows clearly, that until 2036 the same amounts of Nd and Dy are becoming accessible due to decommissioning of EoL-turbines. These contingents could be recovered and potentially recycled before the elements enter the waste streams without recognition. Whereas in 2030 18 t Nd and 1.3 t Dy could possibly be recovered, already in 2036 a maximum Nd-amount of nearly 90 t and roughly 6.6 t Dy becomes accessible. These amounts are equal for both scenarios because they are based on already installed capacities and operating turbines. Therefore, it can be concluded, that the presented scenarios do not only estimate future expansion of the wind energy market and corresponding secondary sources of REE, but additionally are representing the existing anthropogenic stock of Germany until 2036 based on the inputs from the wind energy market.
From 2036 on, turbines installed after 2018, which corresponds to the starting of future projections, will need to be decommissioned. Therefore, divergent accessible REE-contents can be recognized in the BAU and GreenEe scenario. From 2036 on, a rapid decrease of available Nd (28 t) and Dy (2 t) can be observed until 2040 in the BAU scenario (Fig. 34). This is due to the fact that 2020 until 2027 relatively small capacities of permanently excited turbines have been installed according to this scenario. However, the greater amounts of PM-using turbines from 2028 on are correlating to the REE-outflows from the German anthropogenic stock after 2046. Respectively, in 2048 85 t Nd and 6.1 t Dy could be recovered from EoL-turbines.

In contrast to this Fig. 35 shows, representing the GreenEe scenario, the highest accessible REE-content in 2040 (250 t Nd; 18 t Dy) followed by a slow but steady decrease of available REE-content, reaching roughly 200 t Nd and 14.5 t Dy in 2048.

In both German future scenarios, the stocks accumulate over time the greatest REE-amounts from DD-PM turbines located offshore. This is because of the high PM-weight of 650 kg/MW required for direct-drive turbine concepts compared to permanently excited synchronous generators, which use 80-160 kg/MW.

Looking at the accumulated German anthropogenic stock of the BAU scenario (Fig. 36), between 2030 and 2046 Nd and Dy amounts of totally 800 – 1,000 t are bound in wind turbines. In contrast to this, the anthropogenic stock generated by the GreenEe-estimations, holds from 3,100 t up to 4,000 t REE-material between 2030 and 2050 (Fig. 37).
**Fig. 34:** Nd and Dy-amounts [kg] that become available in the German anthropogenic stock due to decommissioning of wind turbines (BAU scenario)

**Fig. 35:** Nd and Dy-amounts [kg] that become available in the German anthropogenic stock due to decommissioning of wind turbines (GreenEe scenario)
Fig. 36: Accumulated Nd and Dy amounts [kg] in the German anthropogenic stock bound in different wind turbine concepts located onshore and offshore (BAU)

Fig. 37: Accumulated Nd and Dy amounts [kg] in the German anthropogenic stock bound in different wind turbine concepts located onshore and offshore (GreenEe)
5.3.2 Denmark

Similarly as for Germany, also in both Danish scenarios (Hydrogen (Fig. 38) and Bio+ (Fig. 39)) equal out-flowing Nd and Dy contents from the Danish anthropogenic stock could be identified until roughly 2035. Whereas in 2025 only 0.05 t Nd and 0.004 t Dy per year will be available in the anthropogenic stock, in 2030 a greater amount of 4 t Nd and 0.3 t Dy could be determined. 2035 is the last year which shows similar outflows in both Danish scenarios with roughly 19 t Nd and 1.4 t Dy. After that, the first impacts of the estimated forecasts can be identified looking at the available REE-content in the following years. From 2036 on wind turbines installed after 2018 reach their end of service time and by decommissioning those, Nd-contents of 29 t and 2.2 t Dy could potentially be recovered, according to the Hydrogen scenario, before potentially entering unrecognized the Danish waste streams (see Fig. 38). The highest peak can be observed 2046, with a maximum output of 45 t Nd as well as 3.3 t Dy. Whereas in the hydrogen scenario a continuous increase in available REE-content in the anthropogenic stock can be observed until 2046, the Bio+ scenario offers a contradictory trend (see Fig. 39). After the maximum amounts of 26.5 t Nd and 1.9 t Dy could potentially be recovered in 2037, due to the peak in 2018 of permanently excited turbines, a steady decrease of available REE-contents can be recognized. This is due to the fact that in general in the Bio+ scenario the gross new-installation-rate is continuously diminishing per year. Therefore, the lower out-flowing Nd and Dy amounts are corresponding to these inputs.

While comparing the Danish anthropogenic stock according to both future scenarios, the Hydrogen scenario would lead to accumulated Nd and Dy amounts of 750 to 800 t after 2034 (see Fig. 40). The greatest quantities are coming from permanently excited offshore turbines as estimated in this scenario. In contrast to this, the future orientated on the Bio+ scenario would accumulate Nd and Dy contents of 250 t to 330 t in the Danish stock between 2024 and 2050 (Fig. 41).
Fig. 38 Nd and Dy-amounts [kg] that become available in the Danish anthropogenic stock due to decommissioning of wind turbines, according to the Hydrogen scenario

Fig. 39 Nd and Dy-amounts [kg] that become available in the Danish anthropogenic stock due to deconstruction of wind turbines (Bio+)
Fig. 40 Accumulated Nd and Dy amounts [kg] in the Danish anthropogenic stock bound in different wind turbine concepts located onshore and offshore (Hydrogen)

Fig. 41 Accumulated Nd and Dy amounts [kg] in the Danish anthropogenic stock bound in different wind turbine concepts located onshore and offshore (Bio+)
6 Discussion

The present work, in general, dealt with the estimation of the German and Danish anthropogenic stock and its NdFeB-magnet amounts as well as containing neodymium and dysprosium contents in the wind energy sector.

6.1 RQ1: Future differences in the German and Danish wind energy market

In this context the first research question asked for possible differences in the German and Danish wind energy market in the future. To be able to answer RQ1, the Danish and German wind energy markets had to be compared. Therefore, it was essential to estimate how the wind energy markets of both countries could potentially develop over time. The following analysis is mainly based on the German basic scenario (Business-As-Usual) and the Danish Hydrogen scenario, described in chapter 4.4.1.1 and 4.4.2.1.

The previously mentioned differences in geographic, demographic size and in the electricity consumption in both countries result also in greater wind energy capacities for Germany than for Denmark. This could be observed in the accumulated stock of installed capacities for GER (Fig. 18, chapter 5.1.1) and DK (Fig. 28, chapter 5.2.1). It becomes obvious how extremely these countries differ from each other regarding electricity demand, its supply, and possible extensions of the wind energy market. In the German Business-As-Usual scenario, the maximum installed capacity of roughly 60 GW is reached in 2030. From this year on, the gross new-build capacity and the decommissioning rate are nearly equal to each other, so that a constant capacity of 60 GW would exist in the future (Fig. 18). However, in the German GreenEe scenario it was calculated that only in onshore locations 90 GW would be required by 2030 in order to reach the politically set targets, for example, 60 % GHG-reductions by 2030. This shows, that in comparison to DK, GER is, seemingly, progressing remarkably. However, in relation to the more ambitious GreenEe scenario, the German BAU scenario demonstrates a future path which shows Germany as not committed to reach its sustainability-targets and to invest in a greater expansion of the wind energy market.

Whereas German wind capacities range at maximum around 60 GW (BAU scenario), DK reaches totally 17.5 GW at maximum in 2043 (see Fig. 28) in the Hydrogen scenario, which shows a very enthusiastic future path regarding the wind energy expansion. Although the installed and required capacities are not directly comparable to each other, it can be concluded, that DK could achieve a constant growth in operating capacity in the future. In contrast to
this, in GER a stagnation of the installed capacity would occur according to the BAU scenario. Obviously, these situations would only happen in case that the countries would strike the paths similar to the described scenarios. This has to be kept in mind when interpreting the findings of the present work. However, the information received from the future estimations and scenario-outputs can be used as basis for orientation in further decision-making processes and the question how regulations and new-commissioning-rates might influence the future wind energy market in DK and GER.

6.2 RQ2.1 & RQ2.2: By which extend can recovered REE-amounts from PM of wind turbines support the countries’ demand?

The second research question, including RQ2.1 and RQ2.2, dealt with the question if it is possible that rare earth elements recovered from PM of EoL-wind turbines can help to meet the future demand of rare earths and magnetic material. In case this can be proven to be achievable, it should be analyzed additionally to which extend the future material supply can be supported by secondary REE- and NdFeB-material. In doing so, NdFeB-magnets from wind turbines were focused as secondary source for Nd and Dy in the present work. With the aim to answer the research question RQ2.1, the amounts of NdFeB-material, Nd and Dy in the countries’ anthropogenic stock are analyzed now to identify the theoretical recycling potential of these two rare earth elements. Furthermore, to answer RQ2.2, the demands from DK of 2012 as well as a future prognosis of the element demand in 2035 were used to calculate the contribution of secondary Nd and Dy to Denmark’s demand in different years. The same was done for GER, considering the PM-imports from 2015.

Due to the fact, that the investments of the last years regarding new-installed capacities are known until 2018, it can be evaluated which capacities and EoL-turbines will have to be decommissioned until 2035 roughly. Therefore, firstly an analysis of the German and Danish anthropogenic stock should be conducted without considering the generated future scenarios of this work at this point. This is done because estimations in the future scenarios started in 2019, so that turbines commissioned after this year will nearly not be taken into account while analyzing EoL-turbines and their REE-contents.
6.2.1 Germany’s theoretical recycling potential and demands in future

As mentioned in chapter 3.2.4.1., in 2015 Germany imported 9,371 tons of permanent magnets (UN Comtrade, 2019). Then, Müller (2019) estimated that of these imports 8,000 tons were NdFeB-magnets. To get an idea of the contained Nd and Dy amounts in the imported NdFeB-material, a calculation using the simplified composition of a NdFeB-magnet (chapter 3.1.2; 31 % Nd, 2.3 % Dy) results in 2,480 t Nd and 184 t Dy in 2015. In the following, rounded values for calculated percentages are mentioned.

The presented results in chapter 5.3.1 show that a steady increase of NdFeB- and REE-output-material from the anthropogenic stock until 2035 can be expected (Fig. 34 and 35). In 2035 around 269 t NdFeB-material (as the average of both German future scenarios) as well as 92 t Nd and 7 t Dy could be identified as theoretical recycling potential from deconstructed wind turbines. When the demand of NdFeB-material, Nd, and Dy would be assumed to be equal to 2015, the determined amounts from secondary sources in 2035 could meet the NdFeB-demand of 8,000 tons by nearly 3 %. Furthermore, the Nd-and Dy-demand could be covered with by 4 % each in 2035.

After 2035, when projections and estimations of the future scenarios start to influence the EoL-turbines and respective capacities, the theoretical recycling potential start to differ for the BAU- and the GreenEe scenario. Therefore, a comparison of both scenarios’ results of 2048 shows that in the BAU scenario, 240 t PM-material, 80 t Nd and 6 t Dy become available for recovery. According to the German demand and imports in 2015, the available material-contents in 2048 could meet the demand by 3 % secondary NdFeB-material, as well as 3 % of Nd and 3 % Dy.

Taking the GreenEe scenario into consideration, the theoretical recycling potential in 2048 could be identified to be 710 t PM-material which could meet the demand by nearly 9 %. Furthermore, 200 t Nd in 2048 could provide 8 % of the German imports (2015) and 14 t Dy would contribute roughly 8 % from EoL-turbines.

It can be summarized that the secondary NdFeB- and REE-contents from deconstructed wind turbines is increasing with time due to, firstly, a general growth of the wind energy sector and installed turbine capacities. Secondly, made assumptions impact the outcomes after 2035 so that estimations of an increasing number of permanently-excited offshore turbines and a contradictory development for onshore turbines influence the NdFeB-contents and REE-amounts, that are available after 2035, accordingly.
An interesting fact is that a difference of ~90 GW more cumulative installed capacity in the GreenEe scenario, compared to the BAU scenario, leads to only a small support in future PM- and REE-supply to meet German demands, considering a full recovery and recycling without losses. However, taking into account how much effort and refining it takes to produce the rare earth elements in primary production, a few hundred tons as output from the anthropogenic stock should not be disregarded.

6.2.2 Denmark’s theoretical recycling potential and demands in future

Similar to Germany, in Denmark a further growing PM-output from the anthropogenic stock could also be identified, reaching 63 t NdFeB-magnet material in 2035 which includes 20 t Nd and 1.5 t Dy. As previously described in chapter 3.2.4.1 Denmark imported 283 t Nd and 17.34 t Dy in 2012. Until 2035, a threefold demand and appropriate import was estimated by Habib et al. (2014), resulting in 943 t Nd and roughly 52 t Dy. Respectively, the projected theoretical recycling potential for Nd from Danish wind turbines in 2035 could meet the Danish demand, according to 2012, by 7 %. Additionally, a full Dy-recovery and recycling in 2035 could meet the Danish demand from 2012 by nearly 9 %.

However, in case of a threefold demand in 2035, 943 t Nd could be covered by 2 % from secondary Nd sources from the wind energy sector, as well as nearly by 3 % of the forecasted Dy-demand.

After 2035, future scenarios and estimations affect the EoL-turbines and respective capacities. Therefore, the theoretical recycling potential starts to differ for the Hydrogen - and the Bio+ scenario. A comparison of both scenarios showed in 2048 for the Hydrogen scenario, 154 t NdFeB-material, as well as 44 t Nd and 3 t Dy. Respectively to the Danish demand of 2012, the secondary material could help to support the supply by 16 % (Nd) and 17 % (Dy). Assuming the projected demand in 2035, the available material contents in 2048 would contribute nearly 5 % (Nd) and roughly 6 % (Dy).

In contrast to this, the Bio+ scenario, which represented a low share of the wind energy in the future Danish energy mix, showed only 50 t NdFeB-magnets from decommissioned turbines, containing 14 t Nd and 1 t Dy. As previously done, also these amounts were set off against the demands and showed that 5 % Nd and nearly 6 % Dy according to the Danish demands in 2012. Using the increased estimated demand for 2035, the amounts recovered from EoL-turbines in 2048 could provide nearly 2 % Nd and 2 % Dy.
It can be concluded that a future path oriented on the Hydrogen scenario would not only lead to great expansions in the wind energy market and its installed capacity, but could also help to decrease Denmark’s dependence on REE-imports. Denmark could, when focusing on permanently-excited turbines, theoretically meet its own country’s demand of PM, Nd and Dy by some percentages.

Nevertheless, it has to be kept in mind that the imported amounts of NdFeB-magnets and Nd- and Dy-content do not necessarily stay in Denmark. A great extent of the imported REE are used for manufacturing wind turbines and other goods that are later on exported and, therefore, leave the Danish anthropogenic stock. However, because the industry is an important factor for a country’s welfare, also these demands of Nd and Dy have to be considered and met in any way.

### 6.2.3 Implications for the EU

To sum up, the results of this study demonstrated that theoretically available secondary NdFeB-magnet-material and Nd and Dy from EoL-wind turbines could partly meet the yearly demands for these materials in GER and DK.

Considering shortly the question whether REE can be reasonably secured by secondary sources in the EU to reduce the reliance on China, the answer would be: theoretically to a little extend. No other European country has more installed capacity in the wind energy sector like Germany. However, the REE-amount depends on the technologies that are used and also smaller amounts of PM can help to meet the future demand of the countries. Potentially, a European smelter and recycling facility for REE could be arranged and any PM from wind turbines could be used to reduce the import dependence.

Nevertheless, to be able to estimate the contribution of these secondary materials to the countries’ demand more realistically, the future development of REE-applications and, accordingly, how the countries’ demand of PM, Nd and Dy will change with time have to be taken into account. Since this information was not focused on in this study, it has to be concluded that the outflows from the anthropogenic stock can support the material-supply to various extends, when no losses and a complete recovery and recycling of the materials is considered. However, a complete independence from REE-imports seems not achievable in both countries. Nonetheless, besides the factor of supply risks, another point in favor of REE-recycling was to reduce the impacts of the balance problem, which could be accomplished, even though it might be of little intensity.
6.2.4 A generalized discussion

Yet in practice, it has to be kept in mind that the PM is only one component, not compulsorily but optionally, of the whole wind turbine. Despite the fact that REE-primary production and refining is connected with heavy pollutions, the negative environmental impacts of tremendous amounts of steel and concrete required for the wind turbines have to be set in relation and are greater compared to the REE-production (Garrett & Rønde, 2013). Currently in Germany, discussions and investigations for regulating the deconstruction of wind turbines as well as for putting a product stewardship for turbine components are considered, but this will take some time.

Even though a full recovery and recycling were considered when interpreting the results, it has to be stated that there is currently no option for REE- and PM-recycling in Europe. Whether a recycling procedure is feasible depends most importantly on the global REE-prices. Therefore, several factors influencing the REE-prices with respect to trade reliances should be analyzed. For example, Mancheri et al. (2019) could identify that global REE-prices depend heavily on national Chinese policies, which have to be kept in mind as well.

Introducing respective recovery and recycling logistics in Europe could be beneficial for a more sustainable handling of primary resources. But the fact that the collected materials would be shipped to China or Japan for refining does not put GER or DK in a better position on the REE-market and does not reduce the supply risk of critical raw materials. Potentially, a combination with primary production in Europe, in case of achieving better social acceptance of mining projects in the EU, would make a recovery and recycling strategy more interesting.

Like it is the case for most of the empirical research, the findings of the present work are limited by some conditions. In this regard the limitations of the present study include most importantly the fact that the presented scenarios and results cannot be seen as a prediction of the future. Instead, they rather represent a possibility to explore ways of future development by using the currently available technologies and policies. It might be possible that turbine technologies do emerge with time and substitutes can be found to create magnets as efficient as NdFeB-magnets. One example might be the trials to replace PM with high temperature superconductors (HTS), although they are still in the testing phase and require, just like permanent magnets, rare earth elements, like yttrium, cerium, and lanthanum (Glöser-Chahoud et al., 2016).

General problems that occurred were the discrepancies and inaccuracies regarding REE-data, like Zepf (2013) mentioned already in his book. With most data and diagrams it was
often not clear whether total installed capacity for a certain time was illustrated, or if gross- or net new-built turbines or capacities were shown. Even institutions reporting and providing large-scale analyses over years offered different numbers of installed wind turbines and various installed capacities [MW/a] from the past although it should be stated fact and exact data should be available.

In summary, with the presented results it can be calculated which amount of NdFeB-material or single rare earth elements, like Nd and Dy, would be required to make an introduction of recycling-logistics (in Europe) economical feasible, considering, for instance, factors like the prices for primary produced neodymium and dysprosium.
7 Conclusion

Securing rare earth elements (REE) for a stable supply require sustainable management strategies in Europe due to a complicated production chain and dependence on China as the main producer of REE. These elements are of high economic importance for Europe but underlie a supply risk. They are used in different applications and elements like neodymium (Nd), dysprosium (Dy), praseodymium and terbium can be found, for instance, as permanent magnets (mostly NdFeB-magnets) in wind turbines. Since there is currently no primary production of REE in Europe, it is of interest to analyze the urban mining opportunities as well as recovery- and recycling possibilities for REE, using end-of-life (EoL) wind turbines as secondary source. It is of interest whether PM-material, Nd- and Dy-contents from wind turbines could potentially help to meet the future demand of REE in Europe while, simultaneously, reducing the dependence on China and help to tackle the balance problem. Although nearly no recycling of PM, and Nd and Dy in particular, do yet take place, the aim of this thesis was to identify current and upcoming stocks and material flows of the permanent magnets and their containing rare earth elements in the wind energy sector. Two European countries, Germany and Denmark, were chosen as case studies to be compared, using available data and regulations for the creation of possible future scenarios, and modeling the theoretical recycling potential of Nd and Dy in both countries. Because of wind turbines’ long service-lifetime, the timeframe for the analyses was set until 2050. The PC-program Umberto® and the information system DyMAS were used for calculations and modeling.

It could have been identified that the German anthropogenic stock contains generally greater amounts of NdFeB-magnets and REE in particular compared to the Danish stock. Assuming no losses and a full recovery and recycling of these materials that become available in the anthropogenic stock, it can be concluded that the countries’ demand could partly be met by using secondary Nd and Dy from EoL-wind turbines. Using the available data about operating wind turbines until 2018, it was possible to evaluate the anthropogenic stock and REE-contents that become available by deconstructing wind turbines by 2035.

Due to the fact, that in both countries an increase in permanently-excited turbines could have been identified in recent years until 2018, the corresponding out-flowing PM-material and the containing REE from EoL-turbines is increasing as well until roughly 2035.

Considering the German PM-imports of 2012 as orientation for the yearly demand, it could be identified that Nd (92 t) and Dy (7 t) from EoL-turbines in 2035 could meet the yearly
German demand by 4 % each. Moreover, roughly 260 t NdFeB-material could be identified. After this year, the NdFeB-, Nd- and Dy-contents from EoL-turbines differ respectively to the capacities that will be installed in the next decades. Therefore, in 2048 between 80 - 200 t Nd and 6 - 14 t Dy could be identified as theoretically recycling potential, which could meet the demand by 3 - 8 % per element.

Similarly, for Denmark 7 % Nd-demand could be covered by 20 t Nd in 2035, as well as 9 % Dy by using the 1.5 t Dy Available at Danish deconstructed wind turbines. According to the different future scenarios, in 2048 14 - 44 t Nd could be potentially be recovered and could help to meet the demand by 5-6%. Furthermore, Dy-amounts of 1 to 3 t (2048) could support the Dy-imports by 6-17 %.

The information provided in this study can be used for further investigations in order to identify best possible recovery and recycling strategies. The long lifetimes of the wind turbines offer a longer timeframe up to the point of decommissioning. So, an information base and some planning could make a better and efficient deconstruction possible and valuable parts could be recovered more easily. The presented results could serve as orientation for further decision-making and estimations at which point an introduction of recovery-logistics (in Europe) for NdFeB-magnets, and Nd and Dy in particular, could be economical feasible, in case of overcoming currently existing recovery – and recycling problems. However, from a current point of view the long service times of wind turbines lead to a delay in scrap generation and, therefore, do not contribute to recycling potentials today.

It can be concluded that the results of this work provide detailed information about the Danish and German anthropogenic stock and its containing NdFeB-, Nd- and Dy-amounts from the Danish and German wind energy sector.
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References


European Commission (2015). *Closing the loop - An EU action plan for the Circular Economy. Communication from the Commission to the European Parliament, the Council, the European economic and social Committee and the Committee of the Regions*. Brussels. Available at: https://eur-lex.europa.eu/resource.html?uri=cellar:8a8ef5e8-99a0-11e5-b3b7-01aa75ed71a1.0012.02/DOC_1&format=PDF.


IEA (International Energy Agency) (2012). 2012 Amendment of the Renewable Energy Sources Act (EEG 2012). 2012. Available at: https://www.iea.org/policiesandmeasures/pams/germany/name-25107-en.php?si=dHlwZT1yZSZZzdGF0dXM9T2s.&return=PG5hdiBpZD0iYnJlYWRjcnVtYiI-PGEgaHJlZj0iLyI-SG9tZTwvYT4gJnJhcXVvOyA8YSBocmVmPSIvcG9saW1nZWNhbnRtZWFzdXJlcy8iPiBvbGljawZIcZCBZCZNWFzdXJlc2VvYT4gJnJhcXVvOyA8YSBocmVmPSIvcG9saWNpZ XNhbnRtZWFzdXJI-


Kurronen, P., Haavisto, M. & Pyrhönen, J. (2010). Challenges in applying permanent magnet (PM) technology to wind power generators. Available at: https://pdfs.semanticscholar.org/e981/2ca05f3fc273bbf95f45ed2c93b4cc0305a7.pdf.


Wuppertal Institut (2014). *KRESSE - Kritische mineralische Ressourcen und Stoffströme bei der Transformation des deutschen Energieversorgungssystems. Abschlussbericht an das Bundesministerium für Wirtschaft und Energie (BMWi)*. Wuppertal Institut für Klima, Umwelt, Energie GmbH, BmWi, BMU. Available at: https://epub.wupperinst.org/frontdoor/deliver/index/docId/5419/file/5419_KRESSE.pdf.


Appendix 1: Comparison of different turbine concepts and their efficiencies

Kurronen et al. (2010) compared the different efficiencies and capacity wins of turbines using a permanent magnet (PM) in comparison to a doubly-fed induction generator (DFIG). It can be observed that at different wind speeds the permanently-excited wind turbines offer the best result compared to the DFIG-turbine with no PM (Kurronen et al., 2010).

<table>
<thead>
<tr>
<th>2 MW drive train with different generator types</th>
<th>DFIG</th>
<th>SG-PM-HS</th>
<th>SG-PM-MS</th>
<th>DD-PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average wind speed: 5.4 m/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual energy production</td>
<td>2435 MWh</td>
<td>2549 MWh</td>
<td>2636 MWh</td>
<td>2641 MWh</td>
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<tr>
<td>comparison with DFIG</td>
<td>100.0%</td>
<td>104.7%</td>
<td>108.3%</td>
<td>108.5%</td>
</tr>
<tr>
<td>Average wind speed: 6.8 m/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual energy production</td>
<td>4041 MWh</td>
<td>4146 MWh</td>
<td>4263 MWh</td>
<td>4233 MWh</td>
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<tr>
<td>comparison with DFIG</td>
<td>100.0%</td>
<td>102.6%</td>
<td>105.2%</td>
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<td>Average wind speed: 8.2 m/s</td>
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<td>Annual energy production</td>
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<td>comparison with DFIG</td>
<td>100.0%</td>
<td>101.7%</td>
<td>104.3%</td>
<td>103.0%</td>
</tr>
</tbody>
</table>

Note. DFIG=doubly-fed induction generator; SG=synchronous generator; DD=direct drive; PM=permanent magnet; HS=high-speed gear; MS=middle-speed gear
Appendix 2: Gross newly build capacities [MW] in Germany from 2001-2018

Distinguished according to the four turbine concepts that were used for modeling the (future) scenarios

<table>
<thead>
<tr>
<th>[MW]</th>
<th>Onshore DD</th>
<th>Onshore others</th>
<th>Onshore DD-PM</th>
<th>Onshore SG-PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>728</td>
<td>1896.4</td>
<td>0</td>
<td>34.8</td>
</tr>
<tr>
<td>2002</td>
<td>1193.9</td>
<td>2043.1</td>
<td>1.3</td>
<td>1.3</td>
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<td>2003</td>
<td>897.3</td>
<td>1747.2</td>
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<td>0</td>
</tr>
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<td>2004</td>
<td>851.2</td>
<td>1182</td>
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<td>3.5</td>
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<td>731.2</td>
<td>1064.8</td>
<td>0</td>
<td>11.9</td>
</tr>
<tr>
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<td>869.4</td>
<td>1302.4</td>
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<td>155.8</td>
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<td>361.5</td>
<td>19.4</td>
<td>65.4</td>
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<td>2017</td>
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<td>2481.2</td>
<td>233.1</td>
<td>489.1</td>
</tr>
<tr>
<td>2018</td>
<td>1264.7</td>
<td>678.3</td>
<td>86</td>
<td>372.8</td>
</tr>
<tr>
<td>[MW]</td>
<td>Offshore DD</td>
<td>Offshore others</td>
<td>Offshore DD-PM</td>
<td>Offshore SG-PM</td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
<td>----------------</td>
<td>----------------</td>
<td>----------------</td>
</tr>
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Appendix 3: Gross new-built capacities [MW] in Denmark from 2000-2018

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Appendix 4: Cumulative capacity in GER (GreenEe-scenario)
Appendix 5: Gross new-installed capacity in Denmark (Bio+)
Appendix 6: Yearly element input to the anthropogenic stock (all scenarios)

German BAU scenario

German GreenEe scenario
Danish Hydrogen scenario

Danish Bio+ scenario