Design of collection strategies for neodymium magnets present in end-of-life wind turbines and electric vehicles in the European Union

Master of Science Thesis

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by

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Summary

The demand for electric vehicles (EVs) and wind turbines has been rising significantly in the EU as the EU wants to become carbon neutral by 2050, and generate 40% of its energy through renewable sources in order to avoid climate change and its consequences. However, both these technologies use several critical raw materials that are essential for their functioning. Wind turbines generate electricity through the use of generators and EVs are driven by the motors. An essential component used in both these technologies is neodymium magnets. Neodymium magnets are made up of rare earth elements (REEs), which are defined as critical raw material by the European Commission as they have significant economic value and a high supply risk associated to them. Out of the various applications of REEs across various products and industries, REEs are most widely used in making permanent magnets (PMs) and in particular neodymium magnets. It is expected that by 2025, the biggest demand of neodymium magnets will come from EVs and wind turbines in the EU. The production of REEs and neodymium magnets is primarily done in China and China holds near perfect monopoly as it produces 94% of the worlds neodymium magnets. At present, the EU is heavily reliant on China to fulfil its neodymium magnet demand of nearly 16000 tons/year, as the production capacity of the neodymium magnets in the EU is less than 1%. Against the massive usage of the magnets in the green technologies, the focus on recovery and re-use of the REMs from the end-of-life (EoL) products is not sufficient as less than 1% of the magnets are recycled in the EU. A large number of wind turbines and EVs are going to reach their EoL, which can be a massive secondary source of neodymium magnets that can be reused or recycled. However, in order to reuse or recycle neodymium magnets, these magnets first need to be collected, which is seen as an opportunity. Only when a high collection rate is achieved, significant amount of magnets can be recycled into magnets or their constituent REEs and contribute to a more secure access of REEs in the EU.

The main objective of the thesis is: ***Design of collection strategies for salvaging neodymium magnets from end-of-life electric vehicles and wind turbines in the EU***. As part of the thesis objective a set of collection strategies for neodymium magnets in the EoL EV motors and wind turbine generators will be presented. Currently, no such strategy is present and it is paramount to develop a set of strategies to avoid the loss of neodymium magnets in different waste streams.

To fulfil the thesis objective, a design approach is used in five stages: Initial Opportunity, Explicate Opportunity, Define Requirements, Design and Develop Artefact, and Evaluate Artefact. In the first stage, Initial Opportunity, the necessary background information is given and a literature review is conducted to analyse the work up til now in the relevant domain. In the second stage, Explicate Opportunity, four analyses have been done.

First, a market analysis is done primarily through desk research, which includes looking at grey literature and scientific articles. Market analysis was conducted to understand the following:
The market conditions that may affect the collection of neodymium magnets, estimated volume of neodymium magnets that will be available for collection and recycling once the EVs and wind turbines reach EoL in the EU, and the supply chain of EoL EVs, wind turbines, PM motors and generators that contain neodymium magnets to understand the flow of neodymium magnets better and identify the correct actors in the supply chain who will play an essential role in the collection process. Through market analyses, it was found that neodymium magnets are offered at very competitive prices by China, which can threaten collection and recycling in the EU. Furthermore, through quantifying the amount of neodymium magnets that may be available at EoL of EVs and wind turbines, it was found that volume of scrap magnets will increase exponentially. To tackle this issue and salvage the neodymium magnets, the scale of collection and recycling has to be increased significantly. Mapping the supply chain revealed that although the wind turbines and EVs serve different markets (one serves industries while the other serves consumers), the EoL PM motors and generators reach the same actor in the supply chain- companies that recycle motors and generators. In addition, it was found that the PM motors are going outside the EU for recycling because of high labour charges in the EU, which implies that the EU is losing neodymium magnets and the REEs that are defined as critical to the EU economy. Thus, necessary measures need to be introduced to stop the flow of neodymium magnets outside EU.

Second, analysis on reuse and recyclability of neodymium magnets was done to understand the dismantling of PM motors and generators to extract the magnets from the assemblies, possibility of re-using the magnets and the recycling technologies that are most suitable for neodymium magnet recycling. It was found that dismantling the PM motors for removing the neodymium magnets was time consuming and thus expensive. The barrier to extracting the magnets from motors with relative ease is due to lack of consideration for 'design for dismantling' and 'design for recycling' during the design phase of the PM motors. This implies that when the volume of EoL PM motors will increase the dismantling of PM motors will pose a big problem. For PM generators, the process was relatively easy and a higher profit could be made due to large amount of magnets and other materials like iron, copper, aluminum etc. Furthermore, the best recycling route was found to be the Hydrogen Processing of Magnetic Scrap (HPMS) which saves nearly 88% energy compared to neodymium magnets produced through virgin materials. However, recycling through the HPMS route demands that there is flow of information about the type of magnets, the chemical composition and the grade of the neodymium magnets in the recycling value chain.

Third, legal analysis was performed by desk research. Scientific articles and EU directives and frameworks were studied to assess the rules that are in place which govern what happens to the EoL EVs, wind turbines, and the neodymium magnets in them. It was found that the current legislation severely limits the possibility of collecting and recycling neodymium magnets from EoL EVs and wind turbines. This is primarily because the aim of the EU to secure access to critical raw materials like REEs and neodymium magnets is not reflected in the legislation in place. Furthermore, the policies like End-of-life Vehicle (ELV) Directive have a mass-based recycling target which promotes only the recycling and recovery of bulk materials like iron, copper, aluminum, plastics, etc. In addition, the Extended Producer Responsibility (EPR) is not applicable to wind turbine industry which shifts the burden of recycling wind turbine and its components to the wind farm owners.

Fourth, stakeholder analysis was conducted with the approach by Bryson, 2004 to identify the stakeholders who will have a direct and an indirect involvement in the collection of neodymium magnets from EoL EV motors and wind turbine generators. Through Power versus Interest grid, the 'Players (who have high power and high interest), 'Subjects' (having high interest but relatively low power), 'Crowd' (having low power and interest), and were identified. The table below gives an overview of all the stakeholders and the category they are placed in.

Table 1: Overview of different stakeholders

Players	**Subjects**	**Crowd**
European Commission	European Group of Automotive Recycling Association	REE mining proponents
EIT RawMaterials	Car dismantling companies	Civil Society actors
European Raw Materials Alliance	Wind turbine dismantling companies	
Member States	Wind farm owners	
Motor/generator collectors and recyclers		
Wind turbine OEMs		
Automobile OEMs		
European Recycling Industries' Confederation		

The analyses was used to make final set of objectives and constraint for the collection strategies. Furthermore a set of eighteen 'Need to have' requirements that the collection strategies should fulfil were made. The requirements were further used to make primary and secondary functions. Three primary functions that were made are as follows: Support the development of secondary market, Address the legal limitations and important stakeholders, and Address specifications for reuse and recyclability.The primary functions were broken down into secondary functions that the collection strategies must perform.

On the basis of the secondary functions, alternative means were developed that could fulfil each of the secondary functions. Based on the alternative means generated, the most suitable ones are selected that could fulfil the secondary functions and meet the the objectives and constraint. This resulted in the final set of collection strategies that were divided into three phases- Short term plan (can be implemented in 3-6 years), medium term plan (can be implemented in 6-9 years), and long term plan (can be implemented in 9-12 years). Within each of the phases, the solutions were categorised into one of the five labels/themes: Legalisation and Regulation, Information exchange, Finance, Infrastructure development, and Material flow. The figure 1 below shows the solutions that can be implemented in the short term, medium term and long term by the EU.

	Legislation and Regulation	Information exchange	Finance and Infrastructure development	Material flow
Short Term Plan	1. Assigning collection rate for PM motors and generators based on calculation. 2. Update the ELV Directive with PM motor take-back requirement. 3. Ban the export of PM motors and generators to countries outside the EU.	1. Run awareness campaign for motor/generator recyclers. 2. AND/OR Spread awareness through organising seminars. 3. AND/OR Spread awareness through approaching associations that represent recyclers. 4. Recommend Member States like Germany, France to invest in recycling through HPMS process. 5. Enforce labelling system for motors and generators containing magnets. 6. Recommend automobile OEMs to share data on type of magnets through International Dismantling Information System (IDIS).	1. Attract private investments for recycling through HPMS process. 2. AND/OR Create tax shields for businesses investing in recycling of NdFeB magnets. 3. AND/OR Provide tax incentives for extracting magnets from PM motors and generators. 4. Provide subsidies to OEMs for choosing to source EU produced recycled magnets (not short term specific but can be applied when required).	1. Commence research and introduce design for dismantling and recycling directive for PM motors and used in EVs. 2. Conduct surveys with motor/generator recyclers to identify safety hazards. 3. Involve OEMs to share their safety protocols while dealing with NdFeB magnets.

	Legislation and Regulation	Infrastructure development	Finance	Material flow
Medium Term Plan	1. Make EoL wind turbine directive with PM generator take-back requirement. 2.Make regulatory initiative targeting PM motors and generators from all industries and introduce EPR covering NdFeB magnets.	1. Develop economical and efficient dismantling process of EV motors and generators. 2. AND/OR Encourage development of new waste stream for PM motor.	1. Provide Carbon credits on amount of magnets extracted.	1. Involving wind turbine OEMs into developing guide for dismantling of PM generators to extract NdFeB magnets. 2. Advice wind farm owners to track the movement of PM generators and the magnets within them.

	Legislation and Regulation	Infrastructure Development
Long Term Plan	Regulating share of recycled magnet to be sourced.	Invest in different recycling technologies

Figure 1: Overview of the proposed collection strategies

Lastly, different validation ways of validating the design were discussed and the solutions were validated by experts in the field of neodymium magnet recycling through the means of a short questionnaire

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AC	alternating current.
BEV	battery electric vehicle.
CAGR	Compound Annual Growth Rate.
CoSEM	Complex Systems Engineering and Management.
DC	direct current.
DFIG	doubly fed induction generator.
DG	Directorate General.
DMP	Data Management Plan.
DSR	Design Science Research.
EIT	European Institute of Innovation and Technology.
EoL	end-of-life.
EPR	extended producer responsibility.
ERMA	European Raw Material Alliance.
EV	electric vehicle.
GW	gigawatt.
HPMS	Hydrogen Processing of Magnetic Scraps.
HREE	Heavy Rare Earth Element.
IDIS	International Dismantling Information System.
IPMSM	Internal permanent magnet synchronous motor.
LREE	Light Rare Earth Element.
MW	megawatt.
OEM	original equipment manufacturer.

PHEV	plug-in hybrid electric vehicle.
PI	power versus interest.
PM	permanent magnet.
PMSG	Permanent Magnet Synchronous Generator.
PMSM	Permanent magnet synchronous motor.
PRO	producer responsibility organisation.
REE	Rare Earth Element.
REM	rare earth magnets.
REO	Rare Earth Oxide.
RMF	rotating magnetic field.
SCIG	squirrel cage induction generator.
SDG	Sustainable Development Goal.
SPMSM	Surface mounted permanent magnet synchronous motor.
VAT	value added tax.

CHAPTER 1

Introduction

1.1 Background

The transition towards green technology has led to the usage of plethora of materials like silicon in solar panels, lithium and cobalt in electric vehicle batteries, rare earth elements in wind turbine generators and electric vehicle (EV) motors. The demand for these materials has been rising as countries across the globe install more wind turbines, switch to emission free transport by using EVs and install more solar panels on the rooftops. The EU-27 has been in the forefront of deploying these green technologies to have a net zero emission of the greenhouse gases by 2050 ("A European Green Deal — European Commission", n.d.) and avoid climate change and its dangerous consequences. However, in order to build these technologies the EU-27 relies heavily on other countries for raw materials that are highly important for the EU economy and have significant supply risk linked to them, these raw materials are referred to as critical raw materials. ("Critical raw materials", n.d.).

1.1.1 Rare Earth Elements

One of the important group of elements from the periodic table called the Lanthanide series are an essential raw material for the development of industries, commercial and household applications(Goodenough et al., 2018). The elements in the Lanthanide series are called Rare Earth Elements (REEs), the REEs constitute of 17 elements (figure 1.1) in total and are divided into Light Rare Earth Elements (LREEs) consisting of lanthanum (La) to gadolinium (Gd) and Heavy Rare Earth Elements (HREEs) consisting of terbium (Gd) to lutetium (Lu) (Panagopoulou, 2018). REEs are referred to as "rare" because the REEs were found only in one of the deposits in the 18th century in Sweden and were never seen before ("History and Future of Rare Earth Elements — Science History Institute", n.d.). However, contrary to their name "Rare earth", the REEs are abundant throughout the earth. Despite the REEs high abundance, the number of ores present is limited. In addition, the extraction of REEs is not economically viable as all REEs exist together and cannot be mined separately. Thus they are mined together and separated later using various physical and chemical processes(Commission et al., 2020). However, not all elements obtained after processing are as valuable as others, for instance, cerium and lanthanum, and need to be disposed off (Commission et al., 2020). Moreover, the REEs are often found with radioactive elements, which makes the extraction of these elements dangerous to humans and other life forms (Bailey et al., 2017). Extracting REEs to produce 1 ton of Rare Earth Oxides (REOs)[1] from ion adsorption clay deposit produces 1000 tons of wastewater (contains acid and heavy metals) and 2000 tons of tailings (a by-product of mining operation); furthermore, the refining process of 1 ton of REOs is estimated to produce 1.4 tons of radioactive waste (Mancheri et al., 2019).

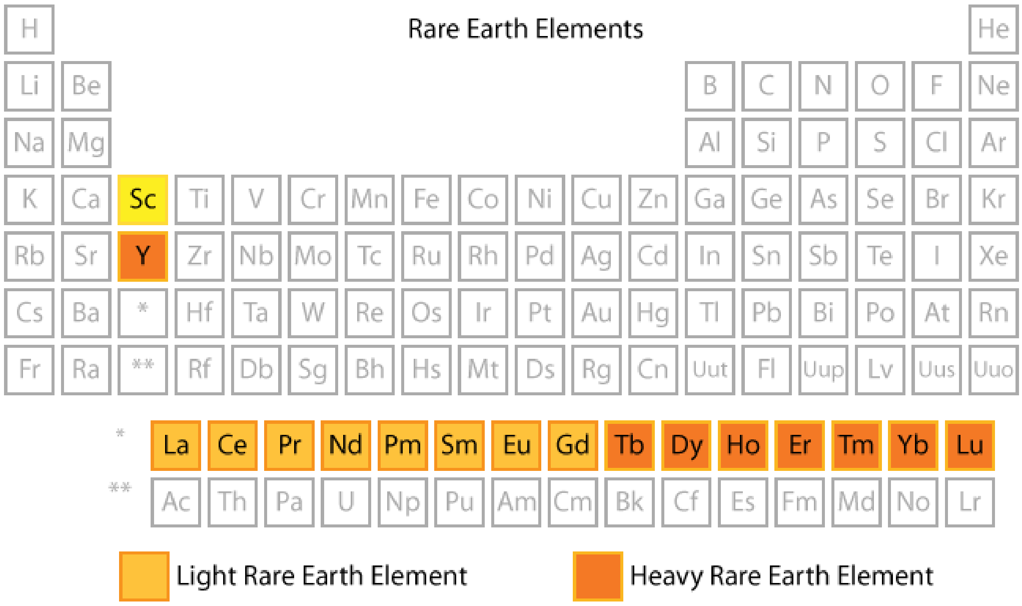


Figure 1.1: Periodic table marked with Light REEs and Heavy REEs (source: "Rare Earth Elements" (2021))

1.1.2 Neodymium magnets

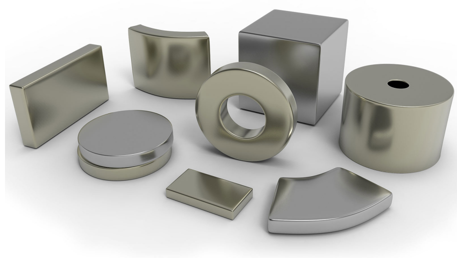
The REEs have been used in making rare earth magnets (REM), catalysts, polishing agents, glass, ceramics etc (Goodenough et al., 2018; Riaño and Binnemans, 2015). Out of the various applications of REEs across various products and industries, REEs are most widely used in making permanent magnets (PMs) and in particular the neodymium magnets, which have led to an increase in the consumption of neodymium (Nd), praseodymium (Pr), and dysprosium (Dy) (Goodenough et al., 2018; Riaño and Binnemans, 2015). Neodymium magnets are the most powerful PMs that are available till date (Coey, 2020; Cui et al., 2022; Weir et al., 2020).They were simultaneously and independently developed by Sumitomo Special Metals Company in Japan and General Motors in the United States of America in 1984 (Kapustka et al., 2020), and since then, no new magnet has been introduced (Cui et al., 2022). Neodymium magnets are primarily composed of three elements; 25-30% neodymium, 60-70% iron, and 1% boron by weight (Maani et al., 2021). Neodymium, the REE, gives the magnet its magnetic property. Neodymium is a metal and is antiferromagnetic in nature which allows it to be magnetised (Weir et al., 2020). Neodymium by itself has a low Curie temperature[2], however, if it is used to make an alloy with different metal like dysprosium (another REE) then the curie temperature can be as high as 300 degree Celsius (Weir et al., 2020). Dysprosium is added in small quantities ($<$ 5% by weight) so that the magnets can perform in hot operating conditions without getting demagnetised. The neodymium magnets are categorised into two

[1] Rare earth oxides- Rare earth elements are very reactive in the presence of oxygen; thus, Rare earth oxides are made and sold as final products due to their thermal stability ("Using Rare Earth Oxides to Make Fluorescent Glasses", 2020)

[2] The temperature at which the magnet starts to loose its magnetic properties ("What is the Curie temperature of magnets? - IMA", n.d.)

types- polymer bonded[3] and sintered neodymium magnets[4] (figure 1.2). The performance of sintered magnets is superior than polymer bonded magnets, thus they are extensively used in wind turbine generators, and EV motors (including both battery electric vehicle (BEV) motors and plug-in hybrid electric vehicle (PHEV) motors), MRI machines, washing machines, hard drives and smartphones (Binnemans et al., 2021; Stanford Magnets, n.d.-a). It is expected that by 2025, the biggest demand of neodymium magnets will come from EVs (including BEV and PHEV) and wind turbines in the EU(Goodenough et al., 2018).

(a) Bonded Neodymium Magnets
(Source:Stanford Magnets (n.d.-a))



(b) Sintered Neodymium Magnets
(Source:Arnold Magnetic Technologies (n.d.))

Figure 1.2: Types of Neodymium Magnets

1.1.3 Why collect neodymium magnets?

The production of the REEs and subsequently the neodymium magnets are primarily done in China. The worldwide production of neodymium magnets in 2019 was 130,000 tonnes, out of which 94% of these magnets were produced in China, and less than 1% were produced in the EU(Gauss et al., 2021). The EU is heavily reliant on China for fulfilling their REE demand due to no active REE mining in the EU (Binnemans et al., 2021). In addition, there is an increased supply risk for the neodymium magnets which are crucial for electricity generation through wind turbines and emission free transport through EVs. At present, the EU sources 16000 tonnes of REMs per year, in particular the neodymium magnets (NdFeB magnets) from China (Gauss et al., 2021) to fulfil their demand for various technologies, including wind turbines and EVs.

Against the massive usage of the magnets in the green technologies, the focus on recovery and re-use of the REMs from the end-of-life (EoL) products is not sufficient as less than 1% of the magnets are recycled in the EU (Binnemans et al., 2021; Gauss et al., 2021). A large number of Wind turbines and EVs are yet to reach their EoL as they have a lifetime of 20-25 years (Pavel et al., 2017) and 10-12 years ("Average age of the EU vehicle fleet, by country - ACEA ", 2022), respectively. With the ever increasing demand for neodymium magnets for emission free mobility and electricity generation in the EU, where there is no REE mining, recycling the REMs in the urban mine becomes crucial (Binnemans et al., 2021) to "securing access to sustainably produced rare earth magnet" (Gauss et al., 2021). Furthermore, environmental pollution due to mining of REEs and the production of the neodymium magnets demands that the neodymium magnets be reused and recycled to avoid the production from virgin materials. However, in order to recycle significant quantities of neodymium magnets from wind turbines and EVs, the recycling value chain needs to be well developed to collect, process, re-use and recycle the REMs to close the material loop, and make the supply chain less dependent on

[3] Polymer bonded neodymium magnets are a complex composite made of powdered magnet, adhesives and resin (Stanford Magnets, n.d.-a).

[4] Sintered neodymium magnets on the other hand are formed by powder metallurgy, this involves heating the powder magnet below its melting point and then pressing it into a compact form called magnet blank (Stanford Magnets, n.d.-b).

China for neodymium magnets produced using virgin materials. In order to recycle sufficient amount of neodymium magnets in the EU, these magnets need to be collected from the EoL wind turbines and EVs. Only when a high collection rate is achieved, significant amount of magnets can be recycled into magnets or their constituent REEs.

1.2 Analysis of relevant domain

A literature study was conducted to analyse the relevant domain on collection and recycling of neodymium magnets. The literature study is based on the methodology described in the section 2, and a table summarising the articles reviewed can be found in the Appendix B. The studies that were reviewed used methods like Dynamic Material Flow Analysis (Ciacci et al., 2019; J. Li et al., 2020), Quantitative Analysis (München et al., 2021), system dynamics modeling (Sprecher et al., 2015), and qualitative analysis (Bonfante et al., 2021; Ferron and Henry, 2015; Løvik et al., 2018). München et al., 2021 studies the recycling potential of neodymium magnets obtained from Hard drives and mobile phones in Brazil. The authors quantify the "recycling potential estimate" of Nd, Dy, Pr and Tb that could be salvaged from the waste generated by hard drives and mobile phones between the period of 2010-2019 is based on the assumption that there is 100% collection and recycling rate. The results show that the recovered Nd, Dy, Pr and Tb from recycling could be used in more than thousand new wind turbines (München et al., 2021). A similar study was done in Europe with wider array of products (Washing and drying machines, wind turbines, EVs, acoustic transducers, etc.) by Ciacci et al. (2019). The study quantifies the stock of Nd from 1990 to 2016 used in various products. The author concludes that almost 50% of annual Nd demand in EU-28 can come from secondary sources (i.e. in-use stock and EoL products) based on the assumption that there will be 100% collection of these secondary sources (Ciacci et al., 2019). Ciacci et al. (2019) highlights that there are waste directives for Waste Electrical and Electronic Equipment (WEEE) and EoL vehicle but they are focused in recovery of metals such as iron, copper and aluminium that are already available in large quantities. This implies that the directives should be updated, but the study fails to address how to ensure a high collection of the secondary sources.

Sprecher et al. (2015) focuses on developing a supply chain resilience framework for neodymium magnets, the authors identify recycling as one of the means to diversify the supply of neodymium magnets but argues that recycling will not serve the masses and emphasize on design for recycling. However, the study fails to take into account that the situation could be improved by developing effective collection system for EoL products containing neodymium magnets. J. Li et al. (2020) studies the mismatch in demand from wind turbines and supply of REEs (Ny, Dy and Pr) for ten regions across the globe, the authors conclude that recycling is one of the long term strategies to tackle the problem but also indicate that recycling of REMs will be hindered as there is no strategy to collect the magnets from offshore wind turbines (J. Li et al., 2020).

Bonfante et al. (2021) conducts literature review to understand what type of sustainability is being studied in REM supply chain and how the studies contribute to achieve the Sustainable Development Goals (SDGs). One of the conclusions that was derived was that a "solid collection scheme and transportation infrastructure" (Bonfante et al., 2021) were necessary for production of magnets from secondary source. Ferron and Henry (2015) conducts a review to highlight the uses of rare earth metals in different products and based on that identifies scrap sources for recycling. The authors identify that collection and transportation of scraps from various sources plays an important role in the development of successful recycling system. Løvik et al. (2018) reviews the ongoing government funded research in the area of critical metals for Europe, and it was concluded that one of the neglected areas is the waste collection of EoL products. To close the supply chain of neodymium magnets, it is important to develop the collection strategies that would target the recovery of neodymium magnets from EoL EVs and wind turbines in the EU. The gaps that can be identified from the literature review are as follows:

1. The articles reviewed that used quantitative models take the assumption of 100% collection for secondary sources containing neodymium magnets. However, how such a high collection rate can be achieved in the first place is not discussed.

2. Collection is identified as a weak link in the recycling value chain by articles that were reviewed. However these articles do not elaborate on how the collection can be improved for secondary sources.

3. Most of the studies considered in the review focus on a wide variety of secondary sources or on single source like hard drives. However, no study as of now has focused specifically on EVs and wind turbines as secondary source of REEs. In addition, none of the studies that were reviewed do not look closely into the supply chain of individual secondary sources. As a consequence, the flow of the devices containing the neodymium magnets are not mapped and the actors in the supply chain which should be addressed are not identified.

1.3 Scope

The focus of this thesis is on two technologies which use neodymium magnets- EVs which includes PHEVs and BEVs, and wind turbines located both onshore and offshore in the EU. From here on, the acronym EV will be used to refer to both BEV and PHEV, and when 'wind turbine' is used, it refers to both onshore and offshore wind turbine unless stated otherwise. EVs and wind turbines are chosen primarily for two reasons.

Firstly, both these technologies are highly demanded in the EU due to climate and carbon neutrality goals of the EU ("A European Strategy for low-emission mobility", n.d.; "Onshore and offshore wind", n.d.). As the EU is part of the Paris Agreement, the EU is switching to energy production through renewable energy resources like wind energy, solar energy, geothermal energy, etc. In addition, the EU is reducing greenhouse gas emissions by making plans of switching from gas powered cars to EVs. The EU policymaker have also voted for banning the sale of gas powered vehicles from 2035 ("EU Parliament votes to ban sale of petrol cars, rejects weak reforms to emissions trading", 2022). With such ambitious plans being in place the demand for EV is increasing each year in the EU. On the other hand, the demand for wind turbines is also increasing significantly as the EU plans to generate 40% of the all its energy from renewable sources ("Renewable energy targets", n.d.). To do so the EU is expected to build 32 gigawatt (GW) of wind farms each year (Komusanac et al., 2022). In 2020, the neodymium magnets used in EV motors and Wind turbines represented 12.5% and 45.62%, respectively, of the total annual consumption of neodymium magnets in the EU (Gauss et al., 2021). By 2025, both wind turbines and electric vehicles are expected to generate the highest demand for neodymium magnets in the EU (Goodenough et al., 2018).

Secondly, the amount of neodymium magnets present in EVs and wind turbines is much higher compared to the amount of neodymium magnets used in hard drives, mobile phone, speakers etc. The larger quantity of magnets also indicates the larger size of the magnets used in EVs and wind turbines. A BEV motor is estimated to contain nearly 2.1 kg of neodymium magnet, while a PHEV motor contains roughly 1 kg of neodymium magnets (Elwert et al., 2016). A wind turbine can contain 80kg/megawatt (MW) to 650kg/MW of neodymium magnet depending on the type of wind turbine (Pavel et al., 2017). This makes both the EVs and wind turbines a good secondary source of neodymium magnets at their EoL. It is also important to note that the EVs also use neodymium magnets in the motors used in the steering wheel, and the audio systems. However, they are not considered in the scope of the thesis.

1.3.1 Geographical Scope

Initially it was decided to limit the geographical scope to four countries- Germany, the Netherlands, France, and Belgium (Western Europe). These four countries were selected because in terms of wind capacity in the EU, the four countries together have nearly 51% of all the wind capacity installed in the EU (Komusanac et al., 2022). Furthermore, Germany has the largest installed wind capacity installed in the EU. In terms of EVs, Germany has the highest number of EV registered till date, followed by France and the Netherlands.

However, later in the thesis, after talking to multiple experts, stakeholders and going through grey literature and scientific literature, it was found that the supply chain of EoL EVs and wind turbines are more or less similar across the EU, respectively. For EVs, it is so because the End-of-life Vehicle directive (Council directive 2000/53/EC, 2020) governs how the supply chain is organised, this is explained in detail in sections 3.5.1, and 5.1. For wind turbines, there are no EU laws in place (explained in section 5.1) that direct the flow of the EoL wind turbines. Thus the EoL wind turbine market is organised in such a way that wind turbine dismantling companies have a similar approach to tackling the materials and components after taking down a wind turbine (explained in detail in section 3.5.2). Moreover, legislation at an EU level is insufficient and missing for targeting neodymium magnets. Thus the scope of the thesis is taken as entire EU.

1.4 Thesis Objective

On the basis of the background presented and the identification of collection of neodymium magnets as an opportunity the objective of the thesis is defined as:

Design of collection strategies for salvaging neodymium magnets from end-of-life electric vehicles and wind turbines in the EU.

The proposed strategies will give an insight into the actions that the EU can implement in order to ensure that neodymium magnets present in the EoL EV motors and wind turbine generators are not lost in different waste stream or exit the EU due to weak and inefficient collection process. The proposed strategies are based on four analyses-

1. The market analysis presented in chapter 3 gives insight into the neodymium magnet market, alternative technologies that do not use neodymium magnets, estimates the amount of neodymium magnets that may become available from EoL EVs and wind turbines, and maps the supply chain of EoL EVs and motors within them, EoL wind turbines and the generators within them, and the neodymium magnets present in motors and generators.

2. The analysis of reusability and recyclability of the neodymium magnets is presented in chapter 4 gives insight into the possibility of reuse and the most suitable recycling technology to recycle neodymium magnets and the technical aspects that are required to be taken into account during collection for efficient recycling.

3. The legal and stakeholder analysis presented in chapter 5 gives insights into the current legislation and tools in place that govern what happens to the EoL EVs, wind turbines and neodymium magnets. Furthermore, the stakeholder analysis presented in chapter 5 gives insight into the stakeholders that need to be involved in order to address the issue of collection of the neodymium magnets from the EoL EV motors and wind turbine generators.

To achieve the thesis objective, a design approach is taken, which is explained in detail in chapter 2.

1.5 Link with CoSEM

The thesis and the Complex Systems Engineering and Management (CoSEM) masters program have a strong interconnection because of the following reasons. First, the collection subsystem is an essential part of a well functioning recycling system, which is a complex socio-technical system. If societies do not have a well functioning recycling system is place then it can lead to valuable resources being wasted. In this case, the neodymium magnets, which may be small in size but essential for the EU to move towards a greener future. However, these magnets come at a cost which is not only financial but environmental and social, as production of these magnets involves mining of REEs which are responsible for not only carbon emissions but also sulfur emissions, wastewater generation, and radioactive wastes (Mancheri et al., 2019). Thus recycling these magnets becomes social and an environmental responsibility which needs involvement of both public and private stakeholders, this makes it an interesting CoSEM problem. Secondly, the thesis examines the market of neodymium magnets and REEs, the existing legislation for collection and recycling, the upcoming technologies for recycling the magnets, the supply chain, which makes it multi-disciplinary in nature. Lastly, an intervention is designed, which can lead to collection and eventually a high collection rate of these magnets for recycling in the EU. All these elements combined make it a CoSEM thesis.

1.6 Thesis Outline

The thesis report consists of nine chapters in total. This chapter gives the background, presents the scope, and states the objective of the thesis, including the design objective. Chapter 2 explains the thesis approach, which includes discussing the selection of suitable design methodology and the thesis flow diagram. The thesis flow diagram is used to show the stages of the thesis along with the sub-questions that are answered in the various stages. Furthermore, the methods used for data collection during the different stages are discussed.

Chapter 3 to 5 present the analyses done in the thesis. Chapter 3 gives an overview of the market for neodymium magnets, which includes insights into the demand for these magnets, the threat of competition and the pricing of the magnets, and the potential volume of neodymium magnets available from EoL EVs and wind turbines. Furthermore, alternative technologies that do not use neodymium magnets are looked into. The chapter ends by presenting the supply chain of EoL vehicles, wind turbines, generators, motors, and neodymium magnets. Next, chapter 4 discusses the dismantling techniques of PM motor and generators, along with possibility of re-using the magnets and the recycling of the magnets. Next, chapter 5 looks into the existing EU laws related to EoL vehicles, wind turbines and magnets. Furthermore, a stakeholder analysis is shown which highlights the stakeholders that will be involved or be affected by the collection strategies.

Then, chapter 6 presents the requirements and functions of the collection strategies. Next, chapter 7 presents the means to achieve the functions along with the designed collection strategies. Then, chapter 8 discusses how the proposed design can be validated. Finally, chapter 9 provides the conclusion, further research that can be done, and academic and societal relevance.

CHAPTER 2

Thesis Process Methodology

2.1 Thesis Approach

Herbet A. Simon first made the distinction between traditional science or exploratory science and the science of the artificial, now known as Design Science (Dresch et al., n.d.). Simon argued that it is not enough to have science that just understands and explains phenomena, systems, and problems (Dresch et al., n.d.). Instead, there should be science focused on solving problems and creating interventions that can enhance or alter the current systems to have a better system (Dresch et al., n.d.). Design science aims to minimise the gap between theory and practice through a method called Design Science Research (DSR). The method uses research to form an artifact or make recommendations (Dresch et al., n.d.).
The objective of the thesis as explained in section 1.4 is to design a set of collection strategies that can be implemented by the EU. In order to design such strategies, a design approach has been taken. As part of the design approach, the DSR framework by Johannesson and Perjons (2014) has been used as a basis to structure the design approach used in the thesis. This framework was found when a suitable design methodology was searched to serve as a guide for this thesis project.

2.1.1 Selection of suitable design methodology

Traditionally, the design methodology by Dym et al. (2004) has been a popular choice amongst students at the Technology, Policy, and Management faculty at TU Delft, and for good reasons. The prescriptive design methodology of Dym et al. (2004) is very well structured but at the same time gives enough room to the designers by offering various design tools for creating a broad design space. Some of these tools have also been used in the design phase of this thesis. However, to take up a challenge and to challenge the status quo, a different design method was sought. In the quest to search for a suitable design method, two other design methods were looked into. The first method was found through the help of graduation committee and the second method was introduced in one of the courses in the CoSEM programme.

1. "A Three Cycle View of Design Science Research" by A. Hevner (2007), in which A. Hevner, 2007 proposes three cycles- the relevance cycle, the design cycle and the rigor cycle. The relevance cycle acts as a bridge between the artefact that is being designed and the environment that it will be used in. The design cycle is an iterative process between building artefact and evaluating it, and lastly the rigor cycle connects the design

with scientific knowledge and expertise. Figure 2.1 shows the design cycles by A. Hevner (2007).

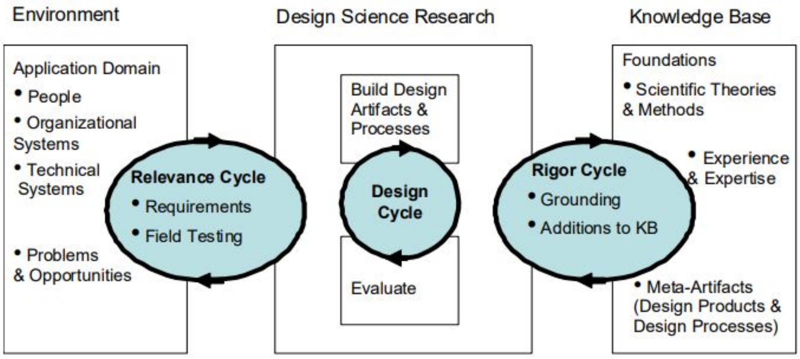


Figure 2.1: Design cycles by A. Hevner (2007)

2. Design Science Research process model by Peffers et al. (2007), in which six activities are defined: Identify Problem & Motivate, Define Objectives of a solution, Design & Development, Demonstration, Evaluation and Communication as seen in figure 2.2.

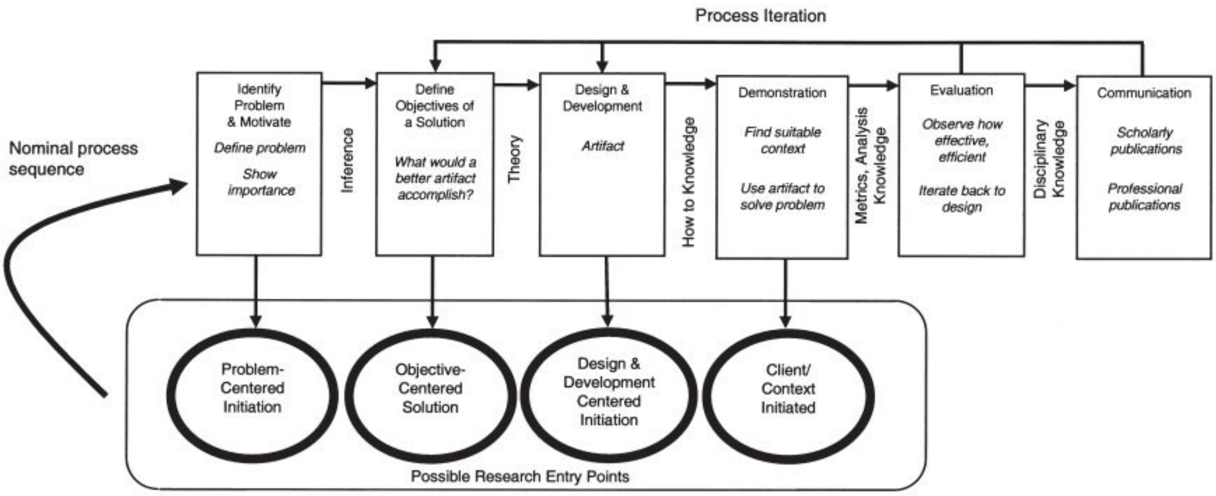


Figure 2.2: DSR process model by Peffers et al. (2007)

The method by A. Hevner (2007) was not selected as it was open-ended and did not provide sufficient guidance related to the design process. The DSR process model by Peffers et al. (2007) was not chosen as it does not include the process of identifying requirements before the Design & Development phase. Moreover, the design process is not explained in detail, making it hard to follow.
The DSR framework by Johannesson and Perjons (2014) is explained in much detail in the book "An introduction to Design Science" (Johannesson and Perjons, 2014) and acts as a good guide not only for the design process but also for using different methods (Questionnaire, surveys, interviews etc.) for research. It is also important to mention that all three DSR frameworks (A. Hevner, 2007; Johannesson and Perjons, 2014; Peffers et al., 2007) have their origin in information systems. However, they can be applied to cases of different nature, such as the socio-technical system (Johannesson and Perjons, 2014) considered in the thesis. Furthermore,

it can be argued that socio-technical systems share similarities with information systems as "information systems and the organizations they support are complex, artificial, and purposefully designed. They are composed of people, structures, technologies, and work systems." (A. R. Hevner et al., 2004).
Figure 2.3 shows the framework by Johannesson and Perjons (2014). The framework consists of five major stages: Explicate Problem, Defining requirements, Design and Developed Artefact, Demonstrate Artefact, Evaluate Artefact. The framework may look sequential; however, Johannesson and Perjons (2014) asserts that the design process is always iterative in nature and the arrows in the framework should be viewed as input and output relationships. In the next section, this framework is combined with the thesis flow diagram, which better represents the iterative nature of the design process.

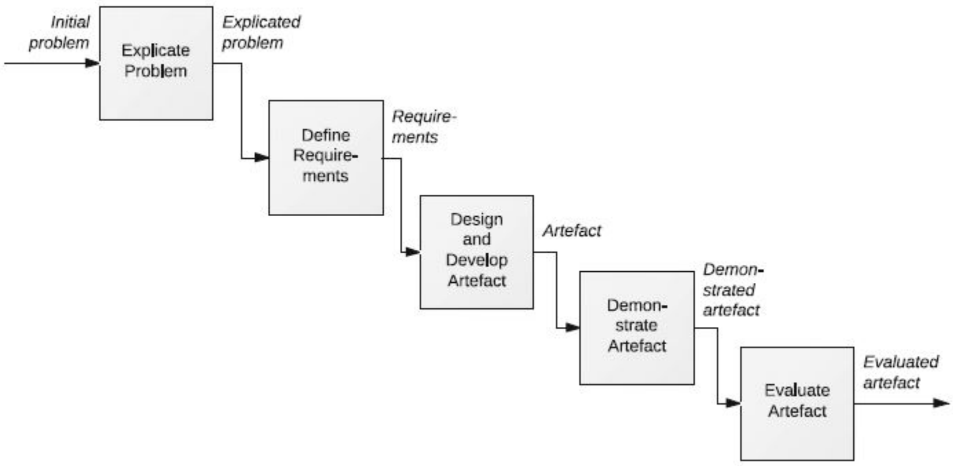


Figure 2.3: Framework by Johannesson and Perjons (2014)

2.1.2 Thesis Flow Diagram

The thesis flow diagram is presented in figure 2.4. The stages from the framework of Johannesson and Perjons (2014) are combined with the thesis flow diagram. The stage 'Demonstrate Artefact' is skipped in the thesis due to time constraints. Furthermore, within each of the presented stages, various methods like quantitative analysis, qualitative analysis, and parts of design methods, in particular, the morphological chart by Dym et al. (2004) have been used.
The thesis flow diagram has three elements: On the left side, the design stage is indicated in italics. In the middle, the rounded rectangular boxes show the chapters, and the rectangular boxes within them show the methods used in that particular chapter. On the right-hand side, the thesis objective and the sub-questions that one or more chapters will answer are shown. It should be noted that the name of the stages as proposed by Johannesson and Perjons (2014) in the framework has been changed. In particular, Initial Problem is renamed as 'Initial Opportunity' and Explicate Problem is renamed as 'Explicate Opportunity'; it is done so because the collection of the neodymium magnets is an initiative that will help the EU in securing access to the neodymium magnets and thus is not a problem but an opportunity.

The thesis flow diagram starts with **Introduction** in chapter 1, which is part of the 'Initial Opportunity', it introduces the topic of the thesis by giving appropriate background and analysing the relevant domain. Chapter 2 is **Thesis Process Methodology**, which is the current chapter explaining the approach and the methods taken in the thesis. Chapter 3, 4, and 5 together will answer the ***SQ1: What is the current state of the system in which the collection strategies will be employed?*** and are part of the 'Explicate Opportunity' stage.

The methods primarily used in chapters 3-5 are desk research, semi-structured interview with experts and a stakeholder, questionnaires, and quantitative analysis. Chapter 3 is **Market Analysis of neodymium magnets**, it will present the market of REMs and in particular neodymium magnets and answer *SQ 1.1- What does the market of neodymium magnets look like?.* Chapter 4 is **Analysing reuse and recyclability of neodymium magnets**, which will analyse the possibility to reuse and recycle the neodymium magnets from EoL EV motors and wind turbine generators, thus answering *SQ 1.2 What is the possibility of re-use and recyclability of neodymium magnets?.* Chapter 5 is **Legal and Stakeholder Analysis**, which will present the analysis of current rules in place that govern what happens to EoL EVs, wind turbines and neodymium magnets. Furthermore, the chapter will present a stakeholder analysis to identify the relevant stakeholders and their interests and positions. Chapter 5 will answer *SQ 1.3 -What legislation are in place that governs the flow of EoL EVs, wind turbines and neodymium magnets?* and *SQ 1.4-Which stakeholders will be involved or affected by collection strategies?.* Chapter 6 is **Requirements and Functions** and is part of the 'Define Requirements' stage. This chapter will use the input from the 'Explicate Opportunity' stage and present a list of requirements and corresponding functions of the collection strategies, thus answering ***SQ 2- What are the requirements and functionalities for designing the collection strategies?***. Chapter 7 is *Conceptual Design* and is part of the 'Design and Develop Artefact' stage, in this chapter the solutions will be generated and based on that a set of collection strategies will be provided for the short term, medium term and the long term that can be implement in the EU. Chapter 8 is *Design Validation*, and is part of the 'Evaluate Artefact' stage. It will present the different ways of validating the proposed collection strategies and thus answers ***SQ 3- What are different ways of validating the design and which is chosen?*** . Finally, *Discussion and Conclusion* will be presented as part of Chapter 9.

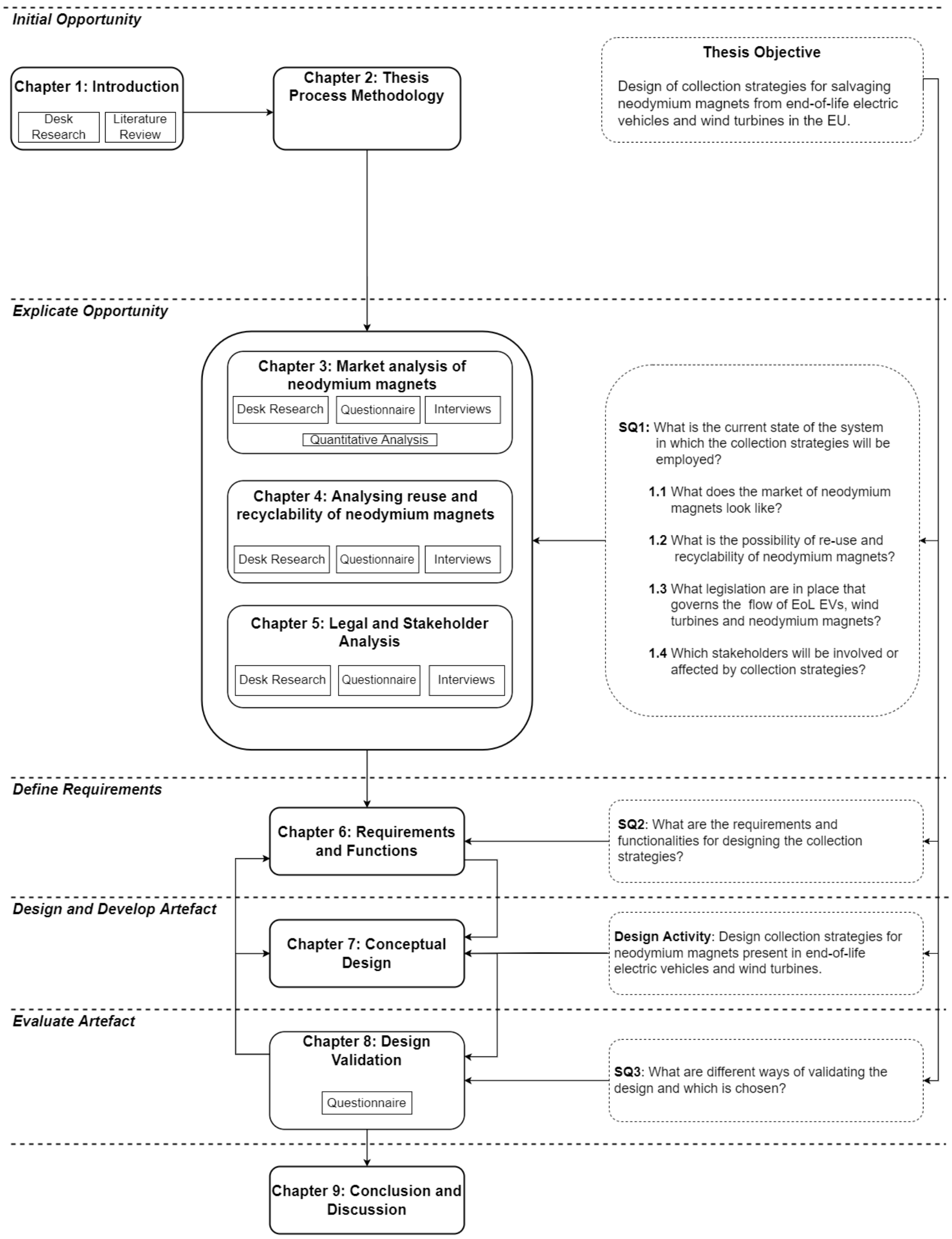


Figure 2.4: Thesis Flow Diagram

2.2 Methods

Various methods have been employed as part of the design approach that have been taken in the thesis. This section is organised as per the the stages (in italics) shown in thesis flow diagram on the left side.

2.2.1 Stage 1: Initial Opportunity

Methods used: Literature Review, Desk research.

Literature Review was used to find the analyse the relevant domain in order to find gaps for the design to be build. The literature search was done through Scopus to find relevant articles related to collection, recycling and supply chain/closed loop supply chain of neodymium magnets. Articles were searched within the title-abstract-keyword section. The search terms used was: rare AND earth AND (metal OR magnet) AND (recycling OR collection) AND ("supply chain" OR "closed-loop supply chain"). Two filters were applied, language of the articles was set as English and the year of publication was set as 2015 onwards. The articles were screened based on reading the title, then abstract, and if needed the conclusion. The articles were included if they were related to supply chain or closed loop supply chain of neodymium magnets. Any articles that were related to material science, or specific recycling techniques detailing chemical processes were excluded. A full search scheme is presented in the Appendix B.1.

Desk research was used for finding information about REMs and types of neodymium magnets, desk research was conducted to find grey literature and scientific articles from Google searches and Google Scholar, respectively.

2.2.2 Stage 2: Explicate Opportunity

This stage includes chapters 3 to 5. The three chapter combined answer the **SQ1- What is the current state of the system in which the collection strategies will be employed?**. The methods used in SQ1 are organised as per the sub sub-questions and are as follows:

SQ 1.1- What does the market of neodymium magnets look like?

Methods used: Desk research, Questionnaire, Quantitative Analysis, Semi-structured interviews.

Desk research was the primary form of data collection for this part. The backward snowballing technique was used to find articles that focused on REE and REM markets to find relevant scientific articles. To use this technique, the articles found in the Literature Review presented in section 2.2.1 were used as a source to review the references. Based on the title of the articles, relevant articles were chosen. Furthermore, grey literature like websites and reports were used to find appropriate information related to the market of neodymium magnets.

Quantitative Analysis is used in the form of making a quantification model that estimates the amount of neodymium magnets that may become available for collection from EoL wind turbines and EVs located in four countries in Western Europe- the Netherlands, Belgium, France, and Germany. Ideally, the quantification should be done for all the EU countries, however, due to time constraints only four countries are chosen due to reasons explained in section 1.3. The model is made using Microsoft Excel, and the data required for the model and the assumptions taken are explained in detail in section 3.4.

Questionnaire was used as supplementary data to map the supply chain of EoL wind turbines, EVs, and motors, generators, and neodymium magnets within them. The use of questionnaire is explained in detail in the next section (2.2.2).
Semi-structured interviews were also used as a supplementary data to map the supply chain

of EoL wind turbines, EVs, and motors, generators, and neodymium magnets within them. The use of semi-structured interviews is explained in detail in the next section (2.2.2)

SQ 1.2- What is the possibility of re-use and recyclability of neodymium magnets?

Methods used: Desk research, Questionnaire, Semi-structured interviews.

Desk research was used to find scientific articles related to dismantling of EV motors, and wind turbine generators through Google Scholar. A search scheme for finding the articles for dismantling wind turbine generators can be found in the Appendix B.2. Furthermore, to find information related recycling techniques for neodymium magnets, grey literature (websites, project reports) and scientific articles were looked into. To keep the search scope for scientific articles related to recycling techniques narrow, the "CORDIS- EU research results" database ("Search — CORDIS — European Commission", n.d.) was used to find recycling techniques that have been used up till now by the EU Horizon 2020 projects. This database gave access to a list of projects that are ongoing and that have been completed. All the projects have their website, which acts as a source for project reports and other relevant information.

Questionnaires were prepared for participants who could not find time for an interview. In total two separate questionnaires were prepared for wind turbine OEM and wind turbine dismantling company, respectively. The questionnaire for Wind turbine OEM was designed using Google Forms. As the participant indicated that he were extremely busy. The questionnaire included a mix of open and closed ended questions to gather the necessary information related to wind turbine generator recycling. The other questionnaire was prepared for a wind turbine dismantling company based in Lithuania using Microsoft Word and sent through email to gather information related to wind turbine dismantling; however, the contact person is yet to responded to the questionnaire.
The disadvantage of the questionnaire is that it does not allow for back and forth questioning (Johannesson and Perjons, 2014), which gives much more detailed information. Furthermore, the questionnaire is a slower method of gathering data compared to interviews. Both the questionnaires can be found in the Appendix A.3.1, A.3.2.

Semi-structured interviews were conducted with experts who have previously conducted research on REEs or neodymium magnets or are currently involved in doing research. Three expert interviews were conducted in total to gain insight into the technical, legal, stakeholder, and market aspects of collection of neodymium magnets from EoL EVs and wind turbine. In addition, one stakeholder interview was conducted with a company that recycles motors and generators (referred as motor/generator recycler in the rest of the thesis). Before conducting the interviews, a Data Management Plan (DMP), participant information document and a consent form were prepared. The DMP detailed the type of data that is gathered, how it is gathered and stored and for how long is it stored. Next the participant information form (summarising the purpose of the interview, and highlighting the) and consent forms (Appendix A.1) were given to the participants who agreed to take part in the study. Furthermore, as per the DMP all the participants were made anonymous in the study.
All the interviews took between 30-60 minutes. The semi-structured interviewing style helped gather more information about specific issues as a set of open-ended questions was prepared before the interviews, which led to an interactive interview session with the experts. However, the disadvantage of conducting interviews is that it takes significant waiting time to get a response from the potential participants and significant processing time to summarise the interviews. The expert interviews can be found in the Appendix A.

SQ 1.3- What legislation are in place that governs the flow of EoL EVs, wind turbines and neodymium magnets?

Methods used: Desk research

Desk research was the primary data gathering method for this part. Scientific articles were found through Google Scholar on the relevant topics related to this part. Furthermore, EU directives and regulations were looked into through European Commission's website ("Waste and recycling", n.d.).

SQ 1.4- Which stakeholders will be involved or affected by collection strategies?

Methods used: Desk research, Questionnaire, Semi-structured interviews.

Desk research was primary source of data gathering for this part. Grey literature (articles, company websites, and reports) was used to find relevant information about the stakeholders and their positions. Furthermore, to structure the stakeholder analysis, the "What to do when stakeholders matter: A guide to stakeholder identification and analysis techniques"," book by Bryson (2004) was referred to. The method of structuring is explained in section 5.2.

Questionnaire was used to gather data from a major wind turbine OEM related to wind turbine generator recycling as explained in the previous section 2.2.2.

Semi-structured interview was conducted with a motor/generator recycling company based in the Netherlands, which specialises in motor/generator recycling to better understand the supply chain of motors and generators and their role in the recycling of neodymium magnets. The summary of the interview can be found in the Appendix A.3.

2.2.3 Stage 3: Define Requirements

This stage answers the **SQ2: What are the requirements and functionalities for designing the collection strategies?**. The input for this stage comes from the last stage- Explicate Opportunity. First, the objectives and constraints of the collection strategies are defined. Then, a list of 'Need to have' and 'Nice to have' requirements for the collection strategies is prepared based on the analyses conducted in chapters 3 to 5. Each requirement can be traced back to the particular sections of the analyses or interviews and questionnaires. Based on a final set of 'Need to have' requirements, the functionalities of the collection strategies are formulated.

2.2.4 Stage 4: Design and Develop Artefact

In this stage, the **Design Activity: Design collection strategies for neodymium magnets present in end-of-life electric vehicles and wind turbines.** is conducted. The input of this stage are the functions that are prepared as part of the last stage. For each of the functions, means are explored with the help of morphological chart. The morphological chart is a matrix in which the leftmost column is reserved for the list of functions that the design must perform, and across each of these functions, means are listed that could help fulfil the function (Dym et al., 2004). The morphological chart helps to expand the design space and create potential alternative designs (Dym et al., 2004). It is important to note that the Morphological chart has not been used in the traditional manner where only one means across each of the function is chosen. Contrary to the traditional method, for some functions, multiple means have been selected. The means that have not been chosen are elaborated in the chapter. Finally, based on the objectives and constraints of the collection strategies defined in chapter 6, the collection strategies are proposed. The proposed collection strategies are categorised into three phases- Short Term Plan (can be implemented in 3-6 years), Medium Term Plan (can be implemented in 6-9 years), and Long Term Plan (can be implemented in 9-12 years). Within each phase, the solutions are categorised into one of the five labels/themes defined in section 7.2.

2.2.5 Stage 5: Evaluate Artefact

In this last stage, **SQ 3: What are different ways of validating the design and which is chosen?** is answered. Different ways in which the design can be validated is presented by the means of logical reasoning. Furthermore, validation of the design is done by sending a validation document along with a small set of questions (presented in 8.2) to all the participants (experts and stakeholders that were interviewed) of the study and additional experts in the field of neodymium magnet recycling. In total, 11 (5 participants of the study and 6 additional experts) people were given the validation document and asked to validate the proposed collection strategies. Out of the 11 people, only 3 positive responses were obtained (2 participants that were interviewed previously-Expert 1 and 2, and an expert in field dismantling, recycling, waste management who is part of the Materials Science and Engineering faculty at TU Delft). Out of the remaining 9 people, 5 people could not validate the document due to busy schedule or personal reasons and the other 4 people did not respond.

CHAPTER 3

Market Analysis of neodymium magnets

This chapter elaborates on the market of REMs and, in particular, the neodymium magnets. The chapter starts by discussing the demand and price of REMs. Next, alternative motor and generator technologies that do not use neodymium magnets are looked at to understand if the PM motors have substitutes and how the change in technology affects the demand of neodymium magnets. After that the amount of neodymium magnets that may be available for collection and recycling from EoL EVs and Wind turbines is estimated for Western EU to understand the potential of collection and recycling. Lastly, the supply chain of the EoL EVs, wind turbines, motor, and generators are mapped.

3.1 Rare Earth Magnets and demand

The usage of REEs is ruled by the production of REMs and in particular, neodymium magnets (Mancheri et al., 2019; Yang et al., 2017). Mancheri et al. (2019) estimates that the market share of neodymium magnets is 30%, which is highest compared to other applications like Phosphors, catalysts, polishing agents etc. that use REEs. The demand for neodymium magnets started to increase after the invention of portable computers or laptops, which required the hard disc drives to be compact enough to fit in the laptops. In addition, the demand for magnets also increased due to the development of electric motors for EVs. However, the use of neodymium magnets is not limited to hard discs and traction motors anymore but is also used in a wide range of applications like wind turbines, magnetic resonance imaging machines, washing machines, smartphones, speakers, etc.

3.1.1 Imbalance between supply and demand

In 2019, the worldwide annual production of neodymium magnets was estimated to be 130,000 tons, and China produced nearly 122,200 tons of these magnets, which accounts for 94% of the world production (Gauss et al., 2021). It is estimated that the global production of neodymium magnets between 2020 and 2030 is increasing at a Compound Annual Growth Rate (CAGR) of 7.1%, which is slower than the global demand, which is estimated to rise at a CAGR of 9.7% between 2020 and 2030 ("Adamas Intelligence, UBS Rare Earth Forecasts Only Tell Half the Story - Adamas Intelligence", 2021). This clearly shows that the supply will not be able to cope with the demand in the coming years. Furthermore, recycling may only partially fulfil the demand for the neodymium magnets required for EVs and wind turbines.

The Balance Problem

The annual production of REOs in 2021 was estimated to be 280,000 tons (Daniel, 2022) compared to 110,000 tons in 2015 (National Minerals Information Center, 2015). However, these numbers do not give the actual representation of individual REE that are present (Binnemans and Jones, 2015). The REE (neodymium, dysprosium, praseodymium) used to make the Neodymium magnets are not available in equal amounts in the ores, this is due to natural difference in proportion of REE (Binnemans and Jones, 2015). The REE that have higher atomic number (HREE) are less readily available than REE with lower atomic number (LREE). In addition, according to Oddo-Harkins rule, elements that have an even atomic number 'Z' in the periodic table are more abundant than elements having an odd atomic number (Nikanorov, 2016). For instance, in LREE ores, Cerium (Z=58) is much more abundant than praseodymium (Z=59) and Lanthanum (Z=57) (Binnemans and Jones, 2015). Similarly, in HREE ores, Ytterbium (Z=70) is more abundant compared odd atomic number REE. However, the use of REE with lower abundance is much higher compared to the more abundant REE. While mining, some REE are much more available compared to other REE that are required by the market. This creates what is popularly known as the balance problem between the demand and the supply; the balance problem is an essential issue for the REE industry which can lead to shortages of highly demanded neodymium magnets (Binnemans and Jones, 2015). Binnemans and Jones (2015) finds that recycling and reduced usage of REE in the technologies can play a part in alleviating the balance problem.

3.1.2 Impact on EVs and Wind turbines

Regarding EVs, Chinwego et al. (n.d.) estimates that there will be a shortage of 48,000 tons of magnets annually for roughly 25 million EV motors that will be produced globally in 2030. The shortages are expected to arise due to limits in the production capacity of Chinese magnet manufacturers and very limited production capacity of other countries like Japan, the United States of America and Europe. Moreover, the demand for magnets from automobile industry is increasing rapidly as countries around the world encourage their citizens to move towards emission free transport options. By 2030, it is estimated that the global EV market alone would require nearly 25% of the entire neodymium magnet production (Dolf Gielen et al., 2022). Seventeen of the EU-27 countries are motivating their citizens to adopt EVs by providing them incentives("Overview – Electric vehicles: tax benefits & purchase incentives in the European Union (2021) - ACEA - European Automobile Manufacturers' Association", 2021). This adds to the demand generated by the customers, which the automobile OEMs have to fulfil by producing more EVs, which increases the demand for neodymium magnets.
The demand for the neodymium magnets generated by the wind industry is also increasing significantly. The EU has planned to increase the share of power generated by renewable energy to 40% by 2030, and to achieve this target the EU needs to install 32 Giga Watts of wind capacity each year from 2021 onward (*SUSTAINABILITY REPORT 2020- ENERCON*, 2020; "Wind Europe, Europe's building only half the wind energy it needs for the Green Deal, supply chain is struggling as a result — WindEurope", 2022). Furthermore, the EU targets to generate 25% of all power by wind turbines by 2050 (Deng and Ge, 2020). Currently and in the future, Germany will be the largest wind market in Europe. "Wind Europe, Europe's building only half the wind energy it needs for the Green Deal, supply chain is struggling as a result — WindEurope" (2022) predicts that France and the Netherlands are the upcoming largest markets in the EU in terms of installations; they will install approximately 2GW and 1.9GW of wind capacity, respectively, from 2022 to 2026. The commitment of the EU towards moving to renewable energy production and mainly using wind turbines implies that there will be a significant increase in the number of wind turbines that are going to be installed both onshore and offshore. With the increase in demand for wind turbines, the demand for neodymium magnets will also increase significantly

as 76% of all offshore wind turbines and 30% of all onshore wind turbines in Europe in 2018 used Permanent Magnet Synchronous Generators (PMSGs) which uses neodymium magnets (Commission et al., 2020).
Two issues can arise if the supply of neodymium magnets does not fulfil the demand for EVs and wind turbines. First, the production of EVs and wind turbines may get affected, which can lead to the EU failing to meet its targets for power generation through renewable energy and phasing out of gasoline and diesel-powered vehicles by 2030. This would ultimately have an impact on the climate goals that the EU wishes to achieve. Secondly, there can be a significant increase in the cost of these magnets, and ultimately the cost of producing EVs and wind turbines will also increase (Serpell et al., 2021).
It can be argued that there can be alternative motor and generator technologies which do not use neodymium magnets that can be used to fulfil the EV and wind turbine demand, respectively. Thus, in section 3.3 both motors and generators that use neodymium magnets and the alternative technologies that are present are looked into.

3.2 Competition and Pricing

China has a monopoly in producing and supplying REOs and neodymium magnets. China is able to control the global price of REEs by having a strong hold over the entire value chain. China owns the value chain by mining the REE, forming REO for essential intermediate products like neodymium magnets (Mancheri et al., 2019). In addition, China has also introduced various policies that allow them to enjoy the monopolistic control (Mancheri et al., 2019).
In 2011, the prices of REOs exploded seven folds to what it was at the time due to Chinese export restrictions (Chen and Zheng, 2019; Mancheri et al., 2019; Sprecher et al., 2015). The yellow bar in the figure 3.1 shows the import data from the partners (i.e. all countries that import REE from China) of REE (in metric tons) from China, and the black line shows the traded value (in millions) as reported by trading partners of China. On the other hand, the blue bar shows the data on REEs as reported by China and the red line shows the corresponding value of the trade. Mancheri et al. (2019) argue that this difference is due to illegal mining activity in China. However, in both the data represented on the graph it can be seen that the exports have decreased significantly while the traded value has increased nearly seven times.

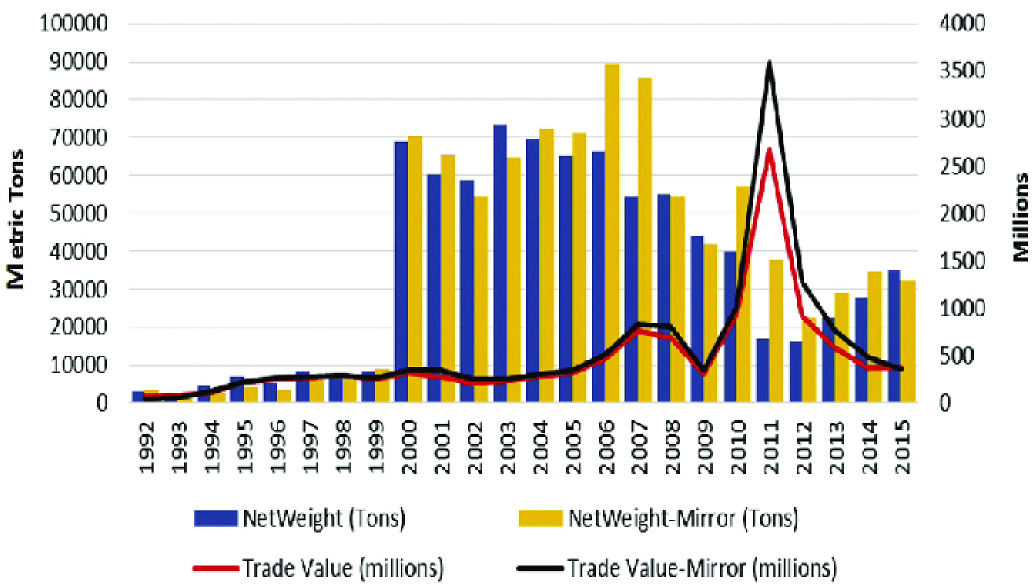


Figure 3.1: Export of REE from China (Source:Mancheri et al., 2019)

This directly increased the prices of rare earth products like magnets. During the same period, many new players tried to enter the market by planning to open REE mines. However, they soon went out of business when the situation turned around in 2013 when China eased the export quotas and increased the production of REE (Mancheri et al., 2019; Sprecher et al., 2015). This implies that China wants to keep enjoying the market power and can alter policies to keep the prices low to make it difficult for new players to enter the market. The Chinese REE industry is controlled by the government, and the mining companies receive subsidies from the central and state government (Gauss et al., 2021) which increases the profit margins of the mining companies. Additionally, there is a value added tax (VAT) refund on the export of magnets, but there is no VAT refund on the export of REOs, metals or alloys, which discourages mining companies from exporting the raw material for magnet production and enables the Chinese magnet manufacturers to offer the magnets to customers at a more competitive price compared to non-Chinese magnet manufacturers due to VAT refund scheme that is World Trade Organisation compliant (Gauss et al., 2021). As a result, the Chinese produced REMs are 20% cheaper compared to the non-Chinese REMs (Gauss et al., 2021).
However, recently the demand for neodymium magnets from EVs and wind turbines has sharply increased which has increased the prices of these magnets, this is partly due to increasing focus on energy transition by various countries across the globe ("Price development of neodymium magnets - supermagnete.de", 2022). The increase in cost of neodymium magnets is linked to three factors- cost of raw material, cost of labour, and cost of production. Three important materials are required for production of sintered neodymium magnets, neodymium, praseodymium, and dysprosium-iron alloy. The prices for all three of the rare earth metals is fluctuating frequently (China Magnets Source, 2022). From 2013 to 2020, the price of neodymium has been relatively stable. However, the price of neodymium in 2022 has been the highest in the last 10 years (figure 3.2), and the same is true for the prices of other elements in the neodymium magnets (figure 3.3). Given the fluctuations in the price of raw material, the cost of neodymium magnets lies between €50-100/kg depending on the quality of the magnets (Binnemans et al., 2021). Wind turbines and EVs use the highest quality of neodymium magnets, and the prices often fall in the upper spectrum of the range provided (Expert 1, A.2.1).

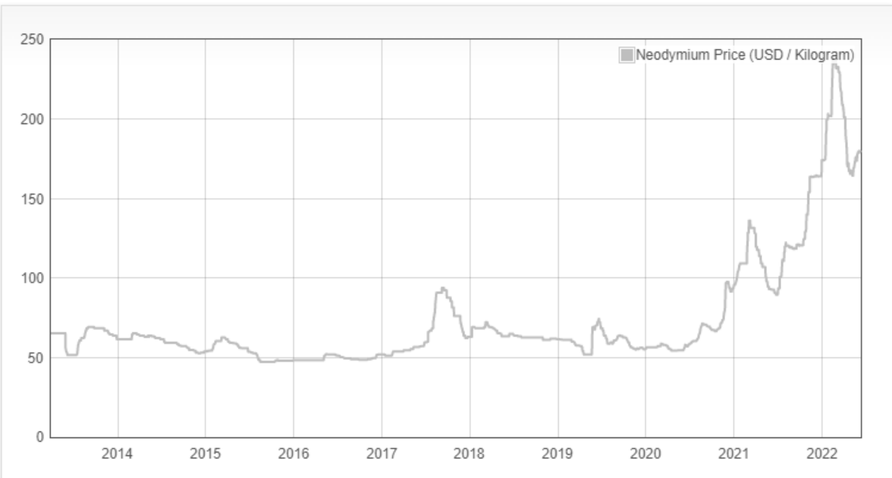


Figure 3.2: Neodymium Prices(per kg) for the Last 10 Years (source:Daily Metal Price, 2022)

PRODUCT (OXIDE)	(% PURITY)	USD/KG		
		2017	2018	24 DECEMBER 2021
Scandium	99.990	4 600	4 600	836
Yttrium	99.999	3	3	11.9
Lanthanum	99.500	2	2	2
Cerium	99.500	2	2	1.5
Praseodymium	99.500	65	63	140
Neodymium	99.500	50	50	143
Samarium	99.500	2	2	4.5
Europium	99.990	77	53	32
Gadolinium	99.999	37	44	76.2
Terbium	99.990	501	455	1 720
Dysprosium	99.500	187	179	452

Figure 3.3: Increase of prices (per kg) of REEs used in neodymium magnets (adapted from Dolf Gielen et al., 2022)

In view of the collection and recycling of neodymium magnets from wind turbines and EVs, it can be said that recycled magnets should be comparable to the price of neodymium magnets produced in China to be a lucrative option for the wind turbine and automobile OEMs in the EU. With the ever-increasing demand for neodymium magnets for emission-free mobility and electricity generation in the EU, where there is no REE mining, recycling the magnets contained in the urban mine becomes crucial (Binnemans et al., 2021) to ”securing access to sustainably produced rare earth magnet” (Gauss et al., 2021). Since the costs related to magnet sourcing are not only financial but also environmental and social since the environmental laws in China are less stringent and the social standards are not that high (Gauss et al., 2021; Mancheri et al., 2019). Thus, these issues need to be factored in when designing the appropriate collection strategies for EVs and Wind turbines.

3.3 Alternative technologies without neodymium magnets

This section is divided into three parts. First part explains the neodymium magnet based generators and its alternatives that are used in wind turbines. The second part, looks into the neodymium magnet based motors and its alternative used in EVs, and the third part discusses about the effects of innovation on demand of neodymium magnets. It should be noted that an overview will be given for the different generator and motor technologies but their functioning will not be discussed in detail as it is beyond the scope of this thesis.

3.3.1 Alternative generator technologies

To understand the different wind turbine generators, it is essential to understand the fundamentals of wind turbine generators. Wind turbine generators are mainly of three types- alternating current (AC) asynchronous generators (commonly known as Induction generators), AC synchronous generators and direct current (DC) generators (Cao et al., 2012). Wind turbines of relatively high power rarely use DC generators and will not be discussed further.

AC asynchronous Generator

AC Asynchronous Generators are also called Induction generators. Induction generators used in wind turbines are of mainly two types: doubly fed induction generator (DFIG) and squirrel cage induction generator (SCIG). These generators do not use permanent magnets (PMs) for excitation and rely on a three-phase AC supply to generate the required magnetic field. Wind turbine original equipment manufacturers (OEMs) choose to use induction generators because of their reliability and simplicity (Simoes et al., 2008).

Thus the well known alternatives to Permanent Magnet Synchronous Generator (PMSG) used in wind turbines are DFIG, SCIG (Commission et al., 2020). As the wind turbines get bigger in size (i.e >3MW), the gearboxes become more complex and the rotational speed of the turbines get slower. With more complex gearboxes used in the wind turbines the maintenance required also increases (Scott Semken et al., 2012).

AC synchronous generator

AC synchronous generators are excited with the help of electromagnets or PMs. Generators that are excited by electromagnets are called Electrically Excited Synchronous Generator (EESG), and generators excited with the help of PMs are called Permanent Magnet Synchronous Generator (PMSG). The use of PMSGs is due to their low mass and high power density (Cao et al., 2012), which decreases the generator's weight and increases the power to weight ratio of the wind turbine (Scott Semken et al., 2012). Furthermore, with the use of PMSGs, the need for gearbox gets eliminated in Direct Drive wind turbines which have become a very lucrative and popular option for offshore wind farms due to low energy losses and maintenance costs (Scott Semken et al., 2012).

Superconducting generators- The future generator

Another alternative that has been developing for a few decades is called the superconducting generator. The superconducting generators are compact and lightweight compared to traditional DFIGs and PMSGs, do not rely on neodymium magnets and can achieve higher torque in the same amount of space as PMSGs (Jensen et al., 2022). However, the superconducting generators come with challenges, like cooling the superconductor to -269 degrees Celsius to -223 degrees Celsius; this poses a challenge from a construction and operation viewpoint (Jensen et al., 2022). The cooling requirements, the high production price and the low production volume of these generators are barriers preventing the wind industry from using superconducting generators (Jensen et al., 2022). Furthermore, the superconducting generators may only be useful for very large wind turbines (>10 MW). They will only be produced if there is a strong demand from the wind farm owners (Jensen et al., 2022).

3.3.2 Alternative EV motor technologies

EV motors can be categorised into 2 types based on the type of current driving it: DC motors and AC motors. DC motors are run by electric charge that is flowing in a single direction while AC motors are run by electric charge that keeps changing its direction ("All you need to know about the motor of an electric car - Renault Group", n.d.). DC motors can be found in EVs but they are generally smaller due to low power ratings and are used in the steering column or the power windows (Karthik, 2019). The motor that drives the EVs are the AC motors. AC motors can be divided into two types- asynchronous and synchronous motors.

Asynchronous Motor (Induction Motor)

Asynchronous motors are also popularly known as induction motor. Induction motor was invented in the late 1800s by Nicolas Tesla. The necessary torque that the electric current needs to produce in the induction motor is gained by electromagnetic induction ("Induction Motor: How Does it Work? (Basics & Types) — Electrical4U", n.d.). The AC supply goes to the stator (which stays stationary or fixed) (figure 3.4) of the induction motor and produces a rotating magnetic field (RMF), the RMF in the stator induces magnetic field in the rotor (Evans, 2021). The rotors magnetic field interacts with the stators RMF which attracts the rotor thus spinning the shaft connected to it.

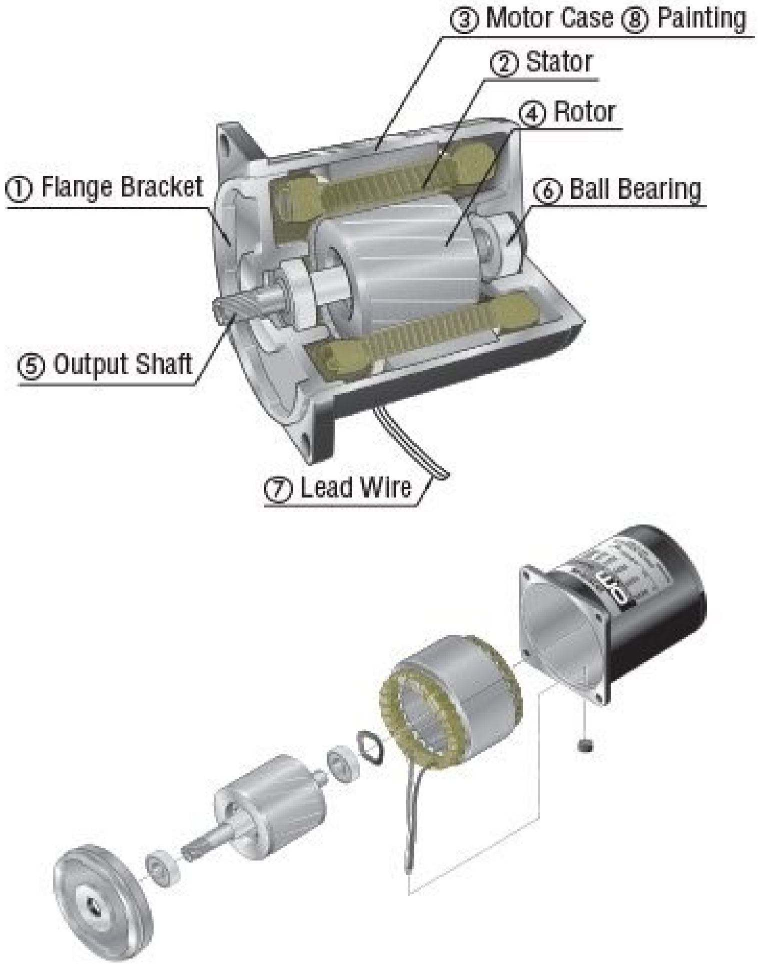


Figure 3.4: Exploded view of Induction motor (Karthik, 2019)

Synchronous motors

The other type of AC motor is Synchronous motor. Synchronous motors have been named so because the rotor rotates at the same speed as that of the rotating magnetic field, thus the rotor is in sync with the rotating magnetic field (Electrical4U, 2021).The motors which consist neodymium magnets- Permanent magnet synchronous motors (PMSMs)) come under the category of synchronous motors.

Permanent Magnet Synchronous Motor (PMSM)

The working of PMSM is dependent on the interaction between the RMF of the stator and the constant magnetic field generated from the neodymium magnets in the rotor. A torque is generated when the magnetic field of the rotor operates with the AC of the stator, thus revolving the rotor ("Permanent Magnet Synchronous Motor : Theory, Design, Working & Uses", n.d.). Mishra et al., 2014 states the following main advantages of PMSMs compared to induction motor:

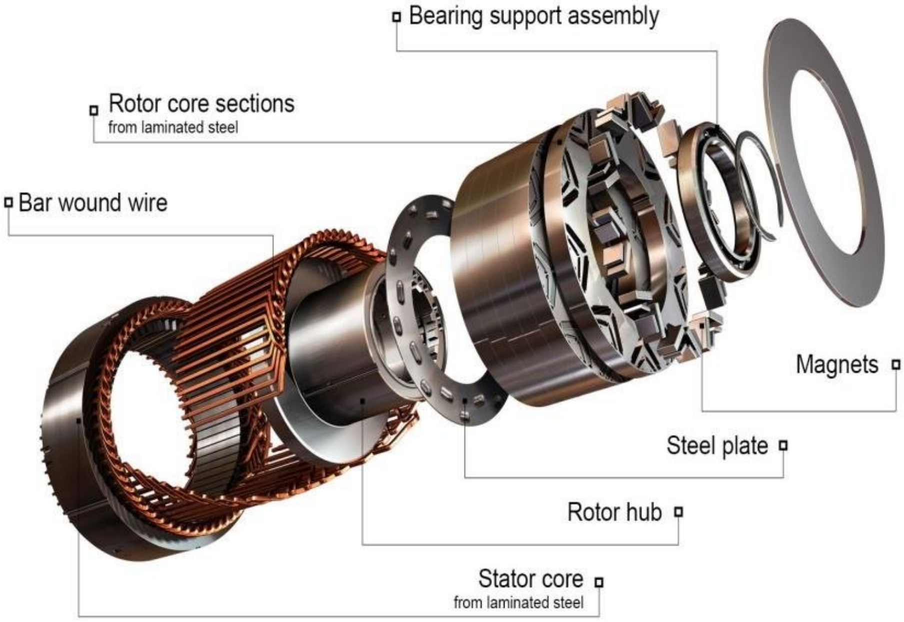
1. High efficiency
2. High power density in more compact form
3. High torque providing higher acceleration

4. Low maintenance

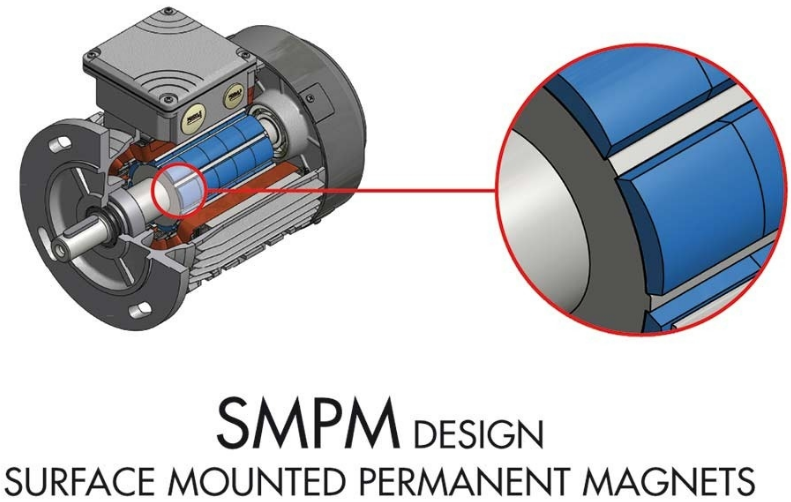
From a technological point of view, the use of neodymium magnets in EV motors reduces the size of the battery by 20-30% for a given range ("REIA Weekly Newsletter", n.d.). This implies that the usage of neodymium magnets in the motors of the EV can make the car more energy efficient and the same battery capacity can give higher range which is more appealing to the customers who have not shifted to EV due to issues in range (Egbue and Long, 2012).

Types of Permanent Magnet Synchronous Motor

Two types of PMSM are broadly used in EVs- Internal permanent magnet synchronous motor (IPMSM) and Surface mounted permanent magnet synchronous motor (SPMSM) (Z. Li et al., 2019). IPMSM is a motor where the neodymium magnets are placed or embedded inside the rotor of the motor (figure 3.5a). Whereas, a SPMSM is a motor where the neodymium magnets are radially placed on the rotor of the motor (figure 3.5b).



(a) Internal Permanent Magnet Synchronous Motor (Source:Ali et al. (2019))



(b) Surface mounted Permanent Magnet Synchronous Motor (Source:"Surface Mounted PMSM-TOMACO Trade Ltd." (n.d.))

Figure 3.5: Types of Permanent Magnet Synchronous Motors

Synchronous reluctance motor

Another synchronous motor that is gaining popularity currently is called the synchronous reluctance motor (3.6).

Figure 3.6: End view of the synchronous reluctance motor (Bishop (2020))

The synchronous reluctance motor works on the principle of reluctance. The rotor consists of iron pieces or any other magnetic material in it which tries to align with the magnetic field of the stator. Once the rotor aligns with the magnetic field of the stator, the magnetic field passes through the rotors magnetic material with least reluctance. Reluctance is a function of relative position of the rotor to the rotating magnetic field; and the torque produced by it is called reluctance torque (Electrical Workbook, 2021). Figure 3.7, shows the magnetic field lines as it is present during the operation of the motor.

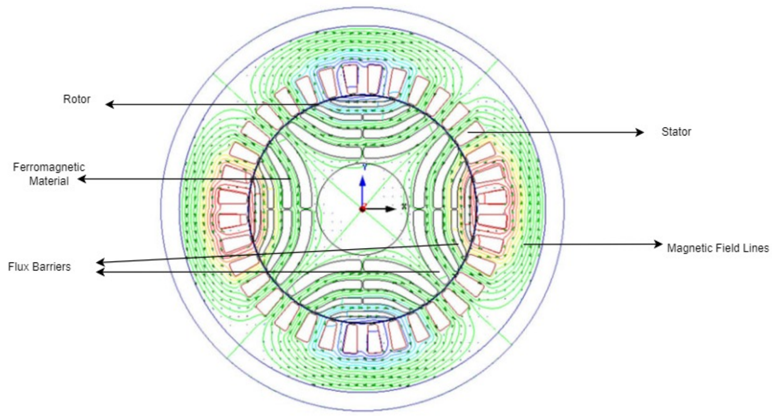


Figure 3.7: Magnetic field lines of synchronous reluctance motor (adapted from Levkin (n.d.))

Synchronous reluctance motors are gaining more interests because of they operate on a higher speed and can be produced at lower costs compared to PMSMs and even induction motors (Credo et al., 2019). Furthermore, the torque generated by Synchronous reluctance motors is constant and there is no risk of demagnetisation due to higher operating temperature compared to PMSM which have the risk of being demagnetised when the operating temperatures start reaching the Curie temperature (Credo et al., 2019). However, no information could be found on the usage of these motors by automobile OEMs, which could be because this motor technology is still under development to be used in EVs (Credo et al., 2019).

3.3.3 How innovation affects the demand of Neodymium magnets

As time progresses, the material efficiency is expected to increase which will decrease the amount of neodymium and praseodymium required to manufacture magnets that have similar strength. Currently, the neodymium magnets are composed of 29-32% of Neodymium, which is expected to reduce to 20% in 2030 (Pavel et al., 2017). Apart from neodymium and praseodymium, researcher are also trying to decrease the amount of dysprosium in the magnets. A magnet consists of 3-5% of dysprosium depending on the operating conditions of the motor or generator, dysprosium is added to the magnets to increase the operating temperature of the magnets so that they can function without getting demagnetised in high temperature operating conditions. To decrease the dysprosium content, the PMSG should be better designed for better cooling of the generator. Some wind turbine OEMs have already managed to drastically reduce the amount of dysprosium to 1% in the neodymium magnets and are trying to completely eliminate the use of dysprosium ("Materials and Rare Earths", n.d.; Pavel et al., 2017).This implies that the efficient use of REEs in the neodymium magnet can allow for reduced amount of magnets per MW of wind turbine (Fishman and Graedel, 2019; "Materials and Rare Earths", n.d.; Pavel et al., 2017). From a collection perspective, it can be argued that the neodymium magnets collected now could be recycled to be put in more motors and generators than they came from.

Now that the PM motor and generator technology has been discussed, it is now important to highlight the volume of neodymium magnets that may become available for collection and recycling from EoL EV motors and wind turbine generators.

3.4 Quantification of volume of Neodymium magnets

The first step in the waste collection process is to quantify the volume of waste generated. To do so, a basic quantification model is created, in which the volume of neodymium magnets that will potentially be present in the EoL wind turbines and EVs is calculated. The calculation is presented for four EU countries located in the west of Europe (the Netherlands, Belgium, France, and Germany). Ideally the calculation should be done for all EU countries, however, due to time constraints only four countries were selected. The rationale for choosing these countries is discussed in the scope section (1.3). The purpose of the quantification model is three fold:

1. Find out what is the quantity of magnets that can be collected.
2. When should the collection process begin and when should the efforts in collection be escalated.
3. Show the amount of magnets that can be lost if not collected and recycled.

3.4.1 Data Requirements- Wind turbine

In order to calculate the volume of Neodymium magnet that will be available at the EoL of Wind turbines, it is essential to gather the necessary data. Furthermore, to simplify the calculation, a set of assumptions are made. Table 3.1 presents the data that is needed and the source of the data.

The data required for wind turbines was gathered from a private database provider called "The Wind Power" ("Wind energy database", n.d.). In order to access the database, a one-month limited access subscription was taken. The database provided the following data for each country: Name of wind farms, area name of wind farms (offshore or onshore), number of turbines in each farm, name of turbine manufacturer, status of wind farm (operational/dismantled/approved/planned), and commission date of the wind farms. Data on dismantled, approved, and planned wind farms are not considered in the model. Thus data from operational wind farms from 2005 to 2021 are taken in the model. The data of offshore wind farms for each of the countries considered was relatively small compared to onshore wind farm data. Therefore, the exact model, the type of generator and drive train (Direct Drive[1] or Mid-speed gearbox[2]) installed in the offshore wind turbines installed in each of the offshore wind farms was found. This data was found either through 'Wind turbine database' ("Wind turbines database", n.d.) or wind turbine OEMs website. For, onshore wind farms, assumptions 8 to 12 were made since the number of onshore wind farms is much larger in each of the country and the wind turbine model and generator type could not be determined for each one of them. The assumptions 8 to 12 are made on the basis of estimates made by C et al. (2016) and Commission et al. (2020).

Table 3.1: Data required and Data source- Wind turbines

Sno.	**Data required**	**Data Source**
1.	Number of operational offshore and onshore wind turbines in all four countries.	Private database-"The Wind Power" ("Wind energy database", n.d.)
2.	**Share of onshore wind turbines that have PMSGs.**	
2.1	Share of onshore wind turbine with Direct-drive mechanism.	See assumptions 10 to 12
2.2	Share of onshore wind turbine with Mid-speed gearbox.	See assumptions 8 and 9
3.	Model of offshore wind turbine and generator type.	Wind turbine database("Wind turbines database", n.d.) Wind turbine OEMs website.
4.	**Amount of neodymium magnets in wind turbines with PMSGs.**	
4.1	Amount of magnets in direct-drive (DD) mechanism (650 kg/MW)	Pavel et al., 2017
4.2	Amount of magnets in Mid-speed gearbox (160 kg/MW).	Pavel et al., 2017
5.	Lifetime of wind turbines.	See assumption 1

Assumptions for Wind turbines

1. Lifetime of both onshore and offshore wind turbines is 20 years.
2. Lifetime of the PMSGs is same as the lifetime of the wind turbines,i.e. 20 years.
3. Both onshore and offshore wind turbines above 3MW in capacity which are installed in or after 2005 are considered in the calculation.
4. All wind turbines (onshore and offshore) having a capacity less than 3MW do not use PMSG and thus contain no magnets.
5. A Direct Drive wind turbine using PMSG contains 650kg of neodymium magnets per MW.
6. A mid-speed wind turbine using PMSG contains 160kg of neodymium magnets per MW.
7. Wind turbine OEM Enercon GmbH does not use PSMGs in their wind turbines thus all wind turbines made by Enercon GmbH contain no magnets.
8. From 2005 till 2015, 5% of all onshore wind turbines have mid-speed gearbox.
9. From 2015- 2021, the share of onshore wind turbines with mid-speed gearbox increases from 5%-12% linearly.
10. From 2005 till 2009, 5% of all onshore wind turbines have DD mechanism.
11. From 2010 till 2014, 17% of all onshore wind turbines have DD mechanism.
12. From 2015 to 2021, the share of onshore wind turbines with DD increases from 19% to 29% linearly.

[1] Wind turbines with no gearbox in between the blades and the generator, i.e. the wind turbine blades are directly connected with generator and move at 20 rpm(C et al., 2016)

[2] A compact gearbox installed between wind turbine blades and generator to increase the rotational speed to 100-500 rpm (C et al., 2016)

3.4.2 Data Requirements- EVs

To calculate the amount of neodymium magnets present in EVs the data and the source are presented in table 3.2.The data required for EVs was gathered from the 'European Alternative Fuels Observatory' (EAFO) ("Homepage — European Alternative Fuels Observatory", n.d.). EAFO is a reference portal for European Commission which provides data about the alternative fuels, infrastructure and vehicles in Europe. The portal was used to collect data on the number of BEVs and PHEVs registered each year in each of the Western EU country from 2008 till 2021. The amount of magnets in the BEVs and PHEVs are based on Elwert et al. (2016). The calculation and the raw data can be found in the appendix (C.1.1). Apart from the data gathered, certain assumptions were made to simplify the calculations (presented below table 3.2).

Table 3.2: Data required and Data source- EVs

Sno.	Data required	Data Source
1.	**Number of EVs**	
1.1	Number of BEVs registered in all four countries.	European Alternative Fuel Observatory (EAFO) ("Homepage — European Alternative Fuels Observatory", n.d.)
1.2	Number of PHEVs registered in all four countries.	European Alternative Fuel Observatory (EAFO) ("Homepage — European Alternative Fuels Observatory", n.d.)
2.	Share of EVs (BEVs, PHEVs) using PMSMs.	See assumption A.
3.	Amount of magnets in one BEV (2.1 kg).	(Elwert et al., 2016)
4.	Amount of magnets in one PHEV (1 kg).	(Elwert et al., 2016)
5.	Lifetime of EVs	See assumption 1.

Assumptions for EVs

1. Lifetime of EVs(BEVs and PHEVs) is 10 years.
   This assumption is based on the assumption made by Gauss et al. (2021) in their report.

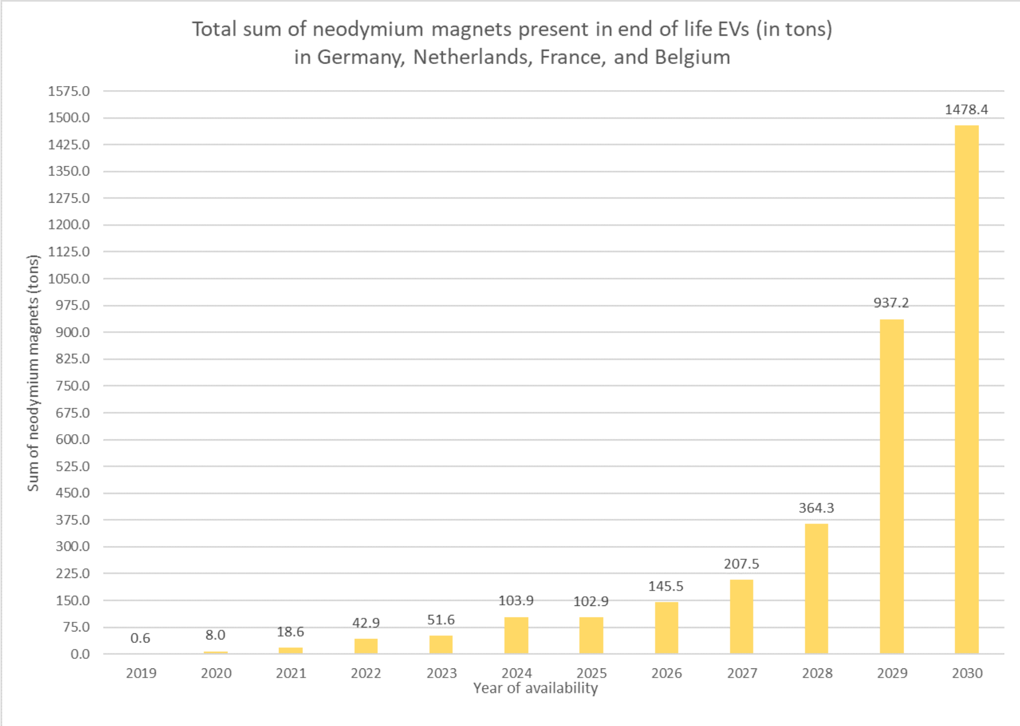
2. Lifetime of PMSMs and the lifetime of EVs is the same, i.e. 10 years.

3. BEVs and PHEVs containing PMSMs account for 60% in 2009 and linearly increase to 79% in 2015. From 2015 to 2020 the % of PMSMs in BEVs and PHEVs increase from 79% to 82%.
   Data for BEVs and PHEVs launched from 2009 to 2014 could not be found, thus a baseline of 60% of BEVs and PHEVs having PMSMs was considered. The assumption from 2015 to 2020, is based on the estimates of "Will Rare-Earths be Eliminated in Electric Vehicle Motors? — IDTechEx Research Article" (n.d.).

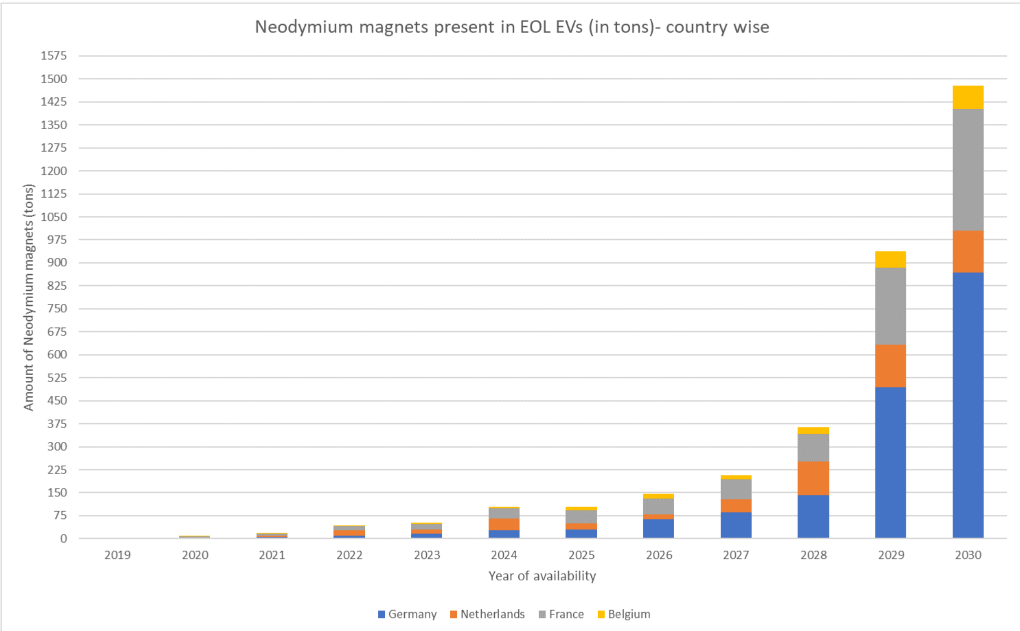
4. BEVs contain 2.1 kg of magnet and PHEVs contain 1 kg of magnet.

3.4.3 Cumulative results

The cumulative results for all four countries for both EVs and wind turbines are presented below. As mentioned before, the results are from four Western EU countries. However, it can be argued that for the entire EU, the volume (represented along the Y-axis in the graphs below) will increase. The results for each of the four countries are presented in detail in the Appendix C.1.1.



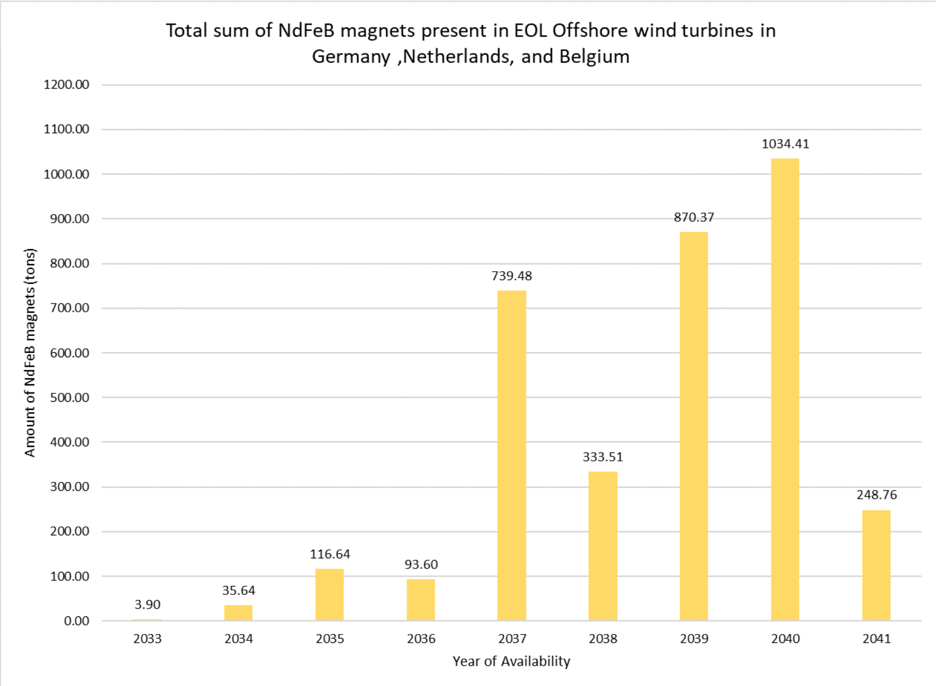
(a) Total sum of neodymium magnets present in EoL EVs (in tons) in Western Europe.



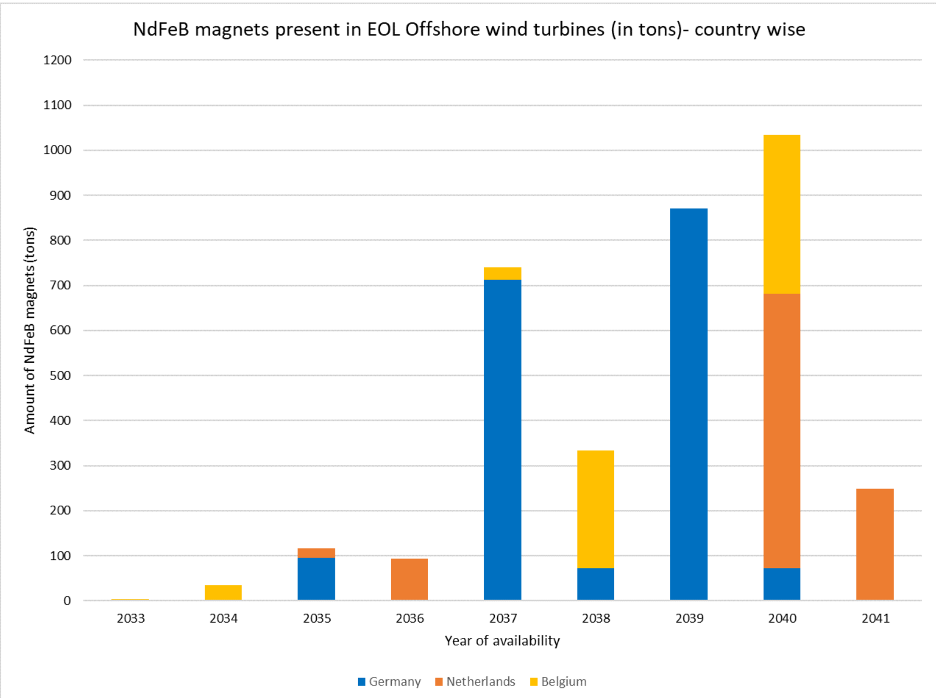
(b) Amount of neodymium magnets present in EoL EVs of Western Europe (in tons)-country wise share.

Figure 3.8: Cumulative data of neodymium magnets present in EoL EVs of Western Europe

From the graph 3.8a, it can be seen that the amount of magnets that may become available for collection and recycling rises exponentially. The increasing trend may be explained by the fact that more consumers in all these countries are buying EVs at an increasing rate which may be a consequence of the incentives that the governments in all these four countries are providing for EVs ("Belgian government pushes electrification of company cars", 2021; "France extends EV incentives until July 2022 — Automotive News Europe", 2021; "German EV subsidies more than doubled in 2021", 2022; "The Netherlands reaches impressive 69% all-electric market share", 2021). Furthermore, from graph 3.8b it can be seen that Germany and France have the highest contribution as the number of EVs that are registered in both the countries are the highest in the entire EU ("Country comparison — European Alternative Fuels Observatory", n.d.). This implies that Germany and France will have to be at the forefront of deploying collection strategies in order to prevent the magnets from being lost in different waste streams.



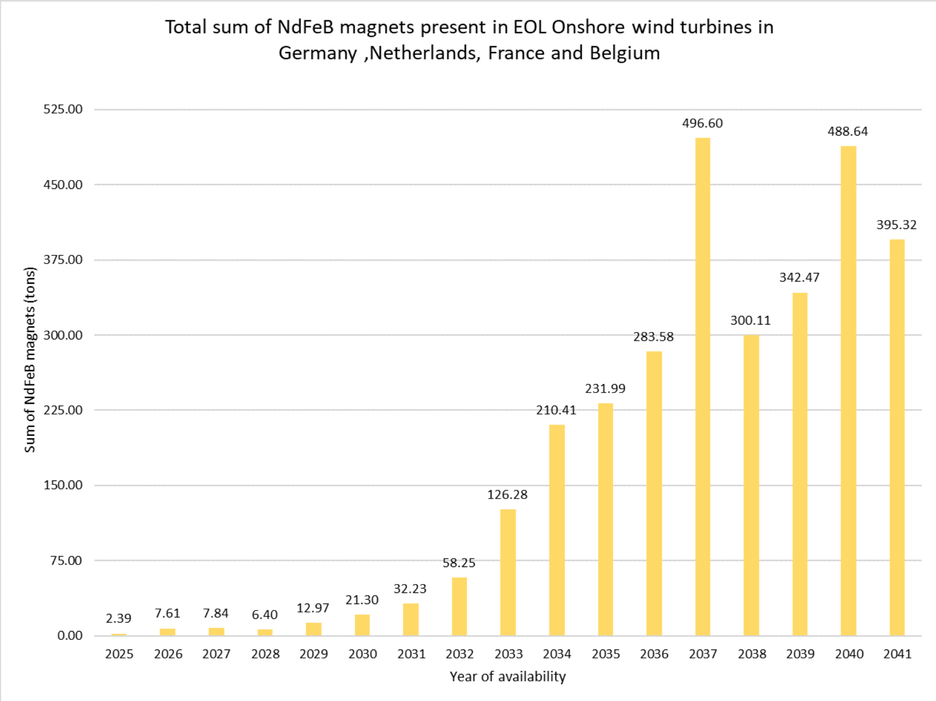
(a) Total sum of neodymium magnets present in EoL offshore wind turbines (in tons) in Western Europe



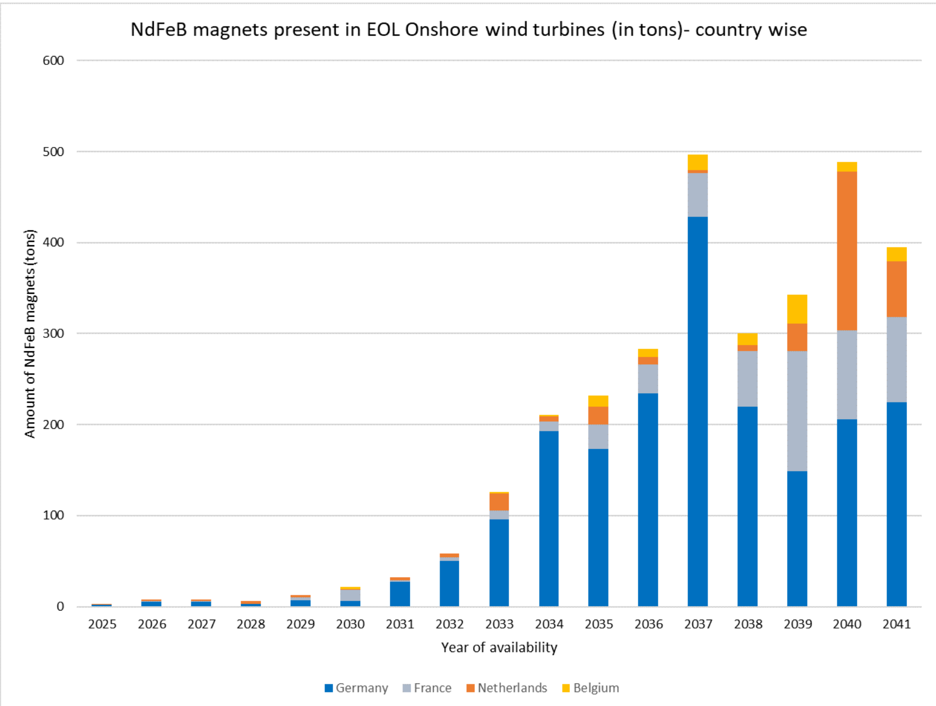
(b) Amount of neodymium magnets present in EoL offshore wind turbines (in tons)- country wise share

Figure 3.9: Cumulative data of neodymium magnets present in offshore wind turbines of Western Europe

From figure 3.10a it can be seen that the amount of neodymium magnets from EoL onshore wind turbines start increasing from 2031 and reaches a peak in 2037. This indicates that additional capacity on top of the capacity required for magnets from EoL EVs would be required for collecting and recycling the magnets coming from EoL onshore wind turbines in 2030.
From figure 3.10b, it can be seen that, overall, Germany will be the biggest source of magnets from onshore wind turbines. Thus, it can be said that Germany should focus on building major capacity for collection and recycling in Western Europe.



(a) Total sum of neodymium magnets present in EoL onshore wind turbines (in tons) in Western Europe



(b) Amount of neodymium magnets present in EoL onshore wind turbines (in tons)- country wise share

Figure 3.10: Cumulative data of neodymium magnets present in onshore wind turbines of Western Europe

From figure 3.9a it can be seen that the amount of magnets from EoL offshore wind turbines in Western Europe are starting to increase from 2034 and rises by multiple folds in 2037 before hitting a peak in 2040. Furthermore, like the amount of magnets coming from onshore wind turbines are largest for Germany, the amount of magnets coming from offshore wind turbines are

also the largest for Germany until 2039 and then followed by Netherlands and Belgium in 2040. Thus, it can be said that the Germany should have a greater focus on collection and recycling of the neodymium magnets compared to the rest countries not only in Western Europe but in the entire EU since Germany has the highest wind capacity in the EU ("Wind industry calls for Europe-wide ban on landfilling turbine blades — WindEurope", 2021).
In context of the entire EU, it can be argued that the graphs presented above will be elongated vertically as the volume of neodymium magnets available for collection will increase. However, it is important to note that some countries in the EU will contribute more towards generating neodymium magnet scraps compared to others due to different adoption rates of EVs and more installation of wind turbines. Figure 3.11 shows the amount of EVs registered across the EU, and figure 3.12 shows the total wind capacity.

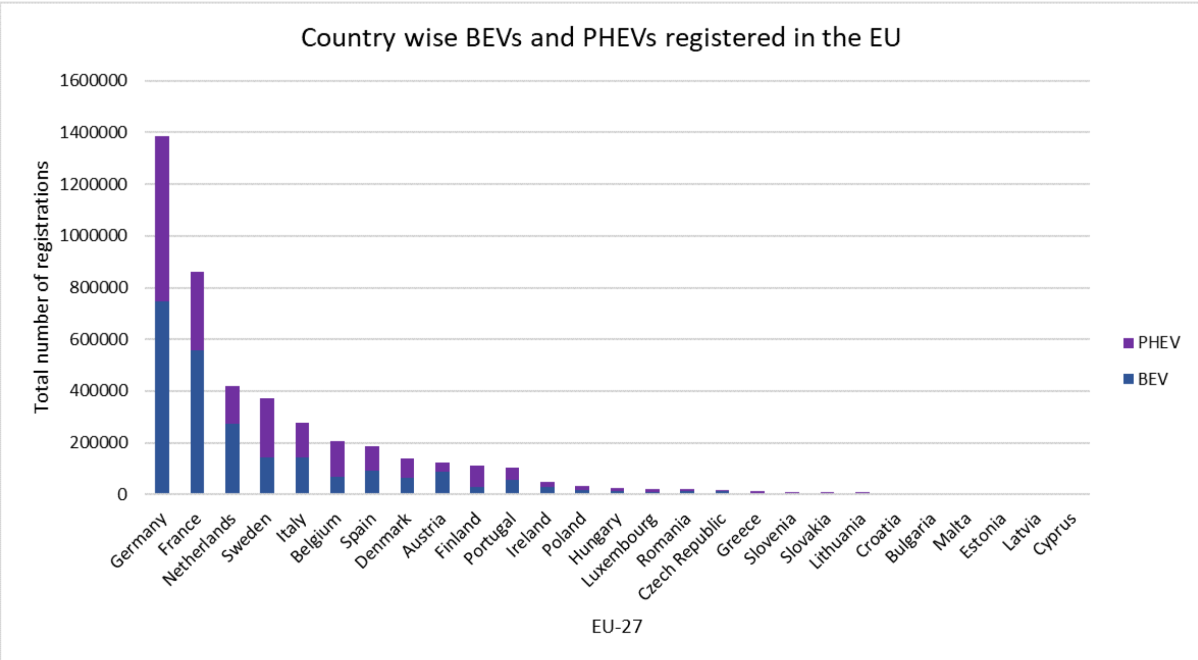


Figure 3.11: Country wise EV (BEVs and PHEVs) registrations in the EU-27 until 2021 (adapted from "Country comparison — European Alternative Fuels Observatory" (n.d.))

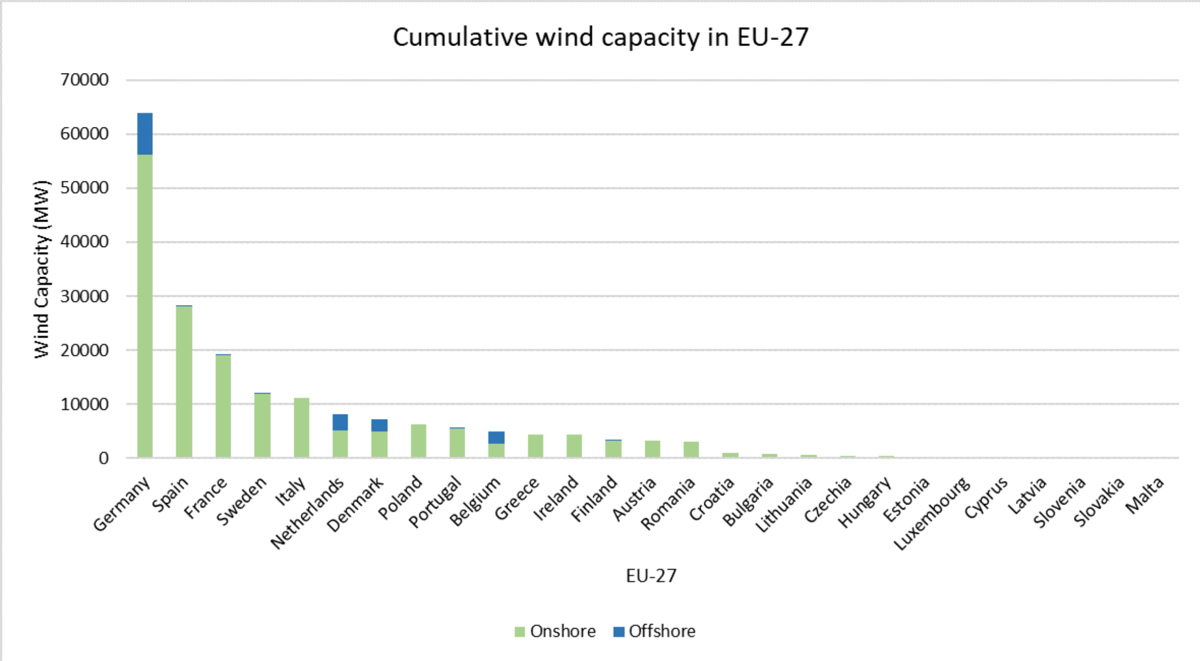


Figure 3.12: Total wind capacity in the EU-27 until 2021 (adapted from Komusanac et al. (2022))

3.5 Supply chain of EoL vehicles, wind turbines and motor/generator

This section is divided into three sections. The first section maps the supply chain of EoL vehicles which is also applicable to EVs. The second section maps the supply chain of EoL wind turbines, and the last section maps the supply chain of EoL PM motors, generators and neodymium magnets. The purpose of mapping these supply chains is to understand the movement of neodymium magnets that are inside the PM motors and generators which were part of EoL EVs and wind turbines, respectively. Furthermore, doing so will help identify the current actors in the recycling value chain of EoL vehicles and wind turbines that need to be addressed in order to effectively organise for collection of neodymium magnets.

3.5.1 Supply chain of EoL vehicles

Figure 3.13 shows the supply chain of the EoL vehicles in the EU. The actors in the supply chain are presented in rectangular boxes, while the processes or activities are placed in rounded boxes. Before going into detail, it is important to mention two points. First, the supply chain for EoL vehicles will be the same for EVs, due to the fact that the EVs still come under the definition of 'vehicle' as provided in Council Directive 70/156/EEC (Council Directive 70/156/EEC, 1970). Second, the overall supply chain for EoL vehicles will not have a lot of deviations from Member State to Member State because of the fact that the way that EoL vehicle supply chain in the EU is organised is according to the ELV directive (Kanari et al., 2003). The EoL vehicle supply chain consists primarily of the following actors.

Customer

1. Customer or last holder/owner of EoL vehicle

Collection, sorting, storage, re-use and recycling

1. Authorised car dealer
2. Approved dismantler
3. Shredder
4. Appropriate recyclers
5. Appropriate refurbishing company
6. Supplier of automobile manufacturers
7. Motor/generator collectors[3]

Customers

1. Motor/generator recyclers[4]
2. After Market
3. Automobile Manufacturers

[3]Based on the interview with motor/generator recycler (A.3), the motor/generator collector is a big company that collects motors and generators from various sources for the purposing of reselling it to recycling companies.

[4]Based on the interview with motor/generator recycler (A.3), the motor/generator recycler is a company that recycles the motor and/or generators which are generally sourced by motor/generator collector. It should be noted that the motor/generator recyclers also recycle other products like cables and transformers. However, for sake of simplicity they are called motor/generator recyclers.

The process of EoL vehicle management starts with the collection of the EoL vehicle. The last holder/owner of the vehicle has two options, either the owner can give their vehicle to the company car dealer or an authorised dismantler along with their car registration details. The car dealer or dismantler are obligated to collect the vehicle free of cost until and unless the car has been significantly modified (Kanari et al., 2003). After the necessary documents have been submitted by the last owner, the car is de-registered, and the last owner gets the certificate of destruction from the dismantler or the dealer ("Car recycling - ARN", n.d.). If the EoL vehicle has been given to the dealer, the dealer sends the vehicle to the dismantler. Approved Dismantlers have access to the International Dismantling Information System (IDIS), which was collectively developed in 1999 by automobile companies in the EU (Lucas, 2001). The dismantler then disassembles the vehicle with the help of IDIS. First, all the fluids like remaining fuel, brake fluid, coolant, and engine oil are collected separately and then these fluids are then sent to the appropriate recyclers who recycle the fluids into their constituent raw materials and send them to various manufacturers ("Car recycling - ARN", n.d.; Kanari et al., 2003; Lucas, 2001). In case of EVs, the coolant which keeps the motor cool, brake fluid and the lithium-ion battery will be removed and sent to appropriate recyclers. After that, the components which can be re-used directly or can be re-used after refurbishing are removed from the vehicle. In gasoline and diesel powered vehicles, the engine, starter motor, headlamps are components that maybe re-used and are sold by the dismantler to refurbishing companies or directly to after market suppliers. If they are not fit for re-use then they are sent to appropriate recyclers. For EVs, it can be assumed that similar practice will be followed, instead of the engine the motor of the EV may be resold if it is in working condition. If the motor is not in working condition then it can be sold to motor/generator collectors who will further sell the collected motor to various motor/generator recyclers (Motor/generator recycler, A.3). The vehicle that has been stripped of all the re-usable parts now is sent to shredding company that shreds the remaining vehicle and separates the ferrous and non-ferrous metal. The separated metals are then sold to smelters which recycle the metals (Kanari et al., 2003). In case of EVs, it is essential that the car dismantlers remove the PM motor before the car gets shredded.

Who pays for the recycling of the vehicle?

In the EU, the producer or vehicle manufacturers are responsible for the vehicles they sell in the market and are obligated to organise for collection of EoL vehicle at no cost (except when vehicle is significantly modified or it has to be towed) (Hagelüken, 2007). The extended responsibility is due to the extended producer responsibility (EPR) policy in place (discussed in detail in section 5.1.3). In each EU country, the manufacturers may choose to organise for collection via their own dealership or by paying a third party organisation, often referred to as producer responsibility organisation (PRO) (Lucas, 2001). Thus, the automobile manufacturers pays for the collection and recycling of their products. The manufacturers may even charge their customers a one-off recycling fee which is transferred to the necessary dismantlers and recyclers. For instance, in the Netherlands, when the customer buys a new car from a car dealer, the car dealer charges a one-off fee of € 30 ("The recycling fee - ARN", n.d.) for vehicle recycling at the EoL of the vehicle. The dealer then transfers this amount to Stichting Auto & Recycling that manages the recycling funds ("The recycling fee - ARN", n.d.). The collected money is used to fund various activities like collection, dismantling, and recycling in the recycling value chain ("The recycling fee - ARN", n.d.). In Belgium, the collection, dismantling and recycling is organised by Febelauto, a not for profit organisation (Soo et al., 2017). In France and Germany, the car manufacturers like Renault and Volkswagen have vertically integrated their supply chain by owning and partnering with dismantlers and waste processing companies (GreenLight, 2021).
Despite the different ways the automobile OEMs use to collect the EoL vehicle in different Member States, the overall supply chain of EoL vehicle recycling does not change as it is guided by the ELV directive (Council directive 2000/53/EC, 2020) (explained on section 5.1.2).

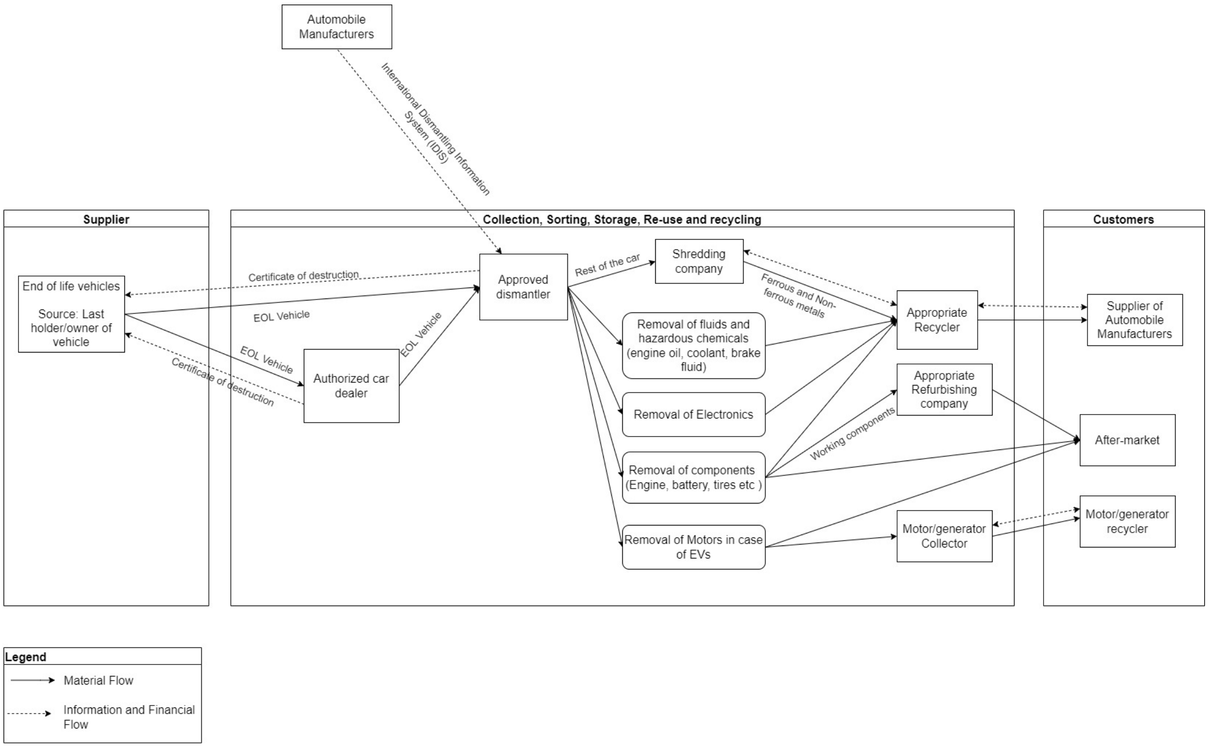


Figure 3.13: Supply Chain of EoL Vehicles (Source: author)

3.5.2 Supply chain of EoL Wind Turbines

The decommissioning[5] of wind turbines is a complicated task due to its size, and it may take several months of planning with multiple stakeholders ("New approach to wind turbine decommissioning — Windpowernl", 2021) before decommissioning the wind turbine(s). Thus, to keep the supply chain uncomplicated, only the essential part and actors in the supply chain are shown (Figure 3.15). Moreover, the purpose of the supply chain is to show the movement of the generator (which may consist of neodymium magnets, depending on the type of generator) after the wind turbine has been dismantled. The supply chain consists of the following actors (placed in rectangular boxes in the figure 3.15):

Supplier

1. Wind farm owner/wind turbine owner

Dismantling and Sorting

1. Dismantling company
2. Waste Management Company
3. Appropriate recyclers

Customers

1. Motor/generator collector
2. Motor/generator recycler
3. Secondary Market

[5]Decommissioning- Removing all wind turbines from the site location and restoring the site to original condition. (WindEurope, 2020)

The process of decommissioning starts with the owner of the wind farm deciding to decommission the wind turbine(s) due to the following reasons:

1. The wind farm owner decides to re-power the wind farm and thus wants to decommission the existing wind turbine. The wind farm owner may choose to re-power[6] the wind farm because of two reasons: The wind turbines have reached their EoL and they need to be dismantled and recycled or the wind turbines are still functional but the owner has decided to sell the wind turbine as the return on investment has been earned.

2. The wind turbine(s) have reached their EoL and need to be dismantled.

3. The wind turbine(s) have been damaged (WindEurope, 2020).

4. The operation of the wind farm is no longer economically feasible (WindEurope, 2020).

5. The land lease in case of onshore wind farm and seabed lease in case of offshore wind farm has come to an end and an extension is not possible (WindEurope-decommissioning document).

6. The license to operate has expired (WindEurope, 2020).

After the owner decides to decommission the wind turbines, the owner is responsible for extensively planning for the decommissioning, monitoring and organising for the recycling of materials (WindEurope, 2020,Wind turbine OEM (A.3.1)). The planning involves hiring a suitable dismantling company which will dismantle the wind turbine(s) and arrange for the recycling of the wind turbine(s). Some dismantling companies may not arrange for recycling of the dismantled wind turbine(s), in that case the wind farm owner needs to hire a waste management company for taking care of sorting the materials and directing them to the appropriate recycling channels (WindEurope, 2020). However, to keep the supply chain simple, it is assumed that the dismantling company is also responsible for arranging for recycling of wind turbine(s).
If the owner decides to sell the wind turbine(s) or its components, then the dismantling company needs to be informed before being given the contract so that the dismantling company can arrange for the recycling of the wind turbine(s). The dismantling company then plans for the dismantling operation while complying with the necessary "EU legislation such as laws, regulations, rules, technical norms, standards, specifications, guidelines and directives" (WindEurope, 2020) for demolition, and waste management that applies at the location where the wind turbine(s) is located. If the wind turbine(s) have not reached the EoL and the wind farm owner has decided to sell the wind turbine in the secondary market, then the wind turbine(s) is dismantled and transported to the buyer who may be in the EU or other parts of the world. Alternatively, even if the wind turbine has reached its EoL, some of the components (like the generator, rotor, rotor blades etc.) of wind turbine may still be in good condition and can be sold in the secondary market ("New approach to wind turbine decommissioning — Windpowernl", 2021) after the wind turbine(s) have been dismantled. The second buyer of the wind turbines or components may be located within the EU or outside the EU. If the components are no longer in working condition or are in poor condition, then the components are separated and sold to the appropriate recyclers. It can be argued that the recyclers would be located in the same country as the wind turbine components are heavy and difficult to transport. Since the wind turbine is made up of various components and each component uses different materials, the focus in this study will be on the generator of the wind turbine which is located in the nacelle[7] of the

[6]"Repowering a wind farm means replacing the old turbines by more powerful and efficient models that use the latest technology." ("Repowered wind farms show huge potential of replacing old turbines — WindEurope", 2022)

[7]The nacelle of the wind turbine houses the generator, gearbox, low and high speed shaft, the brakes and control panel (Breeze, 2016; Rayyan Fazal and Kamran, 2021)

wind turbine (figure 3.14). Based on the interview with Motor/generator recycler (A.3), it is safe to assume that the generator will be sold to a motor/generator collector by the dismantling company which in turn auctions the generator in bulk quantities to motor/generator recyclers or the generators that have stopped working during the operational lifetime of the wind turbine and could not be repaired by the wind turbine OEM then it would be sold to the local motor/generator recyclers.

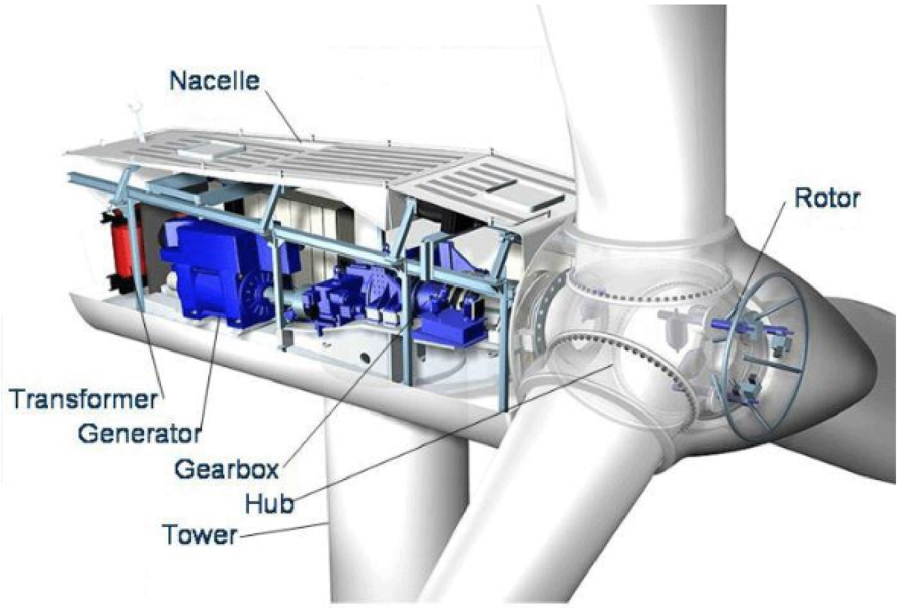


Figure 3.14: Nacelle of wind turbine (Source: "Industry Developments: Cooling Electronics in Wind Turbines — Advanced Thermal Solutions", 2016)

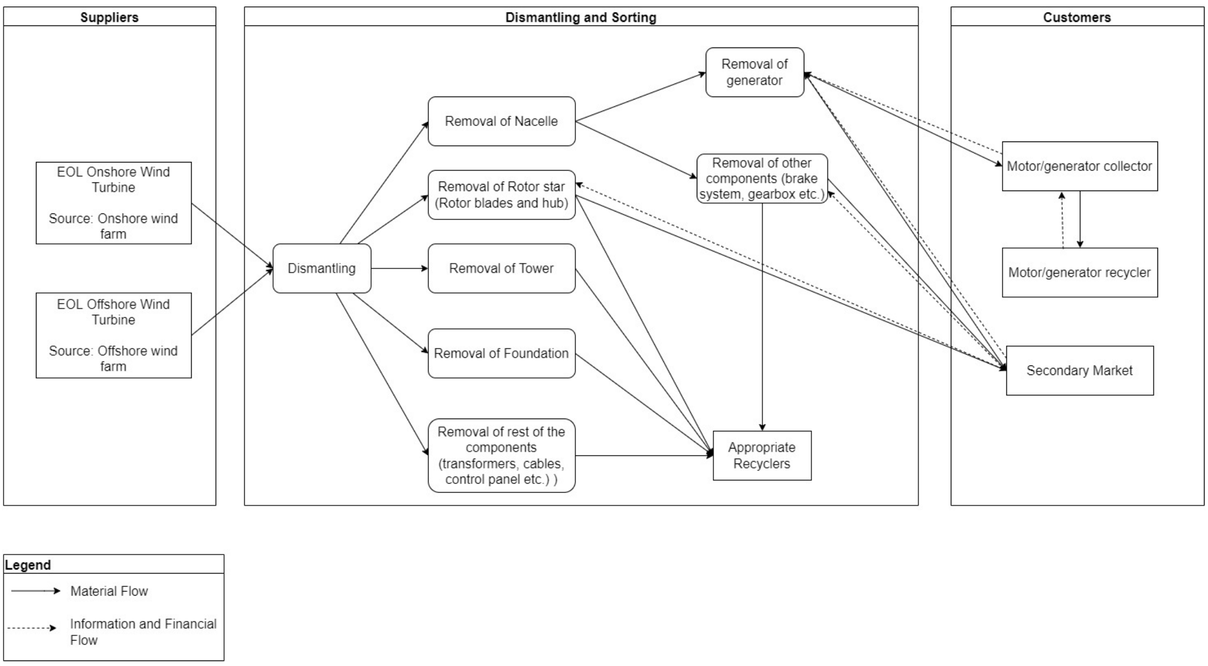


Figure 3.15: Simplified supply chain of EoL wind turbine (Source: author)

3.5.3 Supply Chain of EoL motors,generators and magnets

Figure 3.16 shows the supply chain of the EoL motors and generators. The supply chain consists of the following actors:

Suppliers

1. Car dismantling companies
2. Automobile Manufacturers
3. Auto repair shops
4. Wind turbine manufacturers
5. Wind turbine dismantling companies

Collection and Processing

1. Motor/Generator collector
2. Motor/Generator recyclers

Customers

1. Magnet traders
2. Aluminum, Iron and Copper smelters

The Motor/Generator collector buys EoL motors and generators from various sources, as seen in figure 3.16 and auctions them in bulk amounts (multiple tons) to different small motor and generator recyclers in the EU (Motor/generator recycler, A.3). The motor/generator recycling companies then disassemble the motors and generators to primarily extract the copper, iron and aluminium present in these devices. For generators containing PMs (i.e. PMSGs), the magnets are also removed (disassembly and extraction explained in section 4.1) and sold to magnet traders who currently offer €25000 per ton for the scrap neodymium magnets, the scrap magnets are then sold to companies in Poland. However, what happens to these magnets once they reach Poland is currently unknown. For EV motors, the motor/generator recyclers either disassemble the motors to extract the copper, iron and aluminium or sometimes resell the motors to third countries located in the East for dismantling (Motor/generator recycler, A.3). This is primarily because the motors take time to disassemble and it costs the recyclers more to take them apart due to high labour charges in the EU (Motor/generator recycler, A.3). However, in this process, the neodymium magnets in the EV motors exit the EU and can be assumed to be lost due to non-existent magnet recycling techniques. If the recyclers disassemble the motor in the EU, the constituent materials like copper, iron and aluminium are sold to the respective smelters. Furthermore, the magnets, in this case, are either taken out if the recyclers are aware of their value, or they are not extracted and sold to iron smelters where the magnets get melted with iron and REEs like Neodymium, Dysprosium and Praseodymium are lost in slag[8] (Motor/generator recycler, A.3, Elwert et al., 2016).

[8]Byproduct of metallurgical process which contain impurities (“slag — metallurgy — Britannica”, n.d.

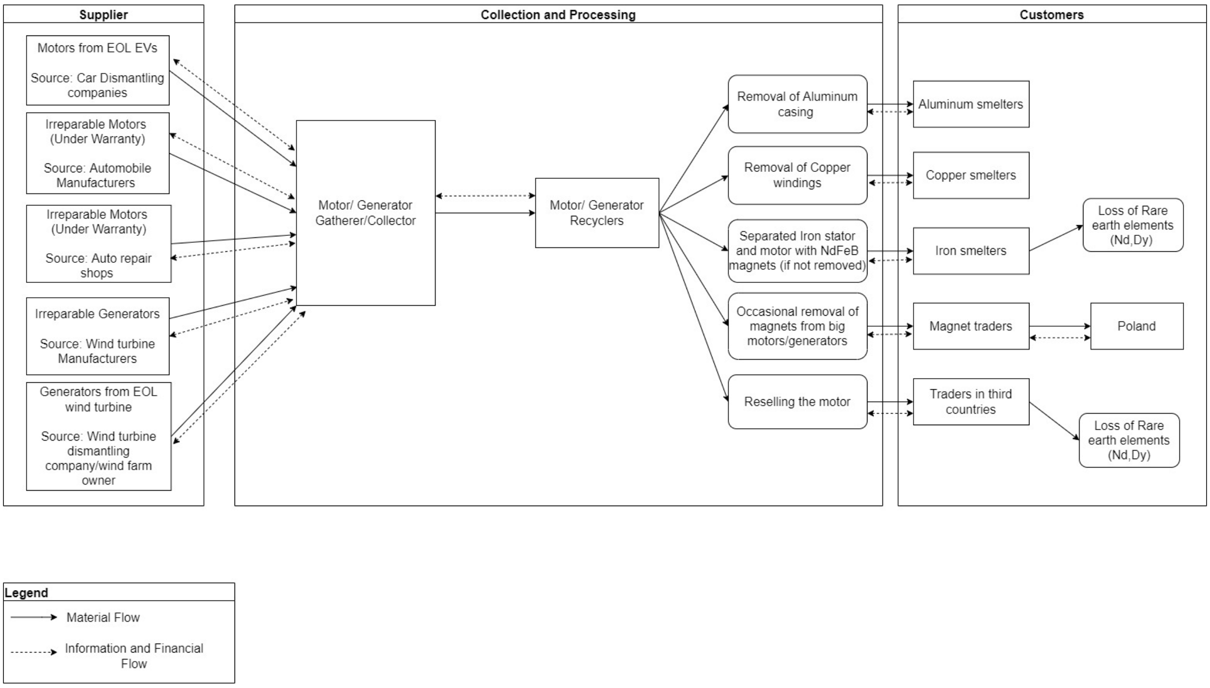


Figure 3.16: Supply Chain of EoL motors and generators (Source: author)

3.6 Conclusion

This chapter has answered the *SQ 1.1- What does the market of neodymium magnets look like?*. This chapter is more of an exploratory chapter which looks into various aspects of the neodymium magnet market. Through this chapter it becomes clearer that recycling the neodymium magnets can alleviate the 'Balance problem' that arises from the fact that the REEs are not available in equal quantities and some REEs like neodymium, dysprosium, praseodymium are available in fewer quantities compared to REEs like cerium and lanthanum. Through the quantification model presented in the chapter it becomes clearer that the neodymium magnets from EoL EVs and wind turbines, can act as a substantial secondary mine that will give access to only the necessary REEs required for neodymium magnet production. Furthermore, the issue of shortage of neodymium magnets is pointed due to which the production of EVs and wind turbines can go down. Unfortunately, this issue cannot be solved by collecting and recycling the neodymium magnets from secondary sources, but it may be a viable option in the long run. In addition, the neodymium magnets produced in China are found to be a threat to the recycling process as the magnets produced in China are offered at a very competitive price. In context of collection and recycling, it implies that if the collection cost is not low enough then it can negatively influence the price of recycled magnets. It was also found that there are significant advantages of using neodymium magnets in EV motors and wind turbine generator, which indicates that the use of neodymium magnets will continue to increase. In the end, mapping the supply chain revealed that the PM motors are going outside the EU for recycling because of high labour charges, which implies that the EU is loosing the neodymium magnets and the REEs that are defined as critical to the EU economy. It may not be a problem now, but when the volume of EoL motors increase then it could mean loosing significant amount of materials due to no collection and recycling strategy in place.

CHAPTER 4

Analysing reuse and recyclability of neodymium magnets

This chapter begins with quantifying the amount of magnets present in EoL EVs and wind turbines in four countries (Netherlands, Belgium, France, and Germany) to show the potential of collection and recycling. Next, the dismantling process of PM motors and generators is explored. Then, the possibility of re-use and different recycling routes are explained, along with the requirements for one of the most promising recycling routes. Lastly, the dangers of dealing with neodymium magnets are presented.

4.1 Dismantling of PM motors and generators

In order to start the collection process, the first step is to get hold off the PM motors from EoL EVs and PM generators from EoL wind turbines, which is explained in the supply chain section 3.5. After the PM motors and generators are separated from the waste stream of EoL EVs and wind turbines, the next step is to dismantle these PM motors and generators to collect the neodymium magnets. Thus, this section elaborates on the dismantling process of the PM motors and generators.

The disassembly and dismantling of EVs and their components for re-use and recycling have not been widely studied (Elwert et al., 2016). However, the manual dismantling of conventional motors and generators for re-purposing and recovery of material have been studied in detail (Elwert et al., 2016). Elwert et al. (2016) studies the dismantling of electric motor removed from a PHEV and concludes that the method used for conventional electric motor dismantling can be applied to EV motors as the main focus of dismantling an electric motor is to recover the copper present in the stator which is also present in PM motors.

The extraction of the magnets from IPMSM (3.5a) and SPMSM (figure 3.5b) requires a different approach due to the different placement of the magnets. Elwert et al. (2016) investigated the mechanical removal of the magnets from both types of PM motors. For SPMSM, the bandages covering the magnets need to be removed and then by the help of heat, the glue needs to be softened and magnets need to be removed by the help of a non ferrous wedge (Elwert et al., 2016). Figure 4.1 shows the bandages on SPMSM and prototype of removal technique.

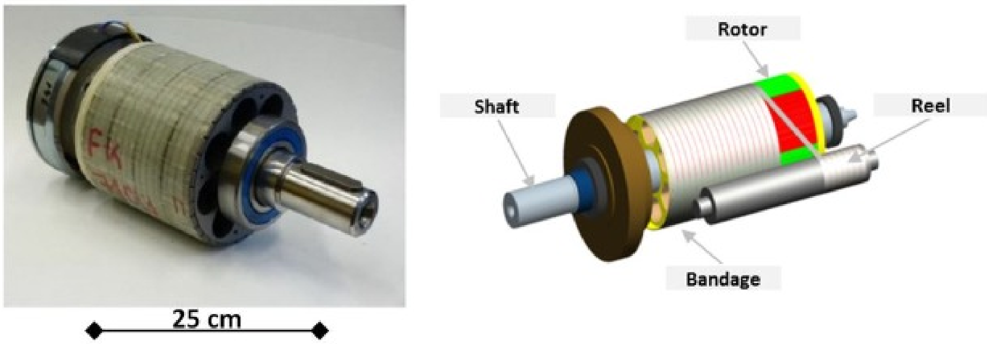


Figure 4.1: Bandage on SPMSM and prototype to remove bandages (adapted from Elwert et al. (2016))

For IPMSM, a prototype with non-ferrous materials was developed to automate the process of removal (figure 4.3). Firstly, the rotor core section, as shown in figure 4.2 and 3.5a need to be separated and then placed inside the prototype setup, which would use an ejector to push out the magnets onto a conveyor belt as shown in figure 4.3b (Elwert et al., 2016).

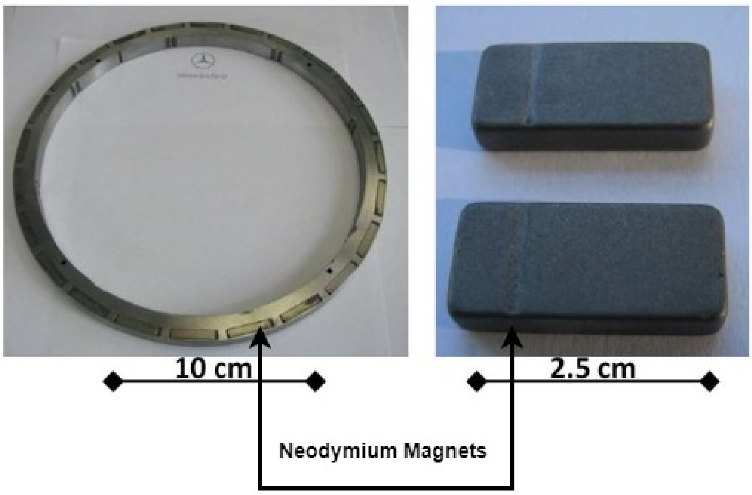
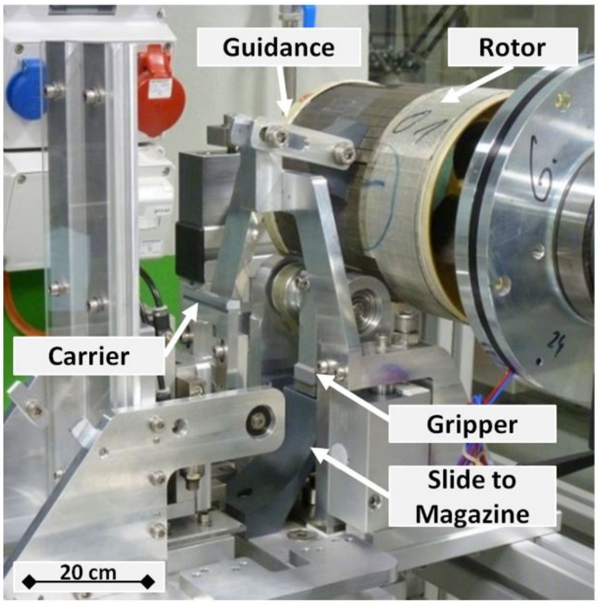
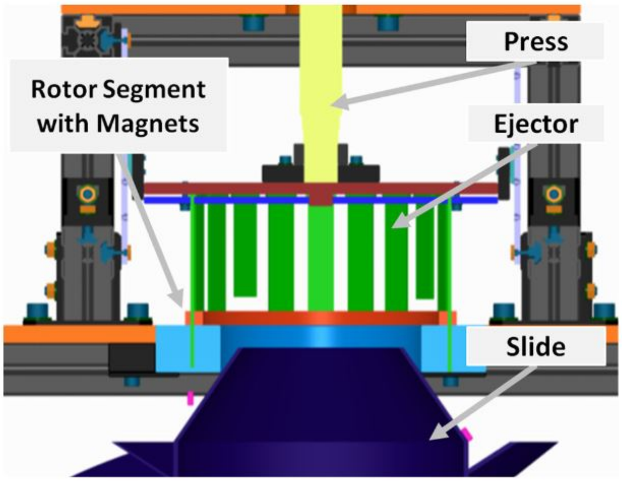


Figure 4.2: Rotor Section and embedded neodymium magnets (adapted from Elwert et al. (2016))



(a) Prototype for Magnet extraction from IPMSM (Source: Elwert et al. (2016))



(b) Cross-sectional view of the prototype (Source:Elwert et al. (2016))

Figure 4.3: Magnet Extraction from IPMSM

Apart from mechanical extraction of the magnets, the magnets can also be removed by chemical and thermal treatment where the magnets are released from the glue via chemicals like caustic soda or dimethylformamide (Elwert et al., 2016). The challenge of extracting the magnets mechanically from the PM motors is that different automobile OEMs design their motors according to their vehicle design and their research, which results in different shapes and sizes of the motors and the position and size of magnets in them. Thus the methods presented above may not work for each type of PM motor. Furthermore, currently the dismantling of the rotor of PM motors is difficult, time consuming and is done manually, which makes it expensive (due to high labour charges in the EU) to dismantle them and collect the magnets from the rotor assembly (Motor/generator recycler, A.3). This drives the motor/generator recyclers to sell the motors to third countries. Thus more research is needed to develop processes that can tackle variety and the volume of PM motors about to come in the future to extract the magnets successfully.

To find the methods for dismantling PM generators from wind turbines and extracting the neodymium magnets, Scopus and Google Scholar were used as databases to find relevant information. However, no articles were found that address the dismantling of electric generators. A search scheme can be found in the in the Appendix B.2. After failing to find answers in the literature, the answer was found through an interview with motor/generator recycling company in the Netherlands, the interview log can be found in the Appendix A.3. A motor/generator recycler shared that in order to dismantle the PMSG, first the housing (figure 4.4) of the generator is removed, then the rotor is separated from the stator. The rotor is then placed in an oven that is heated to 350 degrees Celsius, this demagnetises the permanent magnets placed on the rotor which makes it safe and easy to remove (A.3). The demagnetised magnets are stored for to be sold to magnet traders who sell the scarp magnets to Poland. Furthermore, the copper from the stator, the aluminum, steel, and iron are separated from the rest of the stator and rotor and sent to respective smelters for them to be turned into different products.

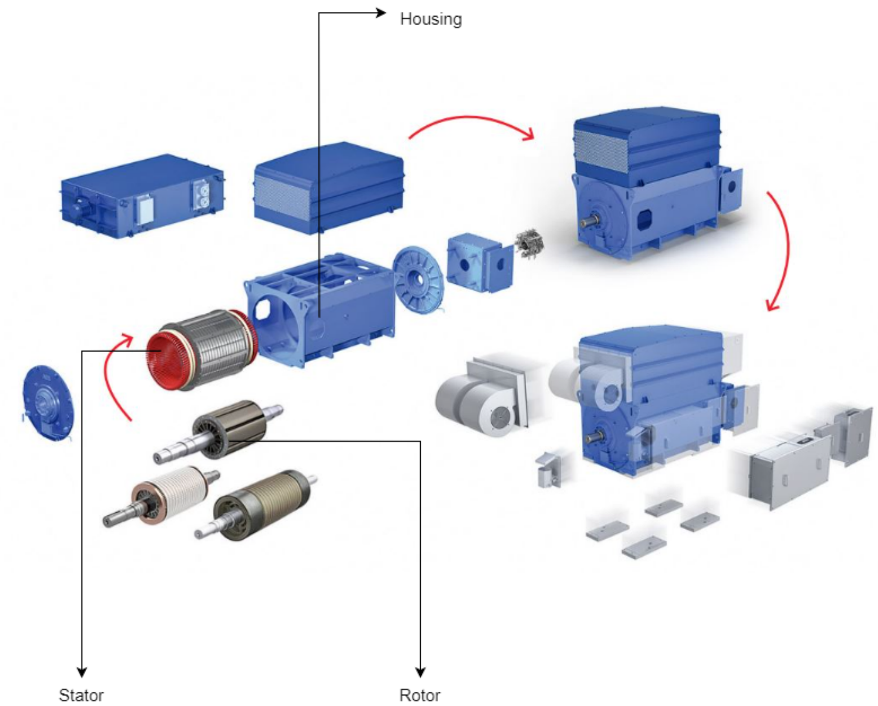


Figure 4.4: Wind turbine generator (adapted from ABB, n.d.)

4.1.1 Possibility of re-using the magnets

The last section described the dismantling process of the PM motors and generators and the challenges associated with it. The dismantling and extraction of the magnets are difficult but not impossible and the next step after dismantling and extracting the neodymium magnets from the motor and generator assemblies can be to either reuse or recycle these magnets. It can be argued that the neodymium magnets present in EoL PM motors and generators should be re-used, and if re-use is not possible only then they should be recycled as also recommended by the EU waste hierarchy (presented in section 5.1.1) defined in the Waste Framework Directive (Council directive 2008/98/EC, 2018).

However, the possibility of re-using the magnets may lead to different set of requirements for collection compared to recycling. Thus, in order to assess whether the EoL neodymium magnets present in wind turbine generators and EV motors can be re-used, scientific and grey literature were explored. Scientific articles were explored through Scopus and Google Scholar. However, there are very limited scientific articles that study the re-use of EoL neodymium magnets obtained from PM motors and generators. Thus in order to get more information on the re-use of neodymium magnets, reports from three EU Horizon 2020 projects (EREAN, DEMETER, SUSMAGPRO) on recycling and re-use of REMs were studied. The details of the project can be found in the Appendix C.2.1

The scarp magnets can possibly take three routes- direct re-use , direct recycling, and indirect recycling (Z. Li et al., 2019). However, direct re-use of the neodymium magnets is challenging due to lack of consideration for recycling stage during design phase of the various devices containing the magnets (Z. Li et al., 2019). In case of PM motors, the magnets are often bonded on the rotor with help of epoxy resin or other adhesives (Expert 1, A.2.1; Expert 2, A.2.2). Z. Li et al., 2019 studied two methods of removing the bonded magnets- mechanical separation, and heat treatment. Removing the magnets by the help of mechanical means often results in fracturing of the magnets. The magnets fracture easily on impact due to its hard and brittle nature (Z. Li et al., 2019; Ott et al., n.d.). Another option to free the magnets from the adhesives is by heating the surface having magnets to a temperature of 200 degree Celsius in order to melt the adhesive. Applying heat can demagnetize the magnets, although the demagnetization temperature for neodymium magnets is nearly 350 degree Celsius but not all neodymium magnets are same and may have varying demagnetization temperatures (Z. Li et al., 2019). In addition, after heat treatment, chemicals like sodium hydroxide, acetone, and dimethylformamide need to be sprayed on the magnets to remove the residual adhesive. However, dimethylyformamide has been listed as a carcinogenic substance by the International Agency of Research on Cancer (Z. Li et al., 2019) and exposure to dimethylformamide has proven to have negative health impacts such as longer coagulation time, decreased number of platelets (Imbriani et al., 1986).
There are very limited studies that study the re-use of magnets from wind turbines. This may be because not enough wind turbines have reached their EoL. However, a major wind turbine OEM (Wind turbine OEM, (A.3.1)) revealed that their PM generators are designed to be dismantled. A motor/generator recycler based in the Netherlands confirmed this, who shared the dismantling process of the wind turbine generator as stated in section 4.1. However, the possibility of re-use of these magnets is still unknown. Thus it can be assumed that they will be directed to the recycling route.
It can be concluded that if the magnets need to be re-used directly then the motors or generators containing the neodymium magnets should be designed in such a way that the magnets can be retrieved without damaging them (Hogberg et al., 2016; Z. Li et al., 2019). This is especially important for PM motors. Currently, retrieving the magnets from the motor assemblies is very difficult as they are epoxied in the rotor (Expert 2, A.2.2; Motor/generator recycler, A.3). Upgrading to a better design of motors and generators may significantly bring down the cost of removing the magnets from the PM motors and generators.

4.2 Recycling Technologies

The last section discussed that the possibility of direct re-use is slim. Therefore this section discusses the recycling of the neodymium magnets.
Collection of neodymium magnets partially depends on whether there are existing recycling technologies in place or not. If there are no recycling technologies for NdFeB magnets or there are no technologies that are being developed then collection of NdFeB magnets should not be the first priority. However, there are a number of recycling technologies/techniques that have been developed. In order to find the different recycling technologies, three technologies that have been used so far in the EU funded projects were looked into. The first two recycling

methods that were looked into extract the REEs present in the magnets through chemical intensive techniques which are environmentally less sustainable and thus presented in the Appendix C.2.2. The third recycling method is a short-loop recycling process or direct magnet to magnet recycling process called Hydrogen Processing of Magnetic Scraps (HPMS) which is gaining popularity (Expert 2, A.2.2). This recycling route may be suitable for neodymium magnets in EVs and wind turbines because of their large size and because of the magnets being sintered (Expert 1, A.2.1). Z. Li et al. (2019) stated that this is a suitable recycling process for large magnets that are not heavily oxidised. Neodymium magnets contain iron in large quantities and due to that the magnets are prone to oxidation (First4Magnets, n.d.). Oxidation of the magnets leads to reduced magnetic strength and makes them crumble ("Neodymium Magnets - Coatings And Adhesives — First4magnets.com", n.d.). Due to the long lifetime of wind turbines and EVs it can be safely assumed that the neodymium magnets used in wind turbines and EVs are coated to prevent oxidation. In previous work, HPMS has been mainly used to extract neodymium magnets from Hard disk drives. However, Z. Li et al. (2019) states that this method can also be used to extract the magnets from EV motors and wind turbines, which has also been demonstrated by pilot project in the University of Birmingham (Mann, 2022) . The process begins with using hydrogen gas to make the neodymium magnets brittle and demagnetized, then the hydrogenated neodymium powder is jet milled[1] to make the crumbled neodymium magnet more suitable for sintering process[2]. The powder is then compressed and sintered to form a densely packed sintered magnet. This processing route is often referred as the "short-loop recycling process" (Walton et al., 2015) as it does not involve the traditional route of magnet manufacturing which involves the intensive mining activity. Another way in which the end product of the HPMS process- the hydrogenated neodymium powder can be used is as secondary ore, which is rich in only a few REEs (Nd, Dy, Pr, Tb) compared to primary ore, which leads to the mining of all the REEs causing balance problem (Walton et al., 2015) explained in section 3.1.1. However, using the neodymium magnet powder for re-sintering to make new magnets is the most energy efficient re-processing route as it saves nearly 88% energy when compared to primary production of magnet through virgin materials ("Mkango and HyProMag recycle rare earth magnets from waste in UK", 2022; Walton et al., 2015). Furthermore, it is possible to reserve more than 90% of the magnetic properties compared to magnet made from virgin material (Walton et al., 2015). Figure 4.5 shows a hydrogen processing of magnetic scrap reactor that is present in University of Birmingham.

[1] Jet milling is a grinding operation where compressed air or an inert gas is used to collide particles into each other to produce a very fine powder ("Jet Mills — Hosokawa Alpine", n.d.).

[2] "Sintering is a thermal process of converting loose fine particles into a solid coherent mass by heat and/or pressure without fully melting the particles to the point of melting" (Lu and Ishiyama, 2015)

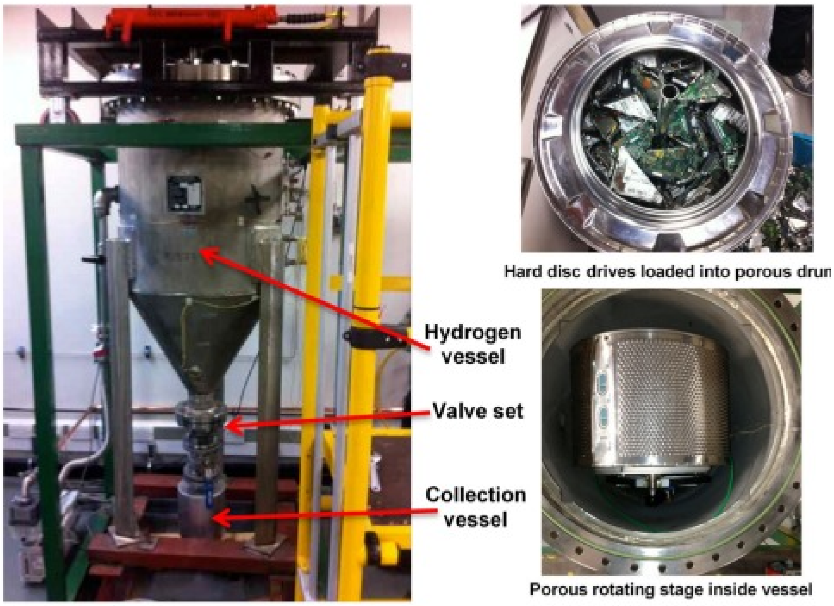


Figure 4.5: HPMS Reactor at University of Birmingham (source:Yang et al. (2017))

4.2.1 Planned capacity to recycle Neodymium magnets

As of now there are four pilot projects that have planned to recycle neodymium magnets though HPMS process in the EU ("Susmagpro plants — Susmagpro — Sustainable Recovery, Reprocessing and Reuse of Rare-Earth Magnets in the Circular Economy", n.d.).

1. MIMplus Technologies This pilot is located in Ispringen, Germany and has a planned capacity of processing 10 tons of Neodymium magnets per year by the HPMS process ("Susmagpro plants — Susmagpro — Sustainable Recovery, Reprocessing and Reuse of Rare-Earth Magnets in the Circular Economy", n.d.). The pilot plans to produce magnet powders from neodymium magnets in Waste Electrical and Electronic Equipment (WEEE).

2. Magneti Ljubljana This pilot is situated in Ljubljana, Slovenia and has planned capacity of processing 50 tons of Neodymium magnets per year ("Susmagpro plants — Susmagpro — Sustainable Recovery, Reprocessing and Reuse of Rare-Earth Magnets in the Circular Economy", n.d.). The pilot will produce magnet powder from production scrap and Hard drives.

3. University of Birmingham This pilot is headed by University of Birmingham, UK and has a planned capacity of processing 50 tons of neodymium magnets per year to make magnet powder from WEEE scrap by HMPS process ("Susmagpro plants — Susmagpro — Sustainable Recovery, Reprocessing and Reuse of Rare-Earth Magnets in the Circular Economy", n.d.).

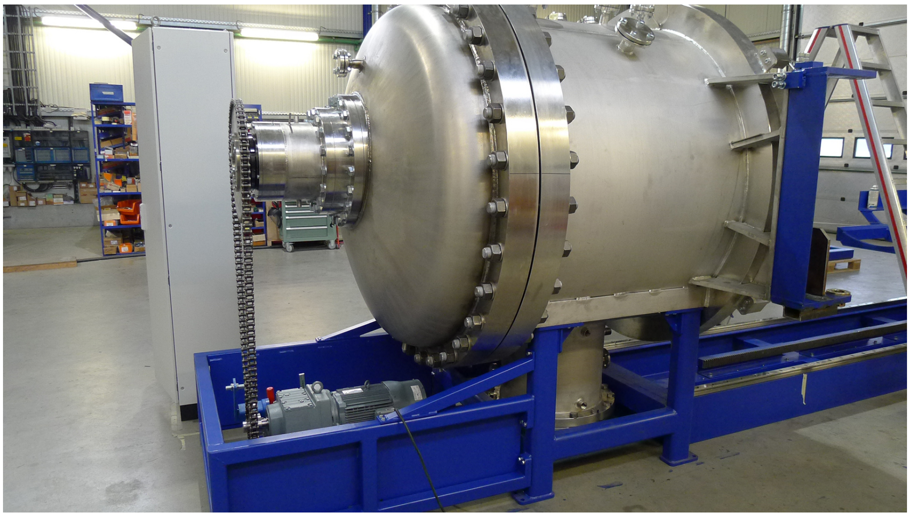


Figure 4.6: Pilot HPMS reactor in University of Birmingham, UK (source:Mann (2022))

4. STENA Recycling This pilot is based in Halmstad,Sweden and has planned capacity of processing 6 tonnes of neodymium magnets per year to make magnet powder by HPMS process ("Susmagpro plants — Susmagpro — Sustainable Recovery, Reprocessing and Reuse of Rare-Earth Magnets in the Circular Economy", n.d.).

For all four pilot projects the total planned capacity will 116 tons which will be realised at their state of maturity. However, the exact year of maturity for these projects could not be found. It can be stated that the extremely energy efficient and environmentally friendly way of producing magnets through the short loop recycling process offered by the HPMS process ("Rare Earth Magnet Recycling - Hypromag", n.d.) makes it very attractive and a plausible route for recycling magnets from PM motors and generators of EVs and wind turbines, respectively. Furthermore, even if the HPMS process is not used, the neodymium magnet powder can be used as a secondary ore for mining only the required REEs.

However, the HPMS process has a few requirements for collection and sorting (Expert 1, Expert 2, and Expert 3). The most important requirement is to the know the composition and grade of the neodymium magnets. Thus, the following sections will explain the different grades, composition of the neodymium magnets and its importance.

4.3 Different grades of neodymium magnets and the importance of classification

Different wind turbine OEMs and electric vehicle OEMs use different neodymium magnets in their products. Same wind turbine OEMs might use different magnet grade for different types of wind turbine generator due to different operating temperatures, the same is true for electric vehicle OEMs. Wind turbine OEMs and automobile OEMs prefer to use the highest grade of neodymium magnet which is of highest strength as this allows the OEM to make their motors and generators compact and powerful (Expert 1, A.2.1). Although, the different grades of the neodymium magnets can be classified broadly as neodymium magnets, the variation in the grades and chemical composition of the magnets is essential for HPMS recycling route of the magnets (Burkhardt et al., 2020).

4.3.1 What are the different grades of Neodymium magnets?

The neodymium magnets comes in variety of grades, the grade of a neodymium magnet represents the strength of the magnet. The grades start from N35 and goes up to N52, 'N' stands for neodymium (First4Magnets, n.d.) and the numbers after that represent the "magnetic flux output per volume" (Shewane et al., 2014), or in simpler words the magnetic intensity of the magnet. A higher number means that the strength of the magnet is also higher. There can be additional letter attached at the end of the grade of the magnet, for instance 'M' or 'EH' which represent the maximum operating temperature of the magnet. A magnet with an M rating can operate at a maximum temperature of 100 degrees Celsius, while EH rated magnets can operate at a maximum temperature of 200 degrees Celsius(First4Magnets, n.d.; Shewane et al., 2014). The grade of the neodymium magnet also indicates some of the properties of the magnets which are used to compare different types of magnets. The properties are as follows:

1. Remanence- indicates the strength of the magnets (expressed in Tesla or Gauss).
2. Coercive force- resistance of the material to become demagnetised (expressed in Amperes/meter).
3. Energy product- the density of magnetic energy (expressed in J/$meter^3$).
4. Curie temperature- the temperature at which the magnets get demagnetised (expressed in Kelvin or degree Celsius).

Figure 4.7 shows a partial list of different neodymium magnet grades and their properties.

	Remanence **Br** mT (kGs)	Coercive Force **Hcb** kA/m (kOe)	Intrinsic Coercive Force **Hcj** kA/m (kOe)	Max. energy product **(BH) max** kJ/m3 (MGOe)	Max. Operating Temperature TW
N35	1170-1220 (11.7-12.2)	≥ 868 (≥ 10.9)	≥ 955 (≥ 12)	263-287 (33-36)	80 °C
N38	1220-1250 (12.2-12.5)	≥ 899 (≥ 11.3)	≥ 955 (≥ 12)	287-310 (36-39)	80 °C
N40	1250-1280 (12.5-12.8)	≥ 907 (≥ 11.4)	≥ 955 (≥ 12)	302-326 (38-41)	80 °C
N42	1280-1320 (12.8-13.2)	≥ 915 (≥ 11.5)	≥ 955 (≥ 12)	318-342 (40-43)	80 °C
N45	1320-1380 (13.2-13.8)	≥ 923 (≥ 11.6)	≥ 955 (≥ 12)	342-366 (43-46)	80 °C
N48	1380-1420 (13.8-14.2)	≥ 923 (≥ 11.6)	≥ 955 (≥ 12)	366-390 (46-49)	80 °C
N50	1400-1450 (14.0-14.5)	≥ 796 (≥ 10.0)	≥ 876 (≥ 11)	382-406 (48-51)	80 °C
N52	1430-1480 (14.3-14.8)	≥ 796 (≥ 10.0)	≥ 876 (≥ 11)	398-422 (50-53)	80 °C
33M	1130-1170 (11.3-11.7)	≥ 836 (≥ 10.5)	≥ 1114 (≥ 14)	247-263 (31-33)	100 °C
35M	1170-1220 (11.7-12.2)	≥ 868 (≥ 10.9)	≥ 1114 (≥ 14)	263-287 (33-36)	100 °C
38M	1220-1250 (12.2-12.5)	≥ 899 (≥ 11.3)	≥ 1114 (≥ 14)	287-310 (36-39)	100 °C

Figure 4.7: Neodymium magnet grades (Source: First4Magnets (n.d.))

4.3.2 What are the compositions of the neodymium magnet and why are they important?

Neodymium magnets are available in various grades as explained above and also in various chemical compositions. The chemical composition of neodymium magnets is roughly 25-30% neodymium, 60-70% iron, and 1% boron by weight (Maani et al., 2021), according to different application dysprosium maybe added in small quantities ($< 5\%$ by weight). Burkhardt et al. (2020) discovered that the magnets present in wind turbines, electric vehicles, audio devices and other EoL products had considerably different chemical composition. This can be partly explained by the fact that the magnets had different grades and partly by the fact that the EoL magnets have different coatings (to prevent from corrosion), different weight composition of Nd, Dy, Pr present in the magnets (Burkhardt et al., 2020). However, it should be noted that the chemical composition of the neodymium magnets do not change with time, it is like the genetic information of the magnet (Expert 2, A.2.2). For short recycling processes like the HPMS, it is essential to know the composition of the neodymium magnets that are being recycled as different chemical composition can lead to inconsistent properties in recycled magnets formed through HPMS route (Burkhardt et al., 2020). Additionally, different coating types and different levels of oxidation could hamper the purity of the waste stream which then would demand the addition of virgin raw materials (Burkhardt et al., 2020).

In order to maximise the recycling potential through HPMS process, the different magnet grades, their chemical compositions, and their coatings should be identified (Expert 1, A.2.1; Expert 2, A.2.2; Expert 3, A.2.3) early on in the process. A major wind turbine OEM shared that they know the exact chemical composition, grade, coating type of the neodymium magnets used in their wind turbines. For EV motors, it can be assumed that the automobile OEMs would know the exact specifications of the magnets since the motors generate heat and there are chances that the neodymium magnets get demagnetised, thus they have to know the chemical composition to make sure that it functions well at certain operating temperature. This information needs to be passed along the recycling value chain to the collectors and the recyclers of the magnets.

4.4 Dangers of neodymium magnets

As mentioned previously, neodymium magnets are the strongest type of magnets that are available and they can be extremely dangerous to work with. Wind turbine PM generators are equipped with large amounts of very powerful neodymium magnets, these magnets can interfere with the functioning of devices like the pacemaker which may "trigger life threatening heart rhythm" ("Hazards Of Neodymium Magnets — First4magnets.com", n.d.). Furthermore, while dismantling of the generators and motors, the force of attraction of the neodymium magnets may cause uncontrollable and sudden movement of tools. Thus it may be a good practice to use tools that are not influenced by magnetic field. The magnets in the generator are removed after demagnetisation (Motor/generator recycler, A.3) but the magnets in the PM motors may be removed without demagnetising them. In this case, special care should be taken while handling multiple magnets as they can move towards each other with high acceleration if they are placed in each others magnetic field, the smashing of magnets may cause the coating of the magnets to chip off and hit the eyes ("Hazards Of Neodymium Magnets — First4magnets.com", n.d.). The magnets coming together uncontrollably can pinch the finger and even crush bones if the magnets are bigger than $30cm^3$ in volume ("Hazards Of Neodymium Magnets — First4magnets.com", n.d.). The nickle coating used to protect the magnets can also cause redness and itchiness in people having nickle allergy ("Hazards Of Neodymium Magnets — First4magnets.com", n.d.). On an average, 1-2% of the men and 12-15% of the women suffer from nickle allergy, although the condition is not life threatening ("Nickel Allergy — Nickel Institute", n.d.) but appropriate precaution should be taken while handling the neodymium

magnets. Lastly, people with metal implants made of ferromagnetic material[3] (for instance, stainless steel implant) should maintain safe distance from these magnets as they cause injury to the individual.
In order to safely handle the magnets, the motor/generator recyclers must have a standard operating procedure to deal with magnets while dismantling the PM motors and generators.

4.5 Conclusion

This chapter has answered the *SQ 1.2- What is the possibility of re-use and recyclability of neodymium magnets?*.Through analysing the dismantling process it was found that the dismantling of PM motors is a bigger challenge than generators. The current approach of dismantling PM motors and extracting the neodymium magnets is expensive and there is a need to scale up the dismantling process in order to handle the volume of EoL PM motors. Furthermore, the barrier to extracting the magnets from motors with relative ease is due to lack of consideration for 'design for recycling' during the design phase of the PM motors. For PM generators, it was found that it is relatively easy to extract the neodymium magnets from the generators, however it cannot be said with certainty that all wind turbine PM generators are designed for recycling. After dismantling and extraction of the neodymium magnets it was found that the it was not possible to directly re-use the magnets. Thus, the best recycling route for the magnets was found to the HPMS process which requires that the magnets need to classified as per their chemical composition, grade, and coating type. Thus, this requires that necessary information is passed along the recycling value chain.

[3]"The ferromagnetic materials are those substances which exhibit strong magnetism in the same direction of the field, when a magnetic field is applied to it." ("Ferromagnetic Materials — Electrical4U", 2020)

CHAPTER 5

Legal and Stakeholder Analysis

This chapter covers two parts- legal analysis and stakeholder analysis. The legal analysis, explores the current waste legislation and regulations in place related to EoL wind turbines, vehicles and REMs. The stakeholder analysis, looks into the potential stakeholders which will be involved or be affected by the collection of neodymium magnets.

5.1 Legal Analysis

The section will assess the rules that are in place which govern what happens to the EoL EVs, wind turbines and the neodymium magnets present in them. In order to do so, the following frameworks and directives were looked into:

1. Waste Framework Directive 2008/98/EC (WFD)
2. End-of-life Vehicle Directive 2000/53/EC (ELV Directive)
3. Extended Producer Responsibility (EPR)
4. Circular Economy and Export of wastes

In addition, it was decided to analyse the proposed battery regulation after Expert 1 (A.2.1) suggested that a similar regulations (as proposed in upcoming battery regulation) can be considered a guide for neodymium magnets.

5.1.1 Waste Framework Directive

The WFD is based on the EU waste Hierarchy (figure 5.1) which defines an order to be followed while dealing with waste. The order is as follows: Waste Prevention, preparing for re-use, recycling, recovery, and finally disposal (Council directive 2008/98/EC, 2018). The WFD is an overarching set of guideline for waste management and delineates when the waste is considered as a secondary resource and not waste. The framework has specific rules for different types of waste emerging from different sources.
In terms of critical raw materials, the framework does not address REEs and magnets specifically but mentions critical raw materials in general. Article 9(1b) of the WFD states that " Member States shall take measures to prevent waste generation. Those measures shall, at least: target products containing critical raw materials to prevent that those materials become waste" (Council directive 2008/98/EC, 2018). However, the directives are lacking collection target of

specific materials/critical raw materials that the Member States should achieve.
The WFD also lays down general requirements of Extended Producer Responsibility (discussed later in the chapter). The specific policies that are relevant for the EVs and Wind turbines are; ELV directive and the Construction and Demolition waste policy, respectively. Wind turbines are considered a part of construction and demolition because wind turbines are not yet part of Waste Electrical and Electronic Equipment Directive (Cherrington et al., 2012), and Article 3 (2c) of the WFD defines construction and demolition waste as waste that is generated as a result of construction and demolition activities, which fits for the dismantling of wind turbines. However, Cherrington et al. (2012) states that "there is currently little legislation present for the regulation of EoL waste management for the wind energy industry in Europe."

Figure 5.1: EU Waste Hierarchy ("Waste Framework Directive" (n.d.))

5.1.2 End of life vehicle Directive

The measures of EoL Vehicles directive are based on the EU waste hierarchy and environmental performance of actors that are involved in the complete life cycle of the vehicles. As per the definition of the 'vehicle' provided in the directive, EVs are also covered under this directive. According to Article 7(2) of the ELV directive, "for all end-of life vehicles, the reuse and recovery shall be increased to a minimum of 95% by an average weight per vehicle and year. Within the same time limit, the re-use and recycling shall be increased to a minimum of 85% by an average weight per vehicle and year" (Council directive 2000/53/EC, 2020). However, this does not encourage the treatment facilities to collect and recycle components that contain elements that are present in small quantities compared to the weight of the vehicle. Hagelüken (2007) states that this traditional weight based approach for recycling have always promoted the recovery of constituents in major quantities like copper, aluminium, steel, and plastics. Although, the EU considers REEs as critical raw material ("Critical raw materials", n.d.), the ELV directive does not mention the recovery of the critical materials that are present in a vehicle. This suggests that the directive does not reflect the EU's interests, and this should be addressed.
Article 4(1b) of ELV directive states that " the design and production of new vehicles which take into full account and facilitate the dismantling, reuse and recovery, in particular the recycling, of end-of life vehicles, their components and materials" (Council directive 2000/53/EC, 2020). However, in case of EVs PM motors, the dismantling of the stator to remove the neodymium magnets is difficult as the magnets are epoxied in the assembly. This clearly indicates that the automobile OEMs are not following the guideline laid down by the directive.
Considering the lifetime of EVs as 10 years, only limited number of EV have reached their EOL. Based on the quantification model for EVs (C.1.3), significant quantities of neodymium magnets have not been lost till now. In order to avoid the loss of these magnets, necessary policy

changes are required which will address the issue of design of PM motors in EVs, collection and recycling in greater detail.

5.1.3 Extended Producer Responsibility

The Organisation for Economic Cooperation and Development (OECD) defines EPR as "an environmental policy approach in which a producer's responsibility (physical and/or financial) for a product is extended to the post-consumer stage of a product's life cycle" ("Extended producer responsibility - OECD", n.d.).

The concept of Extended Producer Responsibility (EPR) was developed in 1990 in Europe for making the producers or manufacturers responsible for the collection and treatment of the products that they put in the market(Cahill et al., n.d.; van Nielen et al., 2022). Through the means of EPR, the responsibility is relocated from the municipalities to the producers, thus reducing the economic and environmental burden of municipality and simultaneously the tax payers (Pouikli, 2020). Furthermore, the EPR indirectly forces the producers to be more aware about the environmental impact of the design of their products.

EPR is an integral part of four sector specific waste directives: directive on packaging and packaging waste, directive on end-of-life vehicle, directive on waste electrical and electronic equipment and directive on batteries and accumulators. However, there are no EPR legislation's for wind industry currently and thus no recycling and recovery targets are set (Cherrington et al., 2012; Wind turbine OEM, A.3.1). Without appropriate legislation's in place, the wind turbine OEMs may not take the necessary actions like organising for collection and recycling of the neodymium magnets that are present in their PM generators.

In case of EVs, the automobile OEMs organise for the collection and recycling of their EoL vehicle by financing the operations of dismantling company (Kanari et al., 2003). The dismantling company dismantles the vehicle and separates the various components for recycling as explained in supply chain of ELV (3.5.1). However, the automobile OEMs are not responsible for the specific collection and recycling of the critical raw materials, for instance, neodymium magnets in the PM motor of EVs, platinum metal group in catalytic converters of gasoline vehicles (Hagelüken, 2007). This leads to components like EV motors being sent to third countries for recycling which eventually leads to loss of critical material as shown in 3.5.3. In order to avoid this situation, the EPR should also apply to components with critical material (Wilts et al., n.d.).

5.1.4 Circular Economy and Export of wastes

Circular Economy

The EU has started focusing its attention on Circular Economy since the last decade. The first circular economy communication: "Towards a Circular Economy—A zero waste programme for Europe" was introduced in 2014 by the European Commission. Shortly after, an action plan for circular economy was released in 2015. In the action plan, circular economy was defined as an economy where the resources, materials and their value is retained for as much time as possible while minimising the amount of waste that is generated "Closing the loop – An EU action plan for the Circular Economy", 2015). Since the release of the first action plan, several circular economy plans and packages have been released. Figure 5.2 shows the circular economy approach taken by the EU Commission.

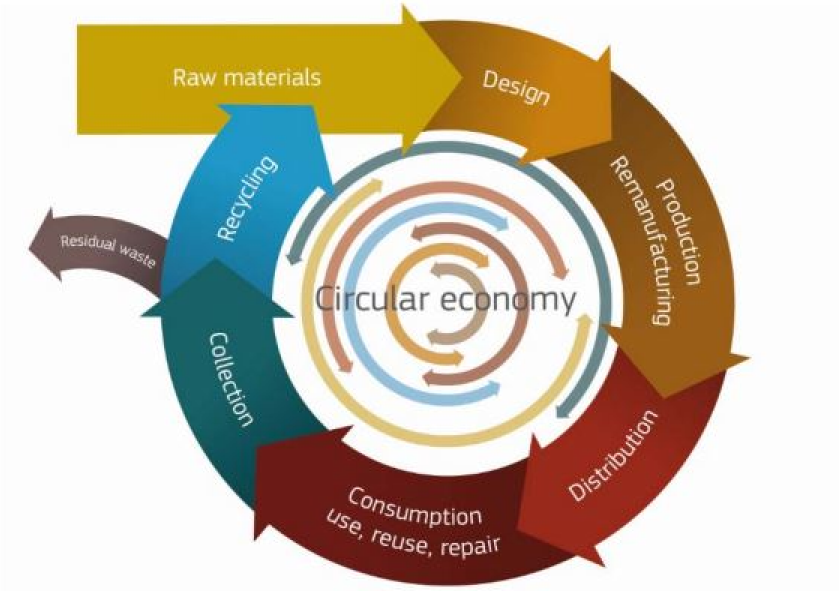


Figure 5.2: Circular Economy approach by EU Commission ("Towards a circular economy: A zero waste programme for Europe", 2014)

The latest circular economy action plan that has been adopted by the European Commission was released in 2020 ("Circular economy action plan", n.d.). This communication addresses several product value chains such as - batteries and vehicles, electronics, plastics and packaging, textiles, and construction and buildings. However, the issue of REEs and specifically REMs like neodymium magnets used in green technologies like wind turbines and electric vehicles is not addressed. Despite this gap, the circular economy action plans and communications will play an important role in achieving climate goals of 2050 (Hagelüken and Goldmann, 2022).
Hagelüken and Goldmann (2022) asserts that circular economy is much more than just recycling the products, it is about developing a better design, using sustainably, repairing when needed, collecting for re-use and recycling. An ideal circular economy implies that no matter when or where the products reach their EoL, they will be recycled efficiently and in an environmentally friendly way. However, the ideal condition is very difficult to achieve as it requires collaboration from not only Members States and all stakeholders within the EU but also outside the EU when the products are exported for re-use.

Export of Wastes

In the past, third world countries have revealed that the EU is dependent on their waste treatment (EU COM(2020) 98, 2020). The export to third world countries takes place for the purpose of re-use/ extending the lifetime of the product, however, the country receiving them often does not have state of the art recycling infrastructure. Hagelüken and Goldmann (2022) calls this "reuse paradox" as it extends the life of the product but resources are wasted due to failing to close the material loop. In context of wind turbines and electric vehicles, the variety of critical metals and materials used in these technologies is increasing and evolving with time (Bobba et al., 2020). The materials are not only critical for the EU but also the third world countries do not have the available technologies to recover the different types of metals. Furthermore, the EU faces the challenge of controlling illegal export of EoL vehicles as every year 3.4 to 4.7 million EoL vehicles are illegally exported from the EU (VRW, 2020). Since a lot of EVs are yet to reach their EoL, illegal exports is not a concern with EVs but it is something that can be in the future. For wind turbines, it can be argued that the chances of illegal export would be non existent due to its massive size. However, the export of the PM generators and motors in wind turbines and EVs, respectively, which contain critical materials like REMs should be monitored closely as to avoid loss of materials. As explained in section 3.5.3, the motors are already being sent to third countries, and it can be argued that the possibility of neodymium magnet recycling would be slim to none.

5.1.5 Proposed battery regulation

The proposed battery regulation (EU COM(2020) 798, 2020) was looked into after it was brought up by Expert 1 (A.2.1). New battery regulation is proposed due to increasing number of EVs, light electric vehicles (LEVs) and Heavy electric vehicles (HEVs) in the EU, which are making the transport sector emission free (EU COM(2020) 798, 2020). The increasing rate of electrification of the vehicles will lead to more battery demand and more EoL batteries, as well as more battery reaching EoL in upcoming years; thus the proposal aims to update the EU's legislation on batteries (EU COM(2020) 798, 2020). The proposal addresses three groups of problems, out of which the second group is focused towards recycling market and the limitations of the current battery directive and regulations, which do not take into account the modern technology and latest market trends (EU COM(2020) 798, 2020). The first and third group of problems are related with production capacity and social and environmental concerns, respectively. However, only the upgrades related to second group of problem and in particular the approach for collection of portable batteries[1] and EV batteries will be studied to see if they can be applied in case of collection of neodymium magnets from EoL EV motors and wind turbine generators.
The following measures from the proposal are interesting and may be applicable in the case of neodymium magnets:

1. Producers of the batteries are made responsible for organising (including finance) for separate collection (including transportation) of the batteries.
2. Collection target for waste portable batteries that should be attained by Producers or parties appointed by the producers (Producer responsibility organisations) shall attain the following collection target in each Member State:
   (a) 45% by end of 2023
   (b) 65% by end of 2025
   (c) 70% by end of 2030

   Producers or Producer responsibility organisations (PROs) are responsible for calculating rate of collection in each Member State.
3. Producers or PROs should accept the take back of EV batteries from end-users, or EoL vehicle dismantling facilities and cover the cost of dismantling and collection of waste batteries.
4. All waste batteries that are collected should enter recycling process.
5. Waste batteries can be shipped out of the EU only when it can be proved by waste holder that treatment will take place as per the requirements defined in the regulation.
6. "Battery passport", shall be made for EV batteries which should be accessible online through electronic systems. The passport should contain information about performance and durability of the battery when the EV battery is put on the market and the status should change when it is being repurposed or recycled.

[1] Portable batteries are defined as batteries which "weigh less than 5 kg, is sealed, not designed for industrial purpose and is not an EV or automotive battery" (EU COM(2020) 798, 2020)

5.2 Stakeholder Analysis

The objective of stakeholder analysis is to get an overview of all the possible stakeholders that may be affected or be involved in the collection of neodymium magnets present in EoL wind turbines and EVs in the future. The analysis includes their positions in the supply chain, their responsibilities, interests and their interdependence. A stakeholder analysis is important in order to identify the concerns of the stakeholder and better understand the information that they hold so that the problem at hand can be solved successfully (Bryson, 2004).

To start the analysis (Bryson, 2004) suggests brainstorming a list of all the possible stakeholders. However, in this case a more structured approach was followed which involved revisiting the previous analysis that have been conducted up till now. First the supply chain for EoL PM motors and generators that has been mapped in section 3.5 was revisited. Second, from the analysis of reuse and recyclability conducted in section 4, additional stakeholders involved in the recycling of Neodymium magnets were identified. Lastly, through brainstorming last set of stakeholders were identified. It is also important to note that some stakeholders are or would be actors in the recycling supply chain of neodymium magnets. This list of stakeholders is as follows:

1. Car dismantling companies
2. European Group of Automotive Recycling Association (EGARA)
3. Wind turbine dismantling companies
4. Automobile OEMs
5. Wind turbine OEMs
6. Wind farm owners
7. Motor/generator collectors
8. Motor/generator recyclers
9. European Recycling Industries' Confederation (EuRIC)
10. Ongoing EU recycling projects
    - Comprises of Knowledge Institutes and Businesses partnering together.
11. Member States
12. European Commission (EC)
    - Comprises of various Directorate General (DG). The DGs that may be involved are: DG Internal Market, Industry, Entrepreneurship and SMEs (GROW), DG Financial Stability, Financial Services and Capital Markets Union (FISMA), and DG Economic and Financial Affairs (ECFIN).
13. European Raw Material Alliance (ERMA)
14. European Institute of Innovation and Technology (EIT) Raw Materials
15. REE mining projects
16. Civil society actors

The list of all possible stakeholders that may be involved or affected are then put in a power versus interest (PI). The PI grid helps in determining which players have power and interest and thus should be taken into considerations for addressing the issue. The PI grid is divided into four sections- Subjects, Players, Crowd, and Context Setters (Bryson, 2004).
Subjects have relatively high interest in the issue at hand but have less power, Players have high interest and high power in the issue at hand, Crowd neither has a lot of interest nor power (in this case the REE mining projects and Civil Society actors in the EU), and Context Setters have high power but little interest in the issue at hand (Bryson, 2004). Figure 5.3 shows the identified stakeholders on the PI grid.

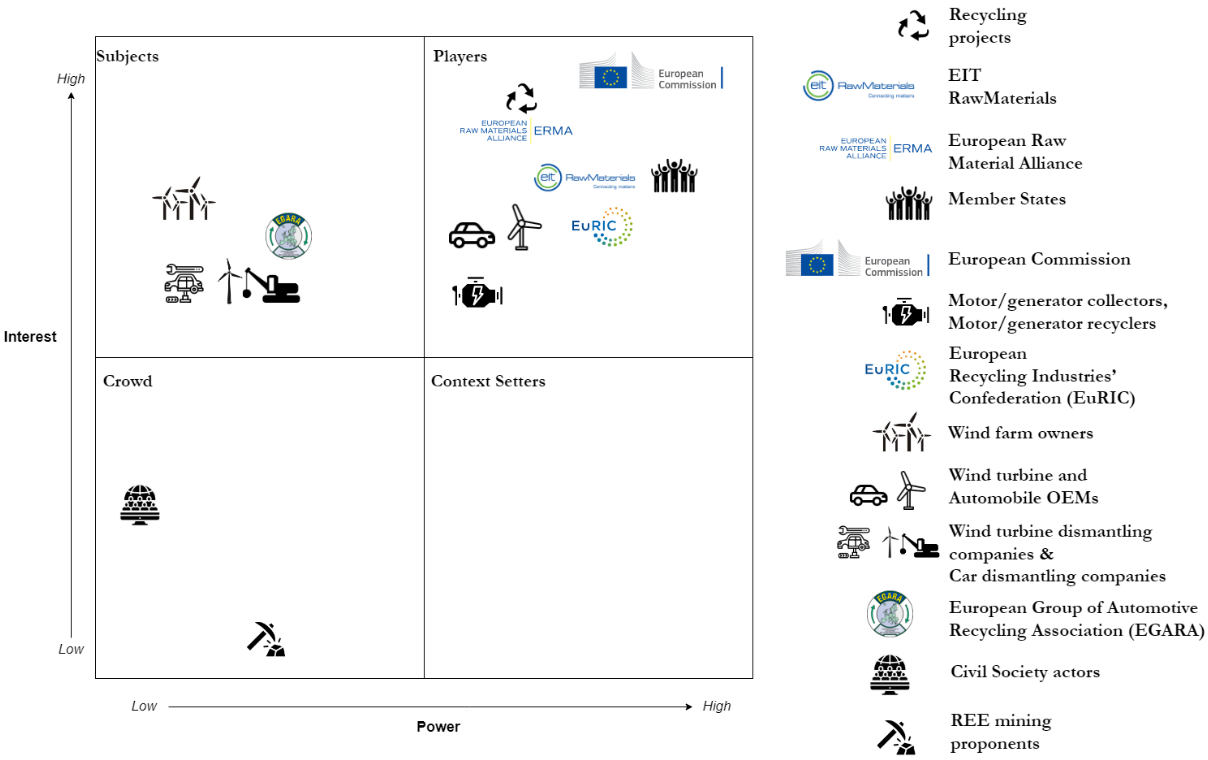


Figure 5.3: Power vs Interest grid of stakeholders

The position and interests of the stakeholders which are *Players*, *Subjects*, and *Crowds* are explained below, respectively.

5.2.1 Players

European Commission

The EU is trying to reach the climate goals of 2030 and 2050. In order to reach these goals, the deployment of renewable energy technology and making the transport sector emission free are essential and urgent. These technologies demand the use of REEs and in particular, the use of neodymium magnets in the PM motors and generators used in wind turbines and EVs. The REEs are also part of the EU list of critical raw material that was prepared by the European Commission (EC). The "EU aims to secure the supply of these materials to build resilience and strategic autonomy for Europe's rare earth and magnet value chains" ("Rare earth elements, permanent magnets, and motors", n.d.). On the other hand the EC initiated European Raw Materials Alliance (ERMA) in 2020 to address EU's challenge of critical raw materials ("Rare earth elements, permanent magnets, and motors", n.d.).
The role of EC will be most crucial as it can propose suitable legislation related to the collection of neodymium magnets from EVs and wind turbines. The EC will also have to work with the

all the potential stakeholders that would be directly or indirectly involved in the collection of the magnets. The EC has several policy departments called Directorate- General (DG) which help in the development, implementation and management of EU laws, policies, and funding programmes ("How the Commission is organised — European Commission", n.d.). The specific DGs and executive agencies that may be involved in this case can be as follows:

1. DG Internal Market, Industry, Entrepreneurship and small, medium enterprises (SMEs) (GROW)
2. DG Financial Stability, Financial Services and Capital Markets Union (FISMA)
3. DG Economic and Financial Affairs (ECFIN)
4. European Innovation Council and SMEs Executive Agency (EISMEA)
5. DG Environment (ENV)
6. Joint Reseach Centre (JRC)

The EC will be a stakeholder who has the potential to have an impact on the collection process.

European Raw Materials Alliance

The ERMA was announced in 2020 as part of an action plan proposed by the EC on Critical Raw Materials. The vision of the ERMA is to secure the access to raw materials of critical and strategic nature for the EU ("About us - European Raw Materials Alliance (ERMA)", n.d.). To do so, the alliance will work with the relevant stakeholders, industries in the value chain, Member States, unions, investors, NGOs, and technical and research organisations ("About us - European Raw Materials Alliance (ERMA)", n.d.). The ERMA plans to make the supply chain chains more resilient by diversification, steering investments towards the value chain of raw materials, stimulating innovations, creating jobs and making frameworks for a circular economy ("European Raw Materials Alliance (ERMA) - Homepage", n.d.).
Currently, the alliance's main target is to focus on increasing the resilience of REMs and the motor value chain in the EU ("European Raw Materials Alliance (ERMA) - Homepage", n.d.). The ERMA has also prepared a report called "Rare Earth Magnets and Motors: A European Call for Action" where various action plans are proposed by the ERMA to diversify the supply chain of REEs make it more resilient (Gauss et al., 2021). Thus, the role of ERMA is very crucial as any policy recommendations given to EC on the collection and recycling of neodymium magnets have a chance of being implemented. This makes them a stakeholder in the collection process as they have the power to influence the EC. Some of the actions proposed by Gauss et al. (2021) that relate to the recycling and collection of neodymium magnets are as follows:

1. Product designs should be such that it enables re-use and recycling of REMs.
2. Products containing REEs and REMs should stay in the EU by means of regulations and standards.
3. Member States should incentivise magnet recycling.
4. Dismantling lines should be setup for economically processing products that contain REMs.

5.2.2 European Institute of Innovation and Technology (EIT) RawMaterials

EIT RawMaterials GmbH is part of the European Institute of Innovation and Technology (EIT) focusing on providing an environment for collaboration between businesses, academia, research and investment for development of breakthrough innovations in the raw material sector. The objective of EIT RawMaterials is to "secure a sustainable raw materials supply by driving innovation, education, and entrepreneurship across European industrial ecosystems" ("About EIT RawMaterials", n.d.). The company is authorised by the EC and manages the ERMA, it has a high interest and also considerable power in securing the supply of neodymium magnets for EU as the company ("About EIT RawMaterials", n.d.).

Ongoing EU funded recycling projects

The EU has recognised the REEs present in PMs as critical raw materials (Bobba et al., 2020). In order to prevent these elements from getting disposed in the waste stream of various products and ensure resource protection, the EU Horizon 2020 has been funding various projects in this direction. Some of the projects in the past that focused on recovery and recycling of REMs are: EREAN, REE4U, DEMETER (more information about the projects can be found in Appendix C.2.1). Currently, SUSMAGPRO is one of the biggest projects that is ongoing in this field.

SUSMAGPRO: SUSMAGPRO (Sustainable Recovery, Reprocessing and Reuse of REMs in a European Circular Economy) is a project funded by European Union's Horizon 2020 research and innovation program. The project was started in 2019 and aims to develop a "recycling supply chain for REMs in Europe and to demonstrate the effective reuse of recycled rare earth materials within several industries" ("About SUSMAGPRO — Susmagpro — Sustainable Recovery, Reprocessing and Reuse of Rare-Earth Magnets in the Circular Economy", n.d.). Currently, SUSMAGPRO focuses on collecting the Neodymium magnets from WEEE products like Hard disk drives and finally producing four types of magnets:
1. Fully dense anisotropic sintered magnets
2. HDDR powder for bonding and hot pressing
3. Anisotropic, polymer-bonded magnets
4. Fully dense anisotropic SDS (net-shaped) magnets with complex shape, Ingots for magnetic alloy production.

The magnets developed by SUSMAGPRO have been tested in motors of electric cars, Siemens Gamesa wind turbines, headphones, water pumps and loudspeakers ("About SUSMAGPRO — Susmagpro — Sustainable Recovery, Reprocessing and Reuse of Rare-Earth Magnets in the Circular Economy", n.d.).

Projects like SUSMAGPRO maybe directly involved in advising the EC on the direction of policies that may help improve the collection and recycling of REMs in the EU, thus they can be called stakeholders in the collection process.

Member States

The Member States will be stakeholders and their role will be crucial in implementing any legislation or regulations that are introduced by the EC. They may also be responsible for the development of recycling value chain of neodymium magnets in their states by the means of implementing necessary policies or financially supporting the necessary businesses (Gauss et al., 2021) like the automobile and wind turbine OEMs, motor/generator recyclers, car dismantling companies, and wind turbine dismantling companies. In addition, they can also be responsible for updating and aligning their raw material policies to support the collection and recycling of the neodymium magnets in their states (Gauss et al., 2021). However, it should be noted that not all Member States will equally generate neodymium scraps as some of Member States have higher number of EVs and wind turbines compared to others as shown in section 3.4.3. This implies that some Member States will need to be more quick than others in taking action to salvage the neodymium magnets. Furthermore, since there are no regulations on the EU level for REEs as discussed in the section 5.1. Necessary directives either need to be updated or new directives should be introduced on the EU level by the EC so that the Member States have a guideline for building national legislation. Doing so will help close a part of the material loop for both EVs and wind turbines and also help Member States towards moving to a circular economy.

Wind turbine and Automobile OEMs

Currently, the role of both wind turbine and automobile OEMs is that of stakeholder, but in the future, they may become part of the neodymium magnet recycling value chain, which would make them actors.

Wind turbine Producers

Wind turbine OEMs are aware that there are supply risks and environmental risks associated with neodymium magnets. The supply risk is due to China's dominance in mining REEs and, subsequently, the production of REMs. Furthermore, the OEMs are also aware of the environmental pollution and social issues caused by the mining of REEs like neodymium and dysprosium that are used in the production of the magnets (*Consolidated Non-Financial Statement 2021-Siemens Gamesa Renewable Energy*, 2021). The producers try to deal with this by finding REM manufacturers that need to follow a suppliers code of conduct designed by the individual producers (*Consolidated Non-Financial Statement 2021-Siemens Gamesa Renewable Energy*, 2021; "Rethinking the use of rare-earth elements — Windpower Monthly", n.d.). Some wind turbine manufacturers for instance, Enercon GmbH., have developed generator technologies that do not use Neodymium magnets (*SUSTAINABILITY REPORT 2020- ENERCON*, 2020). Enercon GmbH. is based in Germany and has developed an Electrically Excited Synchronous Generator (EESGs) which does not require the use of REMs. Other companies have also started to acknowledge the problem and decided to reduce the dependence on REMs in making the generator (Pavel et al., 2017).

A major wind turbine OEM shared that currently the EPR does not apply to wind turbine OEMs and they are not responsible for the collection and recycling of the wind turbines and its components, and it is up to the wind farm owner who is responsible for choosing the correct recycling route for the PMSGs in the wind turbine and the magnets in them (A.3.1). However, it was also revealed that they have started to recycle prototype generators, and their generators are designed to be recycled. Furthermore, in an engagement project from Shareholders for Change ("Rare Metals Supply Chain- Challenges for sustainable energy transition", 2021), five wind energy companies (Vestas, Siemens-Gamesa, Orsted, Iberdrola, and Nordex) were interviewed regarding the issue of recycling components with REEs; all five responded that they need specific targets on rare earth recycling. This indicates that the wind turbine OEMs are waiting for the legislation to give them direction on recycling REEs in their products. It is also interesting to note that although there is no EPR for the wind turbine industry, the wind turbine OEMs are actively trying to find ways to recycle the blades of the wind turbine, which is becoming an increasing problem ("Wind industry calls for Europe-wide ban on landfilling turbine blades — WindEurope", 2021), this initiative suggests that the wind turbine OEMs want to be more circular and sustainable. The Wind turbine OEMs may play a crucial role in organising and financing the collection and recycling of neodymium magnets in their PM generators if the EC expands the scope of EPR. In that case, the EC would also need to organise meetings with the wind turbine OEMs to discuss how the EPR would function and what obligations the wind turbine OEMs would need to fulfil.

Automobile OEMs

Automobile OEMs that manufacture the EVs are also responsible for managing the EoL of the vehicles. As explained earlier in section 5.1.2, currently the Automobile OEMs are obligated to arrange for the collection and recycling of their vehicles in the EU. However, the scope of EPR is limited and does not cover critical raw materials like the REEs and Platinum group metals that are present in their vehicles (Wilts et al., n.d.). Like the wind turbine OEMs, automobile OEMs are aware of the supply risk and potential shortage of neodymium magnets (explained in section 3) that may occur shortly. Some automobile OEMs, like Renault and BMW, are trying to reduce their dependence on REMs by using different types of electric motors (Explained in section 3.3.2) in some of their EV models; some OEMs like Volkswagen and Toyota are reducing the amount of dysprosium and terbium in the neodymium magnets that they use, while OEMs like Mercedes is trying to reduce their dependence in the medium term ("Factbox: Automakers cutting back on rare earth magnets — Reuters", n.d.).

Automobile OEMs were contacted to get their viewpoint and involvement in the future about the collection and recycling of neodymium magnets used in their EV PM motors; however, no response was received.

Similar to the role of wind turbine OEMs, the role of automobile OEMs in the EU will be crucial if the scope of the EPR is expanded by the EC, in which case the collection and recycling of critical raw materials like neodymium magnets would be financed and organised by the automobile OEMs.

Motor/generator collector and Motor/generator recyclers

It is important to mention that the motor/generator recyclers do not only recycle motors and generators but are also involved in the recycling of transformers, cables, etc, but in this study, they are mentioned as motor/generator recyclers. An interview with motor/generator recycler based in the Netherlands was conducted to understand the supply chain of EoL electric motors and generators. The motor/generator collectors currently buy or collect the motors and generators from various sources and sell them to different motor/generator recyclers (Motor/generator recycler, A.3). The supply chain has been described in section 3.5.3 and the summary of the interview can be found in the Appendix A.3. The motor/generator recycling company shared that they are a commercial company and like any other company they like to earn profit from their operations. The extraction of neodymium magnets from the motors is a difficult and time-consuming task due to its design. If the costs are too high to dismantle the motors, then they are re-sold to traders in third countries. In the case of wind turbine generators, the export to third countries is less common due to high quantities of copper, iron, aluminium and neodymium magnets (in the case of PMSGs) that can extracted and sold. However, the motor/generator recycling company that was interviewed claims that a lot of motor/generator recyclers are unaware of the economic value of the neodymium magnets that are present in the motors and even the generators and thus are lost in the recycling value chain of iron.

Information regarding motor/generator collectors was tried to gathered through grey and scientific literature, however, nothing was found.

The role of motor/generator collectors and recyclers will be important, as they will be actors in collecting the neodymium magnets and sending them for recycling. Thus the EC would need to work with them closely to ensure that the motor/generator recyclers and the collectors are aware of the economic, strategic and environmental value of collecting and recycling the magnets. Furthermore, the EC would need to work with them to address the financial challenges related to the extraction of the magnets from the PM motors and generators and to ensure that the PM motors and generators stay in the EU.

Some of the companies/projects/research institutes that are part of the stakeholder groups that are identified under 'Players' are as follows:

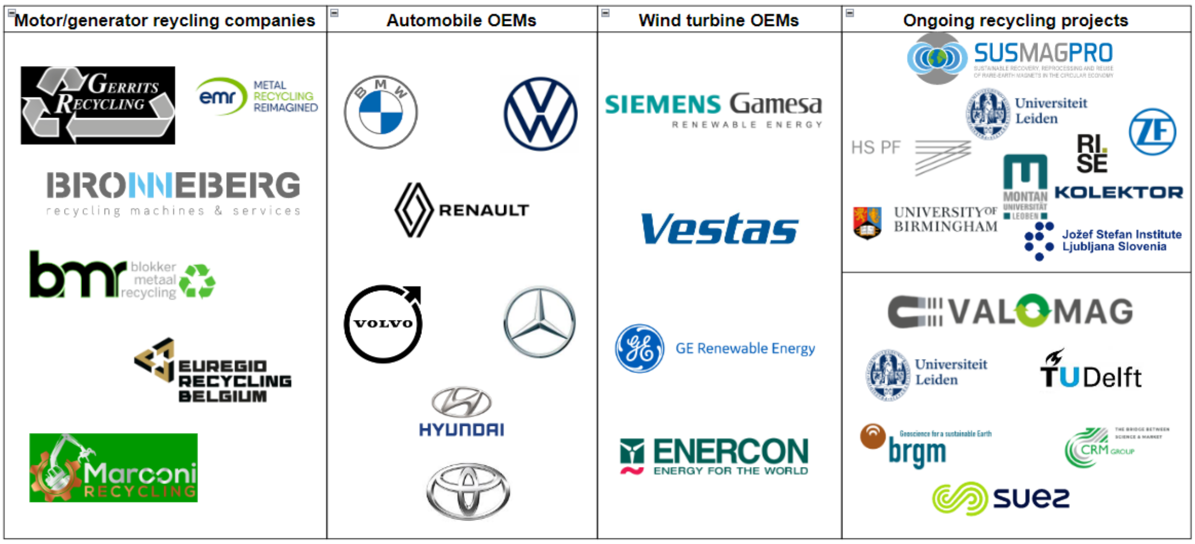


Figure 5.4: Overview of companies/projects/research in different stakeholder group under 'Players'

European Recycling Industries' Confederation

The European Recycling Industries' Confederation (EuRIC) is an association that represents all the recycling companies in Europe. EuRIC has been a trusted interface between the recycling companies and the EC. The association serves "as a platform for information, cooperation and exchange of best practices on all European recycling matters" ("EuRIC - Who we are", n.d.). Thus EuRIC will play an essential role in being part of any negotiations and supporting the motor/generator recycling companies views.

5.2.3 Subjects

Wind farm owner

Wind farm owners are responsible for the commissioning and the decommissioning of the wind turbines on their wind farms. Decommissioning of the turbines is usually done for one of the five reasons explained in section 3.5.2. Due to time constraints wind farm owners were not contacted. However, information was gathered from websites and reports of two of the biggest wind farm owners in the EU - Vattenfall and Orsted.

1. Orsted claims to recycle between 85- 95% of the wind turbines and has made commitment to recycle the last 5% of as well ("Can Wind Turbines Be Recycled? — Ørsted", n.d.).

2. Vattenfall does not make a claim about the percentage of recycling of the entire wind turbine but has committed to landfill ban of blades of the wind turbine ("Vattenfall commits to landfill ban and to recycle all wind turbine blades by 2030 - Vattenfall", n.d.). In addition, Vattenfall has set 100% recycling target for blades by 2030.

Currently, more attention is paid to the recycling of blades by the wind farm owners despite their being any law related to the recycling of the blades. Wind farm owners are often large renewable energy companies which are striving to be a circular business ("Heading for a circular economy – Salzgitter AG and Ørsted launch strategic partnership", n.d.; "Sustainable resource use - Vattenfall", n.d.) thus contributing to the goal of EU being a circular economy. The lack of attention towards the recycling of neodymium magnets that are present in the wind turbines should be addressed with the wind farm owners. Since the wind farm owners are trying to be a circular business they would be interested in finding solution for the collection and recycling of the magnets. Moreover, until there is an EPR which makes the wind turbine OEMs responsible for collecting and recycling the magnets in PM generators, the wind farm owners are responsible for deciding the collection and recycling route of the neodymium magnets, which makes them an actor. Until any regulations are introduced for the wind turbine OEMs, the wind farm owners may be strongly advised to monitor the flow of magnets from the EoL generators.

Wind turbine dismantling companies

There is a growing number of wind turbines reaching EoL shortly, which has created a market for the safe dismantling the wind turbines both on land and at sea(WindEurope, 2020). The dismantling companies like AGIX Energy, INIKTI are offering a turnkey services (“AGIX Energy”, n.d.; “INIKTI - Energy is Everything”, n.d.) to the wind farm owners, where the dismantling companies are responsible for planning, monitoring, and disposal (“New approach to wind turbine decommissioning — Windpowernl”, 2021). This would require these companies to work with the local transport companies, recycling companies and manufacturers of wind turbine in order to dismantle and transport the components from EoL wind turbines to various recycling routes for recovery or re-use of the materials (“Dismantling”, n.d.; “SUEZ develops its expertise in the dismantling and recovery of wind turbines with a recovery target close to 100% - SUEZ Group”, 2021; “Wind Turbine Dismantling - Complete dismantling, disposal and recycling”, n.d.).

A questionnaire was sent to wind turbine dismantling company in order to understand their responsibilities related to recycling of the components and in particular the recycling of the PM generator. However, no response has been received from them at this point. The questionnaire can be found in the Appendix A.3.2. Thus information was primarily found through grey literature (news articles, blogs, reports, company websites etc.). Furthermore, an interview with motor/generator recycler revealed that the motor/generator collectors collect the wind turbine generators and then auction them to smaller motor/generator recyclers. Thus, it is safe to assume that the dismantling companies approach the motor/generator collectors for selling the EoL generators from wind turbines. However, it is still unknown whether the dismantling companies track the flow of the neodymium magnets like for some of the primary materials, which are claimed to be ” traced until they are recycled” (“SUEZ develops its expertise in the dismantling and recovery of wind turbines with a recovery target close to 100% - SUEZ Group”, 2021).

In the context of collection of neodymium magnets from EoL wind turbine generators, the role of the wind turbine dismantling companies may be to track the flow of neodymium magnets and report it to the wind farm owners.

Car Dismantling Companies

The car dismantling companies are responsible for dismantling the ELVs and sort the various materials that are used to make the car. The car dismantling companies are obliged to sort the materials of the dismantled vehicle in order to re-use or recycle 95% of the vehicle. At least 85% of the materials should be re-used or recycled and additionally 10% of the vehicle should be useful for other purposes like energy generation through incineration (“Car recycling - ARN”, n.d.). As discussed in section 5.1.2, the current ELV directive is focused on recovering the major metals. It can be argued that the bottom line for car dismantling companies in the EU is to dismantle the car as per the latest ELV directive and to make a profit by selling the scrap metal like iron, copper, aluminum etc. to the appropriate recyclers. Furthermore, the car dismantling companies also make a profit by selling the used car parts in the secondary market. Based on the interview with motor/generator recycling company (A.3), it can be assumed that the car dismantling companies remove the motors and sell it to motor/generator collector as shown in section 3.5.3. However, if this is not the case and motors are shredded, then the recovery of the neodymium magnets and the REEs present in them cannot be removed economically (Elwert et al., 2016). Thus, the role of car dismantling companies may be to ensure that the motors, especially PM motors in the EVs, are removed and sent to the correct recycling value chain before the rest of the car is shredded; this makes them an actor in the collection process. Furthermore, the car dismantling companies may also be responsible for tracking the scrap motors as these motors may end up in third countries, and valuable resources may be lost.

Some of the companies that are part of the identified stakeholder groups under 'Subjects' are as follows:

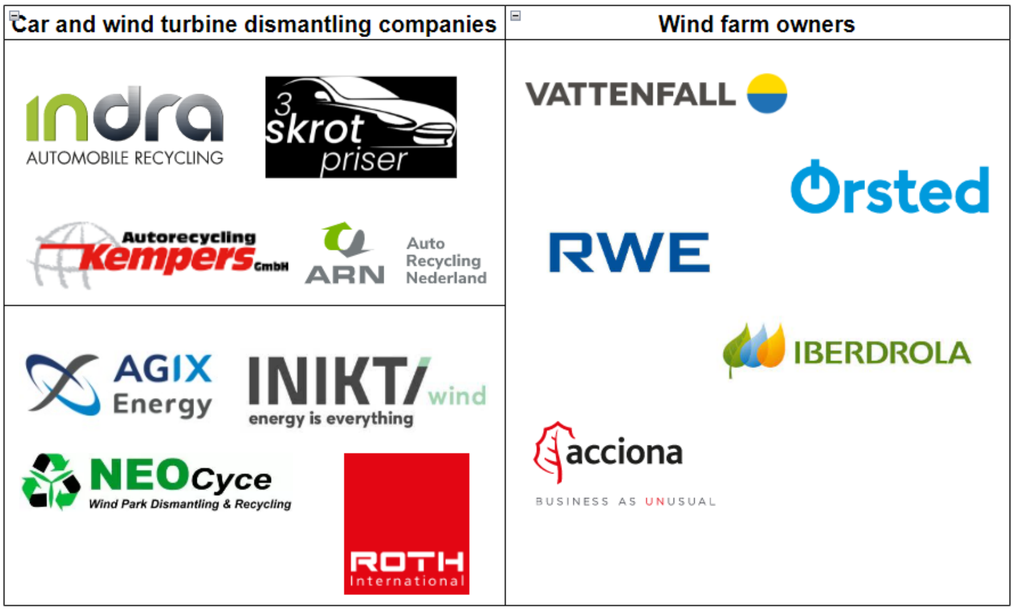


Figure 5.5: Overview of some companies in different stakeholder group under 'Subjects'

European Group of Automotive Recycling Association (EGARA)

The European Group of Automotive Recycling Association (EGARA) was founded in 1991 and it represents the "independent, professional, environmentally conscious dismantlers in Europe" ("Home - Egara", n.d.). At its core, the association supports circular economy in the automobile industry and promotes reuse of components as a first option from the dismantled vehicles. Finally, they support the improvements in recycling of automobiles ("Home - Egara", n.d.). The association has also contributed in the development of ELV directive and the association will be a key subject who needs to be kept informed in the decision making process.

5.2.4 Crowd

REE mining proponents

Currently, Europe has no active REE mines, however, it does have rare earth deposits in France, Spain, Greece, Sweden, and Greenland ("Europe's rare earth deposits could shore up tech industry — Research and Innovation", n.d.). The REE mining proponents consists of REE mining projects, mining companies and research universities that are interested in starting the REE mining in Europe. It can be argued that they have little to no interest in the collection and recycling of neodymium magnets from the secondary mines as they are aware that secondary or urban mining will only partially fulfill the demand of neodymium magnets in the EU and the primary supply would be from magnet manufacturers who are reliant on virgin materials that would be available through mining.

Civil Society actors

The civil society actors (233 in total) have expressed their concerns about EU's critical raw material plan. However, the concern of civil society actors is more towards the start of mining operations in the EU rather than recycling as they state that "although necessary, actions to increase recycling and secondary sourcing can only meet a small amount of the EU's demand in metals and minerals if the EU's consumption continues to expand and grow at its current rate" ("Civil society concerns on EU critical raw materials plans - EEB - The European Environmental Bureau", n.d.). This implies that the civil society actors are not highly interested in recycling nor do they have a lot of power in the context of collection of neodymium magnets. Some of the civil society actors that are active in expressing their concerns about the critical raw material plan are as follows: Friends of the Earth Europe, European Environmental Bureau, Worldwide Fund for Nature, CEE Bankwatch Network, Seas At Risk, Yes to Life No to Mining, European Network on Indigenous Peoples etc ("Civil society concerns on EU critical raw materials plans - EEB - The European Environmental Bureau", n.d.).

Some of the organisations/research institutes that are part of these two stakeholder groups are as follows:

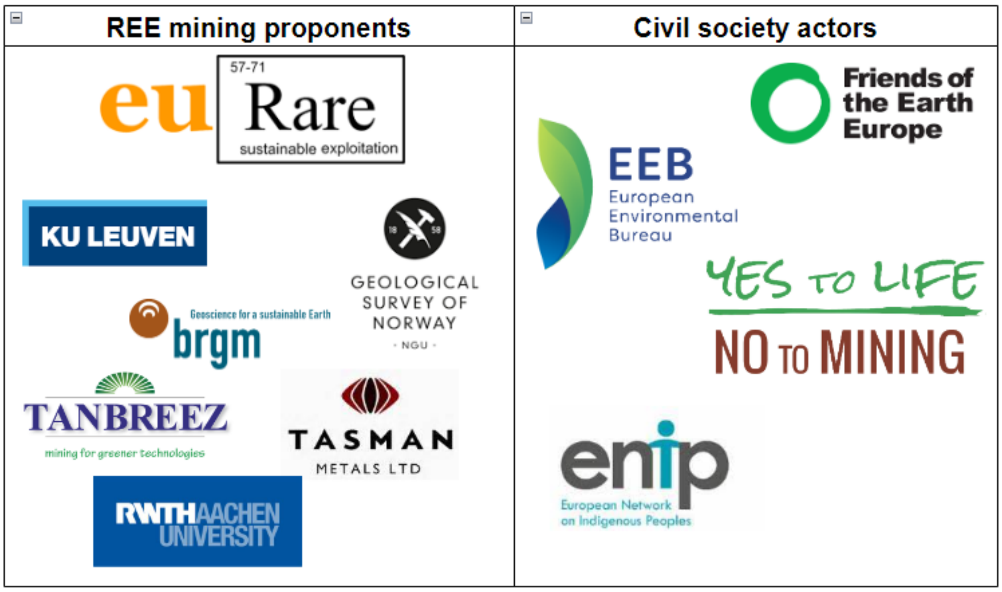


Figure 5.6: Overview of some of the organisations/research institutes part of identified stakeholder group

5.3 Conclusion

This chapter answered two sub sub-questions, *SQ 1.3- What legislation are in place that governs the flow of EoL EVs, wind turbines and neodymium magnets?* and *SQ 1.4- Which stakeholders will be involved or affected by collection strategies?*.

The legal analysis found that the current legislation severely limits the possibility of collecting and recycling neodymium magnets from EoL EVs and wind turbines. This is primarily because the aim of the EU to secure access to critical raw materials like REEs and neodymium magnets is not reflected in the legislation in place. Several issues like the focus on mass-based recycling, no EPR for wind turbines and their components, and limited scope of EPR for the automobile OEMs act as a barrier to collecting and recycling the neodymium magnets. On the other hand, the latest regulation proposal for products like batteries suggests that the EU and the EC are

taking steps in the right direction for batteries and their critical raw materials. Thus, a similar initiative needs to be taken for neodymium magnets.
The stakeholder analysis shows the stakeholders that are directly (the Players) and indirectly related (the Subjects) in collecting neodymium magnets. The Players can either be involved in making appropriate policies for the collection, organising the collection and recycling, or extracting the magnets from PM motors and generators assemblies. The Subjects can be indirectly involved in the collection process by directing the PM motors and generators containing the neodymium magnets to the right recycling route.

CHAPTER 6

Requirements and Functions

The analyses presented in chapter 3 to 5 give a detailed insight of the market conditions, reusability and recyclability aspect, legal aspects and the stakeholders that will be directly or indirectly involved in the collection of the neodymium magnets from the EVs and the wind turbines. The analyses revealed important issues that need to be addressed by the collection strategies to be designed. Based on the analyses, this chapter provides the requirements and the functions that the collection strategies should fulfill, thus answering the *SQ2: What are the requirements and functionalities for designing the collection strategies?*.
The chapter begins with stating the objectives of the collection strategies. Then the market, legal and stakeholder, and reuse and recyclability requirements are listed and explained. Finally, the functions of the collection strategies are presented.

6.1 Objective of collection strategies

Based on the analyses presented in Chapter 3 to 5, four objectives and one constraint for the collection strategies of neodymium magnets from EoL wind turbines and EVs in the EU are defined:

1. Layout the necessary fundamentals (market and legislative conditions) for collection of neodymium magnets to take place.
2. Facilitate the collection of neodymium magnets.
3. Ensure information flow about materials in the neodymium magnet recycling value chain.
4. Enable a high collection rate of neodymium magnets in long run.
5. Keep the PM motors and generators containing neodymium magnets within the EU (Constraint).

Currently, less than 1% of magnet scraps are being recycled in the EU (Gauss et al., 2021). The source of the neodymium magnets in this case comes from two different kind of products; wind turbines which are industrial products and EVs which are consumer products. Although the products serve different markets, the PM motors and generators present in EoL EVs and wind turbines, respectively, reach a common actor in the recycling value chain- the motor/generator recyclers as shown in the supply chain of EoL PM motors and generators (3.5.3). Thus, in order to recycle or re-use these magnets in the EU, it needs to be ensured that the PM motors, generators and the neodymium magnets in them are collected and directed to the right recycling route. Only when there is a high collection rate, the overall recycling rate of the magnets will increase, which in turn will serve a part of the demand generated by wind turbine and automobile OEMs.

6.2 Requirements

Requirements can be seen as something that should be met to achieve the objectives and stay within the constraint defined for the collection strategies. A list of requirements has been made from each of the analyses presented in chapters 4, 5, and 3, respectively. The requirements formed then have been labelled 'Nice to have' or 'Need to have'. Finally, a consolidated list of 18 'Need to have' requirements have been presented.

6.2.1 Market Requirements

The table 6.1 presents the requirements that are formed based on the market analysis in chapter 3, and the stakeholder analysis in section 5.2).

Table 6.1: Market Requirements

Sno.	Requirements	Applicable to	Need to have or Nice to have	References
M1	The process of collection and recycling should be attractive for the recycling companies.	Electric Vehicles & Wind Turbines	Need to have	Motor/generator collectors and recyclers (5.2.2), Interview with motor/generator recycler (A.3).
M2	The price of recycled neodymium magnets should be competitive with the price of magnets imported by China.	Electric Vehicles & Wind Turbines	Need to have	Interview with Expert 2 (A.2.2), Competition and Pricing (3.2)
M3	Collection and recycling setup should aim to process more than 104 tons of NdFeB magnets coming from EoL EVs by 2025 in the EU.	Electric Vehicles	Need to have	Quantification Model (Cumulative data, 3.4.3)
M4	The scale of collection and recycling should significantly increase by 2030 to process NdFeB magnets available from EoL EVs.	Electric Vehicles	Need to have	Quantification Model (Cumulative data, 3.8)
M5	Collection and recycling setup should aim to process additional quantity of magnets from EoL Offshore and Onshore wind turbines from 2030.	Wind turbines	Need to have	Quantification Model Cumulative data (3.9, 3.10)
M6	The scale of collection and recycling should further increase significantly to process large quantity of magnets from EoL Offshore and Onshore wind turbines in 2037 and 2040.	Wind turbines	Need to have	Quantification Model Cumulative data (3.9, 3.10)

M1:

The process of collection and subsequently recycling needs to be attractive enough for electric motor/generator recyclers so that the neodymium magnets in the PM motors and generators are extracted from the assembly and sent to the appropriate recycling route. Currently, the process of extracting the magnets from the PM motors is labour intensive and the motors are either sold to other recyclers situated in third countries or where the labour is cheap (Motor/generator recycler, A.3). This eventually leads to the loss of neodymium magnets and the REEs present in them as there is no recycling method which are known to be used in the third countries.
If the process of collection is financially attractive then the magnets may not exit the EU as they will be extracted, stored and be sold to the necessary magnet recycling company within the EU.

M2:

The price of recycled magnets need to be comparable to the price of the magnets sold by China. This is required because if the necessary demand for recycled magnets needs to be created, then the recycled neodymium magnets need to be comparable in price and quality. The quality of the recycled magnets is already as good as the new ones (Lixandru et al., 2017; "Research shows promising ways to recycle neodymium — Stena Recycling", n.d.). However, the price needs to be comparable as well. Otherwise, the recycled magnets may not be opted for by the OEMs. Eventually, as more magnets are available from EoL PM motors and generators, the price of the recycled magnets will also decrease due to economies of scale. Moreover, the magnets will also be available from other EoL consumer products like hard drives, washing machines, e-bikes etc. which will further add to the volume of magnets available for recycling.

M3 and M4:

Based on the quantification model for EVs presented in section 3.4, the total estimated amount of neodymium magnets present in EoL EVs of Western Europe (Netherlands, Belgium, France and Germany) is shown in figure 3.8a. However, in the context of entire EU, it can be argued that the amount of neodymium magnets available for collection will be much more.

It can be seen in figure 3.8a that nearly 43 tons of magnets are present in EVs that are going to reach EoL in 2022. Since there are no EU policies up till now regarding the neodymium magnet recovery and no magnet waste stream, the magnets can be assumed to be lost in different waste streams. From 2024, the amount of magnets that maybe available for recycling increases more than two times of the amount in 2022 for Western Europe and much more for the entire EU. Thus, in order to capture the upcoming neodymium magnets from EoL EVs in 2024, the scale of collection and recycling in place should be able to process more than 104 tons of neodymium magnets .

From 2024 to 2030, the amount of magnets that will become available from EoL EVs increases exponentially. This implies that in order to salvage the magnets, the EV motors need to be retrieved so that they can be disassembled and the magnets can be extracted for recycling. To account for the exponential increase the scale of collection and recycling should also increase significantly.

M5 and M6:

Based on the quantification model of wind turbines presented in section 3.4, the total amount of magnets that will be available for recycling from onshore wind turbines and offshore wind turbines of Western Europe are shown in figure 3.10 and 3.9. From figure 3.10a it can be seen that the amount of neodymium magnets from EoL onshore wind turbines start increasing from 2031 and reaches a peak in 2037. This indicates that additional capacity on top of the capacity required for magnets from EoL EVs would be required for collecting and recycling the magnets coming from EoL onshore wind turbines in 2030.

From figures 3.10a, 3.9a, 3.10b and 3.12, it can be seen that, overall, Germany will be the biggest source of magnets from onshore and offshore wind turbines in the entire EU. It should be noted that although the graph referred here represents data from Western Europe, the shape of the graph for entire EU will be similar. The difference would be that the volume of neodymium magnets that will be available for collection and recycling will increase. Thus in the context of the EU, the scale of collection and recycling should be able to process additional quantity of neodymium magnets that will be available from wind turbines in 2030 and scale of collection and recycling should be increased significantly to process much larger quantities that will become available from 2037 onwards.

6.2.2 Legal and Stakeholder Requirements

The table 6.2 provides a list of requirements that have been derived from the legal and stakeholder analysis conducted in the section 5.1. The list of requirements presented would help overcome the limitation and fill the gaps in the existing policies and address the necessary stakeholders.

Table 6.2: Legal and Stakeholder Requirements

Sno.	Requirements	Applicable to	Need to have or Nice to have	References
L1	A target for collecting the PMSMs, PMSGs and the neodymium magnets present in them.	Electric Vehicle & Wind Turbines	Need to have	WFD (5.1.1), Proposed Battery Regulation (5.1.5), Interview with Expert 1 and Expert 2 (A.2.2, A.2.1)
L2	The automobile and wind turbine OEMs should be responsible for organising and for collection and recycling of PM motors and generators present in EVs and wind turbines, respectively.	Electric Vehicles & Wind Turbines	Need to have	EPR (5.1.3), Interview with Expert 2 (A.2.2)
L3	Export of EoL PM generators and motors from wind turbine and EVs should be restricted.	Electric Vehicles & Wind Turbines	Need to have	Supply chain of EoL motors and generators (3.5.3)
L4	Monitor the illegal export of EVs.	Electric Vehicles	Nice to have	Circular Economy and Export of wastes(5.1.4)
L5	Establish an EoL Wind Turbine directive that focuses on decommissioning of wind turbines and recycling and re-use of critical materials in them.	Wind Turbines	Nice to have	WFD (5.1.1)
L6	Aligning EU's interests with existing regulations and legislation.	Electric Vehicles & Wind Turbines	Need to have	WFD (5.1.1), ELV directive (5.1.2)
S1	Car dismantling companies must remove motors from EVs before the rest of the EV is shredded.	Electric Vehicles	Need to have	Car dismantling companies (5.2.3)
S2	Wind farm owners should be advised to monitor the flow of magnets from EoL PM generators.	Wind Turbines	Need to have	Wind farm owners (5.2.3)
S3	OEMs want more direction from legislation in place.	Electric Vehicles & Wind Turbines	Need to have	Wind turbine and automobile OEMs (5.2.2)
S4	More awareness should be created amongst electric motor and generator recyclers about collection of magnets.	Electric Vehicles & Wind Turbines	Need to have	Interview with motor/generator recycler (A.3)

L1:

This particular requirement is formed by analysing the WFD and the proposed battery regulation discussed in section 5.1.5. In order to maximise the recovery of the neodymium magnets, there needs to be collection targets for motors and generators in place. Since the wind turbines and EVs are two different types of product being sold to two different types of customers; EV being sold to the common public and wind turbines largely being sold to wind farm owners which are businesses. This demands separate collection targets for EV motors and wind turbine generators. The collection target for wind turbine generators can be set higher than that of EV motors due to the following reasons.

1. The wind turbines are much larger and heavier, which means that the quantity of materials in the generators is also high. The high quantity of materials in the wind turbine generator are attractive for motor/generator recyclers which means that there are less chances for it to be shipped to third countries (Motor/generator recycler, A.3).
2. Wind turbines and the components like generators are industrial products, and the industrial products can be tracked relatively easily (van Nielen et al., 2022).
3. The quantity of magnets in wind turbine generator are much higher compared to EV motors.

In addition to the collection target for the PM motors and generators, there should be some target for the neodymium magnets that are present in the PM motors and generators because ultimately the quantity of magnets extracted from the motor and generator assemblies would be of value in the recycling value chain.

L2:

As mentioned in section 5.1.3, the neodymium magnets or any REEs are not covered under the EPR scheme. By increasing the scope of EPR to neodymium magnets the wind turbine and automobile OEMs will be enforced to collect the magnets themselves or will have to organise the collection and recycling of the magnets present in their generators and motors. If the OEMs are not made responsible for collecting and processing motors and generators containing neodymium magnets, then these magnets may be lost in the supply chain. When producers are more accountable for the recovery of the PM motors, generators and neodymium magnets, higher collection rates could be achieved. Furthermore, the producers will also try to design the generators and motors so that critical materials such as neodymium magnets can be easily recovered.

L3:

The export of PM motors to the third countries for purpose of recycling can and is leading to the loss of neodymium magnets as shown in the supply chain of EoL motors and generators (3.5.3). The problem is much more relevant for EV motors than wind turbine generators as the value of materials that can be recovered from the wind turbine generator is more than the cost it takes to dismantle them. However, for keeping critical materials like neodymium magnets in the EU, the exports must be controlled for both PM motors and generators.

L4:

Up till now the illegal export of EoL vehicles has been a huge problem in terms of exporting the waste as well as loosing critical raw materials present in the vehicles (Hagelüken and Goldmann, 2022). Although, the possibility of export of EVs to third countries is unlikely due to underdeveloped infrastructure for EVs, thus this requirement is 'Nice to have'.
The monitoring of the export of EVs with PM motors and wind turbines with PM generators to the third countries can be beneficial in tracking the amount of neodymium magnets that are going outside the EU and may not return to the EU. However, in this case it is more important to restrict the flow of the motors to the third countries.

L5:

Currently, the wind turbines do not have a EoL directive like vehicles and thus are treated under the requirements of construction and demolition waste. It may be a wise decision to make a separate directive for EoL wind turbines which will guide the process of decommissioning of wind turbines present both on land and in sea. Furthermore, the directive can also include how the EoL components like PM generators, rotor blades, tower, etc. should be treated. However, this is not seen as an urgent issue from the point of view of collection of neodymium magnets and thus is labelled as 'Nice to have' requirement.

L6:

The EU's interests of securing the supply of REMs should be aligned with the existing legislation in place like the ELV directive which currently does not have any framework or guidelines for the collection and recycling of REMs present in vehicles and specifically in EVs. Thus it is important to align the EU interests with the existing legislation and regulations that are in place.

S1:

To retrieve the magnets from EV motors, the first step would be to remove the motors from the EVs. If the PM motors are not removed by the car dismantling companies, then the motors will be shredded along with the body of the EVs. As mentioned in section 5.2.2, the PM motors of EVs have started reaching motor/generator recyclers, indicating that the motors are being removed from EVs. However, to achieve a high collection rate, every car dismantling company in the EU should remove the motors from the EVs.

S2:

Since there are no regulations or legislation explicitly targeting the EoL wind turbines as described in section 5.1, it is the responsibility of the wind farm owners to select the right recycling routes for the components of the EoL wind turbines (Wind turbine OEM, A.3.1). The wind farm owners hire dismantling companies to dismantle and even organise the recycling of the various components. However, it is the responsibility of the wind farm owners to monitor whether proper recycling takes place or not. As explained in section 5.2.3, a greater focus is currently on recycling wind turbine blades. Thus, the wind farm owners should be made aware and be advised to monitor the flow of the EoL wind turbine generator and the neodymium magnets in them.

S3:

As mentioned in section 5.2.2, to involve OEMs in the process of collection and recycling of neodymium magnets present in their products, the OEMs need to be given specific direction through legislation as to how they can be involved in the process of collection and recycling ("Rare Metals Supply Chain- Challenges for sustainable energy transition", 2021). A major wind turbine OEM (A.3.1) brought to light that the wind turbine industry is aware of the potential issue of scrap magnets, and they have recycled several prototype generators. Thus, it can be argued that the OEMs are waiting for the legislation to be introduced to start organising for collection and recycling of magnets present in their products.

S4:

To facilitate the collection and eventually have a high collection rate of the magnets present in the EoL wind turbine generators and EV motors, the motor/ generator recyclers will play an essential role in the collection, storage and routing of the magnets to the suitable recycling chain. As mentioned in section 5.2.2, many motor/generator recyclers are not even aware of the magnets present in the PM motors and generators and often end up in the slag of iron smelters. Thus, it is necessary to create awareness among the motor/generator recyclers about the importance of collecting these magnets and their economic value (Motor/generator recycler, A.3).

6.2.3 Requirements for reusability and recyclability

The table 6.3 presents the requirements that have been derived from the analysis on reusability and recyclability of neodymium magnets that was done in section 4.

Table 6.3: Requirements for reusability and recyclability

Sno.	Requirements	Applicable to	Need to have or Nice to have	References
R1	The design of motors and generators should be such that magnets can be easily extracted without being damaged.	Electric Vehicles & Wind Turbines	~~Nice to have~~ Need to have	Possibility of re-using the magnets (4.1.1), Interview with Expert 2 (A.2.2) and Expert 3 (A.2.3)
R2	The scale of Hydrogen Processing of Magnetic Scrap (HPMS) recycling process should be increased.	Electric Vehicles & Wind Turbines	Need to have	Recycling Technologies (4.2)
R3	Flow of information about the neodymium magnets used in EVs and Wind Turbines.	Electric Vehicles & Wind Turbines	Need to have	Different grades of neodymium magnets and the importance of classification (4.3), Interview with Expert 1 (A.2.1)
R4	Safe handling of NdFeB magnets by motor/generator recyclers.	Electric Vehicles & Wind Turbines	Need to have	Dangers of neodymium magnets (4.4)

R1:

This particular requirement is applicable for both wind turbines and EVs. The requirement was first identified as a 'Nice to have' requirement but later changed to 'Need to have' as it is essential that the PM motors and generators of EVs and wind turbines that are designed now and in the future are easy to dismantle for the magnets to be extracted (Expert 3, A.2.3). This issue is much more of a concern for EVs than wind turbines. Design for easy retrieval of the magnets from the motors and generators would make the extraction process easier and quicker. As discussed in section 4.1, the magnets in EVs are currently epoxied or glued to be held in place; this makes the removal of the magnets from the assemblies difficult and significantly reduces the chances of the magnets being directly reused since the magnets break while being removed due to their material property. Furthermore, the difficulty of removing materials from the assembly causes the cost of the operations to increase (Hagelüken, 2007), which will directly increase the cost of the recycled magnets.

R2:

The magnets used in wind turbines and EVs are sintered magnets which are an ideal choice for recycling the magnet through the HPMS process (Expert 1, A.2.1) as discussed in section 4.2. If the collection of the magnets is improved then it is wise to increase the capacity of the recycling process simultaneously to process the collected magnets in time, in this case via the HPMS process.

R3:

This requirement is related R2. As discussed in section 4.3, it is important the neodymium magnets are classified as per their chemical composition during the collection process to have an efficient recycling process via the HPMS route. Necessary information needs to be passed by the wind turbine and automobile OEMs about the neodymium magnets. If the grade, the chemical composition, and the type of coating these magnets are known then it could make the process of collection easier and depending on this information the magnets can be sent to the HPMS recycling route (Burkhardt et al., 2020). This will make the entire recycling value chain more efficient. If the OEMs do not share the grade and the composition of the magnets then additional tests will need to be conducted to check the chemical composition of the magnets which would require additional resources thus making the process of collection more expensive and time consuming which will in turn have a negative impact on the cost of recycled magnets. In worst case scenario the recycled materials will fluctuate in the chemical composition which will need to be compensated by adding virgin materials (Burkhardt et al., 2020).

R4:

There is a need to develop safe handling practices for neodymium magnets as they can prove to be dangerous if not handled properly as discussed in section 4.4 . A list of measures that can be taken are presented in the next chapter.

6.3 Final requirements

The final list of requirements are presented in table 6.4 below. The table contains 18 'Need to have' requirements as labeled in tables 6.1,6.2, and 6.3.

Table 6.4: Final list of 18 requirements

Sno.	Requirements
1	The process of collection and recycling should be attractive for the recycling companies.
2	The price of recycled neodymium magnets should be competitive with the price of magnets imported by China.
3	Collection and recycling setup should aim to process more than 104 tons of NdFeB magnets coming from EoL EVs by 2025 in the EU.
4	The scale of collection and recycling should significantly increase by 2030 to process NdFeB magnets available from EoL EVs.
5	Collection and recycling setup should aim to process additional quantity of magnets from EoL Offshore and Onshore wind turbines from 2030.
6	The scale of collection and recycling should further increase significantly to process large quantity of magnets from EoL Offshore and Onshore wind turbines in 2037 and 2040.
7	A target for collecting the PMSMs, PMSGs and the neodymium magnets present in them.
8	The automobile and wind turbine OEMs should be responsible for organising and for collection and recycling of PM motors and generators present in EVs and wind turbines, respectively.
9	Export of EoL PM generators and motors from wind turbine and EVs should be restricted.
10	Aligning EU's interests with existing regulations and legislation.
11	Car dismantling companies must remove motors from EVs before the rest of the EV is shredded.
12	Wind farm owners should be advised to monitor the flow of magnets from EoL PM generators.
13	OEMs want more direction from legislation in place.
14	More awareness should be created amongst electric motor and generator recyclers about collection of magnets.
15	The design of motors and generators should be such that magnets can be easily extracted without being damaged.
16	The scale of Hydrogen Processing of Magnetic Scrap (HPMS) recycling process should be increased.
17	Flow of information about the neodymium magnets used in EVs and Wind Turbines.
18	Safe handling of NdFeB magnets by motor/generator recyclers.

6.4 Functions of Collection Strategies

The functions are categorised into primary/main and secondary functions (Dym et al., 2004). Primary functions are defined as functions that must be performed and secondary functions are functions which support in performing the primary function (Dym et al., 2004). Three primary functions are derived from the analyses that need to be fulfilled to achieve the objectives of the collection strategies.

1. Support the development of secondary market.
2. Address the legal limitations and important stakeholders.
3. Address specifications for reuse and recyclability.

In order to perform the primary functions, secondary functions are defined for the primary functions. The secondary functions are formulated based on the final list of requirements (table

6.4). Some of the final requirements are merged into one function or are covered by multiple functions, as shown in figure 6.2. The Figure 6.1 shows the primary and their subsequent secondary functions.

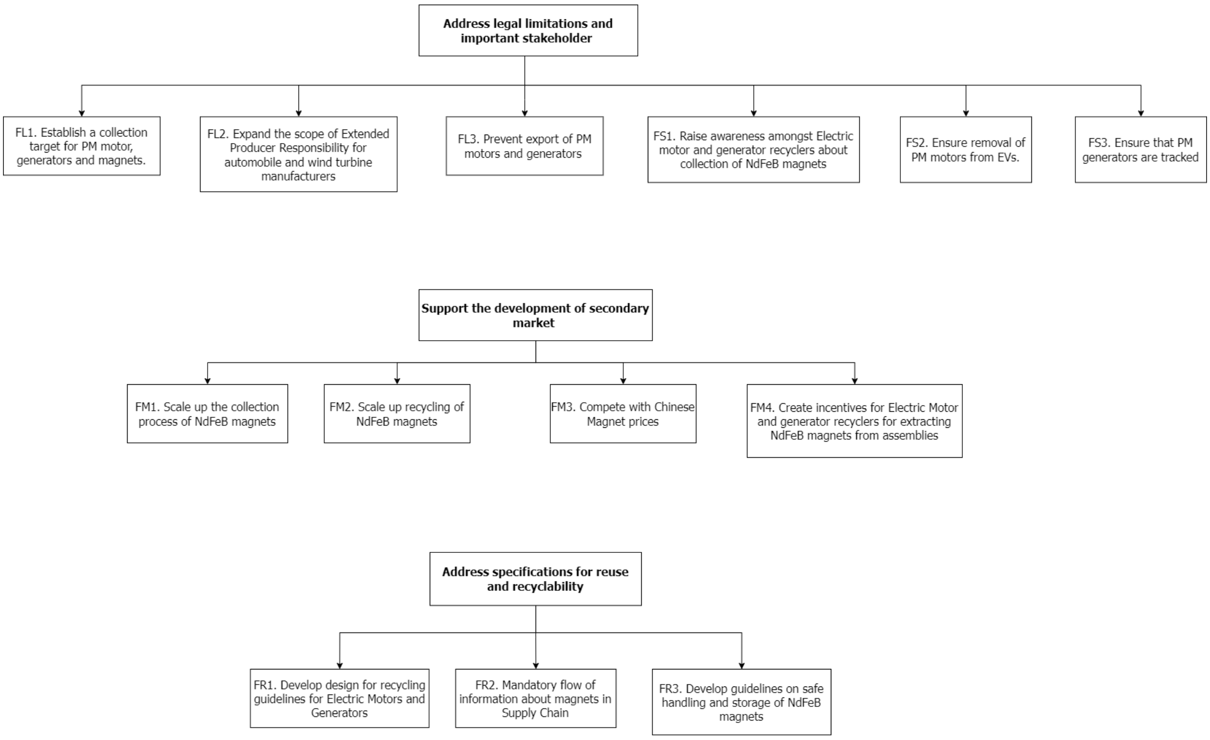


Figure 6.1: Primary and Secondary Functions

List of requirements	**Functions**	**FL1**. Establish a collection target for PM motorand generators.	**FL2**. Expand the scope of Extended Producer Responsibility for automobile and wind turbine manufacturers	**FL3**. Prevent export of PM motors and generators	**FS1**. Raise awareness amongst Electric motor and generator recyclers about collection of NdFeB magnets	**FS2**. Ensure removal of PM motors from EVs.	**FS3**. Ensure that PM generators are tracked	**FM1**. Scale up the collection process of NdFeB magnets	**FM2**. Scale up recycling of NdFeB magnets	**FM3**. Compete with Chinese Magnet prices	**FM4**. Create incentive for Electric Motor and generator recyclers for extracting NdFeB magnets from assemblies	**FR1**. Develop design for recycling guidelines for Electric Motors and Generators	**FR2**. Mandatory flow of information about magnets in Supply Chain	**FR3**. Develop guidelines on safe handling and storage of NdFeB magnets
1. The process of collection and recycling should be attractive for the recycling companies.											X			
2. The price of recycled neodymium magnets should be competitive with the price of magnets imported by China.										X	X			
3. Collection and recycling setup should aim to process more than 104 tons of NdFeB magnets coming from EoL EVs by 2025 in the EU.								X	X					
4. The scale of collection and recycling should significantly increase by 2030 to process NdFeB magnets available from EoL EVs.								X	X					
5. Collection and recycling setup should aim to process additional quantity of magnets from EoL Offshore and Onshore wind turbines from 2030.								X	X					
6. The scale of collection and recycling should further increase significantly to process large quantity of magnets from EoL Offshore and Onshore wind turbines in 2037 and 2040.								X	X					
7. A target for collecting the PMSMs, PMSGs and the neodymium magnets present in them.		X												
8. The automobile and wind turbine OEMs should be responsible for organising and for collection and recycling of PM motors and generators present in EVs and wind turbines, respectively.			X											
9. Export of EOL PM generators and motors from wind turbine and EVs should be restricted.				X										
10. Aligning EU's interests with existing regulations and legislation.		X	X	X										
11. Car dismantling companies must remove motors from EVs before the rest of the EV is shredded.						X								
12. Wind farm owners should be advised to monitor the flow of magnets from EOL PM generators.							X							
13. OEMs want more direction from legislation in place.		X	X	X									X	
14. More awareness should be created amongst electric motor and generator recyclers about collection of magnets.					X									
15. The design of motors and generators should be such that magnets can be easily extracted without being damaged.												X		
16. The scale of Hydrogen Processing of Magnetic Scrap (HPMS) recycling process should be increased.									X					
17. Flow of information about the neodymium magnets used in EVs and Wind Turbines.													X	
18. Safe handling of NdFeB magnets by motor/generator recyclers.														X

Figure 6.2: Requirements vs secondary functions

6.5 Conclusion

This chapter develops requirements for each of the analyses conducted in chapters 3 to 5. Each of the requirements can be traced back to particular sections of the analyses and to interviews that were conducted with experts and stakeholders. To fulfil the objectives and constraint of the collection strategies, three primary functions were formulated- Support the development of secondary market, Address legal Limitations and important stakeholders, and Address specifications for reuse and recyclability. To fulfil the primary functions the secondary functions were defined. Some of the requirements were combined into one of more of the defined secondary functions. The secondary functions will be used in the next stage, where different means are generated to fulfill these secondary functions.

CHAPTER 7

Conceptual Design

This chapter develops the design space by generating alternative means to the secondary functions which were defined in the last chapter. A morphological chart is created where all the functions are listed and corresponding to those functions different means are suggested. Finally, short term, medium term, and long term collection strategies are proposed, each consisting of five labels/themes under which different solutions are placed.

7.1 Generating solution space

In this section, a morphological chart is presented (figure 7.1) with secondary functions that were formulated in the last chapter and alternative means to achieve these functions are listed across each of the functions. The means were developed based on interviews conducted with experts who are working or have worked in the field of neodymium magnet recycling, analyses presented in chapters 3 to 5, and brainstorming. For each of the functions one or more means were written down. Some means were found to be the solution to multiple functions and thus are presented across multiple functions . In the next section, the designed collection strategies are presented by choosing the most suitable means for each of the functions. The rest of the means which were not chosen are explained in the Appendix D.1.

Functions	Means 1	Means 2	Means 3	Means 4	Means 5	Means 6
FM1. Scale up the collection process of NdFeB magnets.	All means of FMS2.	Make regulatory intiative targeting PM motors and generators which regulates collection of NdFeB magnets.	Provide tax incentives for extracting magnets from PM motors and generators.	Develop economical and efficient dismantling process of EV motors and generators.	Encourage development of new waste stream for PM motor.	
FM2. Scale up recycling of NdFeB magnets.	Invest in different recycling technologies.	Attract private investments for recycling through HPMS process by creating tax shields.	Recommend Member States like Germany, France to invest in recycling through HPMS process.	Regulating share of recycled magnet to be sourced.		
FM3. Compete with Chinese Magnet prices.	Develop economical and efficient dismantling process of EV motors and generators.	Provide tax incentives for extracting magnets from PM motors and generators.	Create tax shields for businesses investing in recycling value chain of NdFeB magnets.	Increase production capacity of REEs and REMs in the EU.	Provide subsidies to OEMs for choosing to source EU produced recycled magnets.	
FM4. Create incentive for Electric Motor and generator recyclers for extracting NdFeB magnets from assemblies.	Provide tax incentives for extracting magnets from PM motors and generators.	Provide Carbon credits on amount of magnets extracted.				
FL1. Establish a collection target for PM motor, generators.	Assigning collection rate for PM motors and generators based on calculation.	Assigning collection rate for PM motors and generators based on comparision.	Randomly assigning collection target for PM motors and generators.			
FL2. Expand the scope of Extended Producer Responsibility for automobile and wind turbine OEMs	1. Update the ELV Directive with PM motor take-back requirement. 2. Make EoL wind turbine directive with PM generator take-back requirement.			Make regulatory intiative targeting PM motors and generators from all industries and introduce EPR covering NdFeB magnets.	Cover both PM motors and generators from EV and wind turbine in WEEE directive with special focus on recovering NdFeB	
FL3. Prevent export of PM motors and generators.	Ban the export of PM motors and generators to countries outside the EU.	Allow export of PM motors and generators only when receiving country has necessary recycling technology.	Introduce export quotas for PM motors and generators going outside the EU.	Impose export tax for PM motors and generators going outside EU.		
FS1. Ensure that PM generators are tracked.	Advice wind farm owners to track the movement of PM generators and the magnets within them.	Invest in tracking database for PM generators and magnets.	Create PM generator passport			
FS2. Raise awareness amongst Electric motor and generator recyclers about collection of NdFeB magnets.	Run awareness campaign for motor/generator recyclers.	Spread awareness through organising seminars.	Spread awareness through approaching associations that represent recyclers.			
FS3. Ensure removal of PM motors from EVs.	Strongly advice car dismantling companies about removing PM motors from EVs.	Update the ELV Directive with PM motor take-back requirement or refund scheme.	Give incentive for removing the PM motor from EVs and directing it to right recycling route.			
FR1. Develop design for recycling guidelines for Electric Motors and Generators.	1. Commence research and introduce design for dismantling and recycling directive for PM motors and used in EVs. 2. Involving wind turbine OEMs into developing guide for dismantling of PM generators to extract NdFeB magnets.					
FR2. Mandatory flow of information about magnets in Supply Chain.	Enforce labelling system for motors and generators containing magnets.	Blockchain to share information.	OEMs share data with Member States about the number of PM motors, PM generators installed each year and quantity of magnets in them.	OEMs share data about magnets in ProSUM and motor/generator recyclers access it through the ProSUM database.	Recommend automobile OEMs to share data on type of magnets through International Dismantling Information System (IDIS).	
FR3. Develop guidelines on safe handling and storage of NdFeB magnets.	Conduct surveys with motor/generator recyclers to identify safety hazards.	Involve OEMs to share their safety protocols while dealing with NdFeB magnets.				

Figure 7.1: Morphological Chart

7.2 Proposed Collection Strategies

The proposed collection strategies are categorised into three phases- short-term plan, medium-term plan, and long term plan. The short-term plan can be implemented within 3-6 years, the medium-term plan can be implemented in the next 6-9 years, and the long-term plan can be implemented in 9-12 years. The duration of the three plans was decided based on the results of the quantification model for EVs and wind turbines in presented in section C.1.3 and C.1.4. Furthermore, the solutions are further categorised into five labels or themes:

1. Legalisation and Regulation
2. Information exchange
3. Finance
4. Infrastructure development
5. Material flow

The labels were identified after generating possible means in section 7.1. It was found that the solutions could be categorised into one or more of the five labels stated above. If the solutions can be put into more than one label, they are elaborated in any one of the labels in which the solution falls. Lastly, at the end of each solution, the requirements that are fulfilled are mentioned.
The figure 7.2 below gives an overview of all the chosen means in the short term (highlighted in green), medium term (highlighted in yellow) and long term (highlighted in red) plan.

Functions	Means 1	Means 2	Means 3	Means 4	Means 5	Means 6
FM1. Scale up the collection process of NdFeB magnets.	All means of FS2.	Make regulatory intiative targeting PM motors and generators which regulates collection of NdFeB magnets.	Provide tax incentives for extracting magnets from PM motors and generators.	Develop economical and efficient dismantling process of EV motors and generators.	Encourage development of new waste stream for PM motor.	
FM2. Scale up recycling of NdFeB magnets.	Invest in different recycling technologies.	Attract private investments for recycling through HPMS process by creating tax shields.	Recommend Member States like Germany, France to invest in recycling through HPMS process.	Regulating share of recycled magnet to be sourced		
FM3. Compete with Chinese Magnet prices.	Develop economical and efficient dismantling process of EV motors and generators.	Provide tax incentives for extracting magnets from PM motors and generators.	Create tax shields for businesses investing in recycling value chain of NdFeB magnets.	Increase production capacity of REEs and REMs in the EU.	Provide subsidies to OEMs for choosing to source EU produced recycled magnets.	
FM4. Create incentive for Electric Motor and generator recyclers for extracting NdFeB magnets from assemblies.	Provide tax incentives for extracting magnets from PM motors and generators.	Provide Carbon credits on amount of magnets extracted.				
FL1. Establish a collection target for PM motor, generators.	Assigning collection rate for PM motors and generators based on calculation.	Assigning collection rate for PM motors and generators based on comparision.	Randomly assigning collection target for PM motors and generators.			
FL2. Expand the scope of Extended Producer Responsibility for automobile and wind turbine OEMs	1. Update the ELV Directive with PM motor take-back requirement. 2. Make EoL wind turbine directive with PM generator take-back requirement.			Make regulatory intiative targeting PM motors and generators from all industries and introduce EPR covering NdFeB magnets.	Cover both PM motors and generators from EV and wind turbine in WEEE directive with special focus on recovering NdFeB	
FL3. Prevent export of PM motors and generators.	Impose export tax for PM motors and generators going outside EU.	Allow export of PM motors and generators only when receiving country has necessary recycling technology.	Introduce export quotas for PM motors and generators going outside the EU.	Ban the export of PM motors and generators to countries outside the EU.		
FS1. Ensure that PM generators are tracked.	Advice wind farm owners to track the movement of PM generators and the magnets within them.	Invest in tracking database for PM generators and magnets.	Create PM generator passport.			
FS2. Raise awareness amongst Electric motor and generator recyclers about collection of NdFeB magnets.	Run awareness campaign for motor/generator recyclers.	Spread awareness through organising seminars.	Spread awareness through approaching associations that represent recyclers.			
FS3. Ensure removal of PM motors from EVs.	Strongly advice car dismantling companies about removing PM motors from EVs.	Update the ELV Directive with PM motor take-back requirement or refund scheme.	Give incentive for removing the PM motor from EVs and directing it to right recycling route.			
FR1. Develop design for recycling guidelines for Electric Motors and Generators.	1. Commence research and introduce design for dismantling and recycling directive for PM motors and used in EVs. 2. Involving wind turbine OEMs into developing guide for dismantling of PM generators to extract NdFeB magnets.					
FR2. Mandatory flow of information about magnets in Supply Chain.	Enforce labelling system for motors and generators containing magnets.	Blockchain to share information.	OEMs share data with Member States about the number of PM motors, PM generators installed each year and quantity of magnets in them.	OEMs share data about magnets in ProSUM and motor/generator recyclers access it through the ProSUM database.	Recommend automobile OEMs to share data on type of magnets through International Dismantling Information System (IDIS).	
FR3. Develop guidelines on safe handling and storage of NdFeB magnets.	Conduct surveys with motor/generator recyclers to identify safety hazards.	Involve OEMs to share their safety protocols while dealing with NdFeB magnets.				

Figure 7.2: Morphological chart highlighting all the solutions for short (7.3), medium (7.4) and long term plan (7.5).

7.3 Short Term Plan

The short term plan elaborates on the strategies that can be implemented in the next 3-6 years to layout the necessary fundamentals for collection and start the process of collection. The morphological chart for short term plan with all the chosen means is highlighted in green in figure 7.2.

7.3.1 Legislation and Regulation

The label 'Legislation and Regulation' consists of solutions that need that need legislative and/or regulatory actions by the EC.

FL1. Establishing collection target for PM motors and generators.

In the short term, more attention should be towards setting a collection target for both PM motors and generators, respectively. Three solutions are presented in the Morphological chart, however the most appropriate solution to set the collection target for PM motors and generators is the following.

Assigning collection target for PM motors and generators based on calculation

To set collection target for PM motors and generators based on calculation, the following three parameters need to be determined for both PM motors and generators.

For PM motors:

1. Amount of PM motors being installed in the EVs each year in the EU.
2. Amount of PM motors reaching EoL in a particular year.
   This can be calculated based on estimated lifetime of PM motors. Given the amount of PM motors installed in an year, adding the lifetime of the PM motors to that year can give a rough estimate on the amount of PM motors that would be reaching EoL in a particular year in the future.
3. Amount of PM motors exported.
   The amount of PM motors exported need to be taken into consideration for estimating the amount of PM motors that would be available for collection.

Similarly for PM generators,

1. Amount of PM generators being installed in the wind turbines each year in the EU.
2. Amount of PM generators reaching EoL in a particular year.
   This can be calculated based on estimated lifetime of PM generators. Given the amount of PM generators installed in an year, adding the lifetime of the PM generators to that year can give a rough estimate on the amount of PM generators that would be reaching EoL in a particular year in the future.
3. Amount of PM generators exported.
   The amount of PM generators exported need to be taken into consideration for estimating the amount of PM generators that would be available for collection.

Then, based on the data, a suitable collection target (in %) can be assigned for the PM motors and generators, respectively. Furthermore, the collection target for both these motors and generators then should be increased periodically. For instance, for PM motors, collection targets can be set to 70%, for medium term the collection targets can be set to 90% and in the long term the collection target can be set to 100%. Similarly, for PM generator, in the short term, the collection target can be set to 85%, for medium term 95% and for long term 100%. It can be argued that the collection target for PM generators can be higher than that of PM motors since the wind turbines are industrial products and the chances of the PM generator being lost in waste stream are very low.

Requirements fulfilled: *7- A target for collecting the PMSMs, PMSGs and the neodymium magnets present in them* is only partially fulfilled as the solutions provided do not define collection target for neodymium magnets but only the PM motors and generators containing them. Currently, it cannot be defined how much should be the collection target (in %) for the magnets present in the motors and generators as it depends on factors like losses during transport, and extraction. However, it can be said that all the neodymium magnets removed from motor and generator assemblies should enter recycling process.

FL2. Expand the scope of Extended Producer Responsibility for automobile and wind turbine OEMs

In the short term, the automobile OEMs must be addressed first rather than the wind turbine OEMs. This is because the lifetime of EVs is shorter than wind turbines, and a larger quantity of magnets will be available for collection from EVs in the short term. Thus, automobile OEMs can be responsible for organising the collection and recycling of the PM motors and the neodymium magnets within them. Furthermore, doing so may relieve some pressure (financial and organisational) from the motor/generator recyclers, magnet recyclers, and the EU. Moreover, the OEMs would also be more circular and benefit from the collection and recycling system. To do so, the following solution presented below can be implemented.

Update the ELV Directive with PM motor take-back requirement

The EC can update the ELV directive so that the automobile OEMs are made responsible for the collection and recycling of the PM motors in the EV. The OEMs can be directed to setup a take back scheme, where they are responsible for organising the take back of the PM motors and its recycling. In the Member States, the OEMs may choose to collaborate to setup a collective collection system with the help of PROs, who can manage the financing of the various actors in the value chain, for instance, car dismantling companies, the motor/generator recyclers, magnet recyclers, logistics provider, etc. The OEMs may also delegate the cost of recycling the magnets within the PM motors to the end user. This can be done by setting a one-off fee for recycling of the magnets that are present in the users EV.
There may be many different approaches that can be applied within the EPR scheme, which should be left to the Member States and the OEMs to figure out. In any case, it is important to include the automobile OEMs in the problem of collection and recycling of the magnets so that it can be tackled effectively. Furthermore, it is also important to note that this solution can also help with ensuring that the car dismantling companies will remove the PM motors from the EVs.

Requirements fulfilled: *8- The automobile and wind turbine OEMs should be responsible for organising collection and recycling of PM motors and generators present in EVs and wind turbines, respectively* is partially fulfilled right now as this solution targets only EVs. In addition, this solution also fulfills requirements *11- Car dismantling companies must remove motors from EVs before the rest of the EV is shredded*, *6- Aligning EU's interests with existing regulations and legislation* and *13- OEMs want more direction from legislation in place.*

FL3. Prevent export of PM motors and generators

At present, the scrap motors from EV are being sold to traders in third countries by motor/generator recycling companies in the EU because it is expensive to take apart the electric motors due to high labour charges and thus it is more profitable to sell them to countries in the East. In case of generators, they are largely processed in the EU because of high amount of scrap material that can be recovered with relative ease compared to motors. However, in any case, both the export of PM motors and generators to third countries not only increases the burden on their inefficient and informal recycling systems but also implies that the neodymium magnets will be lost. In order to prevent the export of PM motors and generators, the possible solutions that could be implemented is:

Ban the export of PM motors and generators to countries outside the EU
The ban of PM motors and generators to countries outside the EU would be highly beneficial in keeping the neodymium magnets and the critical REEs in them within the EU. This will allow for the possibility of collection of Neodymium magnets present in the motors and generators and then be directed to the right recycling route. This solution can be implemented by updating the existing waste shipment regulation (Regulation (EC) No 1013/2006, 2006).
The other means presented in the Morphological chart can be good alternatives to discourage the motor/generator recycling companies exporting the PM motors and generators but they are not selected as they do not fully meet the constraint of keeping the EoL PM motors and generators in the EU. Furthermore, the other solutions are reliant on the Member States who may choose to not impose any taxes or bans on the export, thus, regulation at an EU level is more effective.

Requirements fulfilled: Both the solutions fulfil requirement *9- Export of EOL PM generators and motors from wind turbine and EVs should be restricted.* and also *10- Aligning EU's interests with existing regulations and legislation.*

7.3.2 Information Exchange

This label represents solutions that are related to passing relevant information in the supply chain for magnet collection and recycling or are related to informing the necessary stakeholders about the type of action they should take.

FM1. Scale up the collection process of NdFeB magnets and FS2. Raise awareness amongst Electric motor and generator recyclers about collection of NdFeB magnets

The solutions presented below are part of two functions- FM1 and FS2. The scale up of collection of magnets from PM motors and generators requires support from various motor/generator recyclers in each of the EU countries. As mentioned in earlier sections, a lot of motor/generator recyclers are unaware or ignorant about the magnets in the EoL motors and generators that they buy and thus the magnets are lost to either third countries or to other waste streams. In order to prevent this, awareness needs to be created amongst the motor/generator recycler about the economic and ecological advantage of extracting magnets from EoL PM motors and generators. One of the solutions related to scaling up of collection process is elaborated in the Finance section (7.3.3). The three possible solutions presented below through can be implemented to raise awareness.

1. **Run awareness campaign for motor/generator recyclers**
   In each of the EU countries, an awareness campaign can be run in order to inform the various motor/generator recyclers about the economic and environmental benefits of collecting neodymium magnets from PM motors and generators. The awareness campaign can be

started in countries which have high wind capacity and high number of electric vehicles, for instance, Germany, France, Spain, the Netherlands. To do so, recycling companies will need to be identified which recycle electric motors and generators and be approached for spreading awareness about the collection of neodymium magnets present in PM motors and generators coming from EVs and wind turbines.

2. **Spread awareness through organising seminars** Alternatively, the motor/generator recyclers can be invited in seminars which address the issue of collection and recycling of neodymium magnets. Prior to the seminar, a survey can be conducted to know the general awareness of these recycling companies about the issue of REMs. As mentioned in the earlier solution, these seminars can be organised first in countries which have high number of EVs and wind turbines.

3. **Spread awareness through approaching associations that represent recyclers.** Associations like European Recycling Industries' Confederation (EuRIC) can be approached. EuRIC is an umbrella organisation for the "European Recycling Industries" and acts as a reliable medium between the recycling industry and the EU for passing information, sharing best practices, and cooperation ("EuRIC - Who we are", n.d.). Thus, EuRIC can be involved in order to spread awareness about the economic potential of collection the magnets and they are valuable to EU for becoming a carbon neutral economy.

All three of the solutions can be used in combination to spread awareness by the ERMA. Furthermore, the ERMA can also ask for support by research institutes that are already involved in magnet recycling projects on an EU level like Delft University of Technology, Netherlands, Leiden University, Netherlands Pforzheim University, Germany, Jožef Stefan Institute, Slovenia, KU Leuven, Belgium etc.

Requirements fulfilled: All three solutions together fulfil the requirement *14- More awareness should be created amongst electric motor and generator recyclers about collection of magnets.*

FM2. Scale up the recycling of NdFeB magnets

The process of collection and recycling are closely connected to each other, if the scrap magnets are collected but are not demanded by the magnet recyclers then there is a high possibility that the value of the scrap magnets will start decreasing. Having a higher recycling capacity may increase the demand for the scrap magnets due to pull effect. Thus to scale up the recycling, three solutions are proposed which can be implemented in the short run. One solution is presented below while the other two solutions are elaborated in the 'Finance' theme (7.3.3).

Recommend Member States like Germany, France to invest in recycling through HPMS process

It can be argued that Member States like Germany and France will generate more waste magnets from EoL PM motors and generators coming from EVs and wind turbines, respectively, due to the higher wind capacity and more number of EVs. Thus it becomes essential that these countries have a well developed recycling system in place of neodymium magnets. In the short term, the EC can strongly recommend Germany and France to invest in the scale up of the HPMS recycling. As discussed in section 4.2, HPMS is a suitable technique to recycle magnets from EVs and wind turbines. Furthermore, HPMS recycling is a short loop recycling process

which requires the least amount of energy and has the least environmental impact compared to pyrometallurgical and hydrometallurgical recycling routes.
Higher investments by bigger countries would also ensure that smaller EU countries and countries which do not have large amount of wind turbines and EVs are not burdened in the future if regulations for recycling neodymium magnets are introduced. Initially, in order to support the scale up the EU and the Member States can support the industry by either subsidising the operation or by giving tax incentives (elaborated under the Finance label in 7.3.3) to those who are willing to set up industrial scale HPMS plants.

Requirements fulfilled: This solution fulfils requirement *16- The scale of Hydrogen Processing of Magnetic Scrap (HPMS) recycling process should be increased* and it can also be said that it will contribute in fulfilling requirement *3- Collection and recycling setup should aim to process more than 104 tons of NdFeB magnets coming from EOL EVs by 2025 in the EU.*

FR2. Mandatory flow of information about magnets in Supply Chain

To ensure efficient and high quality magnet recycling, necessary information needs to passed along the value chain. In order to do that, two solutions are proposed for the short term.

1. **Enforce labelling system for motors and generators containing magnets**
The EC can enforce a labelling system to be used for PM motors and generators. The label must provide the production type (sintered or bonded), chemical composition of the magnets, the grade, and the type of coating present on the magnets of both motors and generators.
Burkhardt et al. (2020) describes a labelling technique called the DMC (Digital Matrix Codes) where information can be saved in form of alphanumeric codes which can formed into a scannable barcode and be printed on the magnets in a small size of 3.4mm x 3.4mm. The code can either be "laser-engraved or ink-jetted" on the coating of the neodymium magnets (Burkhardt et al., 2020). This labelling system is being currently developed by MaXcycle project (figure 7.3) which is funded by ERA-MIN 2 [1].

Type of Magnet select from drop down list	Type of Coating select from drop down list	Heavy RE-Content [%] enter value in mass%	Magnet Grade select from drop down list	Certified Producer Code select from drop down list
NdFeB_sintered	Zn	0,30	N27 EH	Magneti

MAXYCLE MAGNET CODE: A 2 003 N27 EH P123M

Figure 7.3: MaXcycle code (left) and bar-code (right) (source:Burkhardt et al. (2020))

It can be argued that labelling the magnets may not be the best approach as when the magnets are extracted from the PM motors and generators, the magnets can be damaged which in turn may damage the magnets. Furthermore, it may not be feasible to label each magnet, instead the labelling could be laser-engraved on the motor and generator itself.

2. **Recommend automobile OEMs to share data on type of magnets through International Dismantling Information System (IDIS)** The labelling of the motors and generators is crucial step in recycling the magnets through the HPMS process. However, enforcing it may be a time consuming. Thus an alternative solution that can be implemented in the mean time is the use of IDIS. IDIS has been used by the automobile

[1] "ERA-NET cofund on Raw Materials (ERA-MIN) is a global, innovative and flexible pan-European network of research funding organisations, supported by EU Horizon 2020, ERA-MIN aims to support the European Innovation Partnership on Raw Materials (EIP RM), the EU Raw Materials Initiative and further develop the raw materials (RM) sector in Europe through funding of transnational research and innovation (R&I) activities. " ("ERA.MIN —", n.d.)

OEMs across the world to share data about the pre-treatment, dismantling, handling and recycling of the vehicles with the car dismantling companies ("IDIS — Discover IDIS" (n.d.)). The same information sharing platform can be used to provide the details on the type of magnets that are used in the PM motors of EVs. However, this solution can be argued to only work for a small duration as when the volume of PM motors start to increase, it will be a slow process to check the make and model of each and every motor via a database. Moreover, this solution can only be applicable to PM motors and not wind turbine generators.

Some of the other means presented in the morphological chart (7.1) for this function are not selected as they are less practical than the chosen ones. The use of ProSUM may not be viable solution as the approach of ProSUM is top-down rather than bottom-up. Furthermore, the use of block chain can be good solution however it requires a lot of investment. Moreover, IDIS is already an existing solution which can be used to pass information along the recycling value chain.

Requirements fulfilled: These solutions fulfill the requirement *17- Flow of information about the neodymium magnets used in EVs and Wind Turbines*

7.3.3 Finance and Infrastructure development

The solutions that are related to labels Finance and Infrastructure development of collection and recycling of neodymium magnets are presented below.

FM1. Scale up the collection process of NdFeB magnets, FM2. Scale up recycling of NdFeB magnets, FM3. Compete with Chinese Magnet prices, and FM4. Create incentive for Electric Motor and generator recyclers for extracting NdFeB magnets from assemblies.

1. **Attract private investments for recycling through HPMS process by creating tax shields**
   At the moment there is a total planned processing capacity of 116 tons that will be available at the mature stage of the four projects as mentioned in section 4.2.1. However, much more processing capacity is required in order to process the scrap magnet that will be available from 2025 onwards. In order to scale up the recycling of HPMS process, the EU should attract more private investments so that all the burden does not lie on the Member States or the EU. Furthermore, the Member States and the EU can be joint partners in setting up the recycling plants with private investors, by this way, the burden may be equally divided between the Member State and the private investors. This may also be important as the initial investment cost of setting up recycling plants is high.
   The Member States can create tax shields for businesses that invest in recycling of neodymium magnets through HPMS process. Implementing this can be a good way to attract more businesses to take part in recycling of neodymium magnets and motivate the existing players to increase their processing capacities. One of the actions suggested by Gauss et al. (2021) is to "allow for companies not to pay revenue tax before recovering their investment." This may be good solution that can be implemented in the short term and can be continued till sufficient capacity is developed.

2. **Provide tax incentives for extracting magnets from PM motors and generators**
   To make the recycled magnets attractive for the OEMs in the EU, the price of the recycled magnets needs to be equal to less than the price of the magnets imported from China. The recycled magnets can be made cheaper by decreasing the cost of operations in the

entire recycling process, i.e. the cost of dismantling, logistics, and the cost of processing the scrap magnets. In the context of collection, if the motor/generator recyclers are given some incentive to collect the magnets from the motors and generators, the volume of scrap magnets collected may increase. In the short term, it may be essential to provide tax incentives to have a high collection rate. Furthermore, providing a tax incentive is also a means of reaching more and more recyclers who process electric motors and generators. Moreover, when there is an economic incentive, the recyclers may develop appropriate technological processes (Hagelüken, 2007). Consecutively, when the volume of incoming scrap magnets increases, then the price of processing per unit of scrap magnets will decrease due to economies of scale.
Additionally, this solution may reduce the impact of banning the export of PM motors to third countries by making it more attractive for motor/generator recyclers in the EU. Some of the ways of providing the tax incentive are as follows:

(a) **Tax incentive based on profit earned on the sale of collected magnets**
The Member States can provide tax incentives to motor/generator recyclers on the profit they earn because of selling scrap magnets to the magnet recyclers located in the EU. In order to provide such an incentive, the amount of magnets sold to the magnet recyclers will need to be monitored. To avoid any fraudulent behaviour, the records from both magnet recycler and motor/generator recycler will need to be checked in order to provide the tax incentive. Furthermore, the percentage of tax exemption would need to be determined by the individual Member States.

(b) **Tax incentive on the amount of money spent on recycling equipment**
Another way of supporting the motor/generator recyclers is through providing tax incentive with respect to the amount of money spent on any equipment or processes that are bought or developed specifically to dismantle and extract the magnets from the motor and generator assemblies. However, this incentive scheme will only be applicable when such technical equipment will be built and be available on the market or when the motor/generator recyclers are willing enough to make their equipment or processes in order to extract the magnets. Furthermore, specific criteria to avail the incentive and a limit on the tax incentive (for instance 15% of the cost of installed equipment) will need to be made.

3. **Provide subsidies to OEMs for choosing to source EU produced recycled magnets**
Subsidies can be given to automobile OEMs and wind turbine OEMs to use recycled neodymium magnets in their PM motors and generators respectively. When the prices of the recycled magnets are comparable to that of magnets produced in China, the OEMs may fulfil a part of their demand from locally produced recycled neodymium magnets. However, the price of neodymium magnets keep fluctuating (Expert 1, 3.2) which may threaten the secondary neodymium market. When the prices of Chinese magnets are less than that of recycled magnets, the OEMs may choose to source the magnets from Chinese manufacturers in which case the demand for locally produced recycled magnets may fall which in turn may lead to lower revenues for the actors in the supply chain and this may hamper the process of collection of the magnets. In order to avoid such events, the Member States and the EU can decide to give subsidies to the OEMs for sourcing locally produced recycled magnets when the prices of Chinese magnets become a threat to the secondary market (Gauss et al., 2021). It is also important to note that this solution may be implemented as and when required, and is not specific to short term plan.

Requirements fulfilled: The solutions provided above fulfil requirement *6- The scale of Hydrogen Processing of Magnetic Scrap (HPMS) recycling process should be increased*, and it can be argued that requirements *3- Collection and recycling setup should aim to process more than 104 tons of NdFeB magnets coming from EOL EVs by 2025 in the EU* and *2- The price of recycled neodymium magnets should be competitive with the price of magnets imported by China* are also fulfilled by these solutions. Furthermore, requirement *1- The process of collection and recycling should be attractive for the recycling companies* is also fulfilled by these solutions.

7.3.4 Material Flow

The solutions presented under this label are directly or indirectly linked to material flow but can also be placed under the label 'Information exchange'.

FR1. Develop design for recycling guidelines for Electric Motors and Generators.

The 'design for recycling' motors and generators will not be useful for collecting the magnets from PM motors and generators already in EVs and wind turbines. However, it is crucial to develop guidelines for 'design for recycling' so that the PM motors and generators are designed in such a way that they can be easily dismantled, and the magnets can be easily extracted without any damage; this will also increase the possibility of directly re-using the magnets or using the magnets with re-manufacturing. In the short term, more attention is required to be focused on PM motors instead of generators since the generators are made to be dismantled easily as per a major wind turbine OEM. Thus the guideline for design for recycling guidelines for PM motor can be developed in the following way:

Commence research and introduce design for dismantling and recycling directive for PM motors and used in EVs
It is paramount to involve automobile OEMs to be a part of the solution as it is because of their product design it is difficult to remove the neodymium magnets from the motor assembly easily. In particular, the dismantling of the rotor is rather cumbersome and it is difficult to remove the magnets from the rotor of both IPMSMs (Internal Permanent Magnet Synchronous Motor) and SPMSMs (Surface mounted Permanent Magnet Synchronous Motor) which were described in section 4.1. The automobile manufacturers are aware of the issue, however, it is not known whether the automobile manufacturers are working on the problem or not, as some of the manufacturers that were approached for an interview to gather this information did not respond. In the short term it is very important that the automobile manufacturers design the motors in such a way that the neodymium magnets can be economically extracted. This will not only make their products more sustainable, and their company more circular but also they could benefit as the recovered magnets could be directly re-used or be recycled and then be available for purchase.
In order to implement this solution, first the ERMA can approach the OEMs to start working with some of the research universities that are members of ERMA cluster Rare Earth Magnets and Motors (Gauss et al., 2021). Also, researchers from DEMETER (C.2.1) project who developed PM motor that are completely recyclable can also be included to work with the OEMs. The next phase should be the introduction of a directive by the EC that gives guidelines on design for dismantling and recycling of the EV motors.

Requirements fulfilled: As this solution relates to only automobile OEMs, requirement *15- The design of motors and generators should be such that magnets can be easily extracted without being damaged* is partially fulfilled.

FR3. Develop guidelines on safe handling and storage of NdFeB magnets

As the volume of neodymium magnets increases, it is important to issue a guideline for motor/generator recyclers who may be extracting the magnets from the motors and generators. The guideline can include measures to safely handle the NdFeB magnets and the proper way to store them before they are shipped to recyclers as it can be dangerous to work with these magnets as explained in section 4.4. Thus the following solutions can be adopted in order to develop this guideline:

1. **Conduct surveys with motor/generator recyclers to identify safety hazards**
   Since the motor/generator recyclers have already started to get PM motors and generators, they might be aware of the Do's and Dont's of working with magnets. Thus a survey can be conducted with motor/generator recyclers to gather information on their current practices and safety and storage instructions (if any) that they have developed.

2. **Involve OEMs to share their safety protocols while dealing with NdFeB magnets**
   The wind turbine and automobile OEMs also work with these magnets as the PM motors and generators that they manufacture or their suppliers manufacture for them would be required to handle these magnets on a daily basis. Thus it may be an easier solution to approach these OEMs to share their best practices on dealing with the neodymium magnets in order to avoid any injuries.

Based on the analysis presented in section 4.4, a list of measures that can be taken by the motor/generator recyclers is presented below. It is important to note that this list is by no means exhaustive and only shows some of the measures based on preliminary research.

1. People with pacemakers and metal implants which are ferromagnetic in nature should not be in the vicinity of the magnetic field of the neodymium magnets.

2. If the magnets are not demagnetised before removal then special tools should be used to dismantle the PM motors and generators to avoid any sudden and uncontrolled movement of tools towards the rotor of the motor and generator which contain the neodymium magnets.

3. Devices like wrist watch, televisions, computers should be placed at a safe distance from the PM motors and generators.

4. Protective eye ware and gloves should be worn to avoid any injuries if magnets clash into each other.

5. Special care should be taken if the magnets are not demagnetised before being stored.

6. The storage of non-demagnetised magnets should be done properly in order to avoid any uncontrolled flying of objects (tools, other smaller components containing iron) in the vicinity of the storage space.

7. If magnets are removed without being demagnetised then demagnetisation should be considered before storage.

Requirements fulfilled: This solution fulfils requirement *18- Safe handling of NdFeB magnets by motor/generator recyclers.*

7.4 Medium Term Plan

The medium term plan elaborates on the strategies that can and should be implemented within the next 6-9 years to process the volume of magnets that will be available for collection and recycling, and to prepare for the volume of magnets coming from EoL EV motors and wind turbine generators in the long term. The morphological chart for medium term plan with all the chosen means are marked in highlighted in yellow in figure 7.2.

7.4.1 Legalisation and Regulation

FL2. Expand the scope of Extended Producer Responsibility for automobile and wind turbine OEMs

In the medium term, it is important to start focusing on the volume of magnets that may be available for collection and recycling from the wind turbines. In order to do that effectively, the EPR should be introduced for wind turbine OEMs. Furthermore, the effort should be towards regulating the collection of the neodymium magnets. Thus to do so, two solutions that can be implemented are as follows:

1. **Make EoL wind turbine directive with PM generator take-back requirement**
   In order to make the wind turbine OEMs responsible for the PM generators and the magnets within them, the first step that the EC can take is to introduce a directive which covers the decommissioning of the wind turbines as currently there is no directive which offers a framework for the decommissioning of the wind turbines. As part of the directive, the wind turbine OEMs can be made responsible for the components like the PM generator which contains neodymium magnets. Making them responsible for the collection and recycling of the PM generators and the magnets within them may reduce the burden (financial and organisational) from actors in the neodymium magnet recycling value chain. The OEMs may choose to use a refund scheme, where the OEMs charge an additional amount to the wind farm owners when they purchase the turbine. The amount can be returned when the wind farm owners provide the wind turbine OEMs the necessary reports which can show that the PM generators and the magnets have been recycled properly or when the wind farm owners decide to give the PM generators back to the OEMs. This scheme may also enforce the OEMs to track the PM generators if the choose to resell the wind turbine or the generator for reuse. An alternative to refund scheme is the take back requirement, where the OEMs are responsible for organising for the collection and recycling of the magnets in the PM generator.
   Again, it should be left up to the Member States and the wind turbine OEMs to decide what approach they take to implement the EPR.

2. **Make regulatory initiative targeting PM motors and generators from all industries and introduce EPR covering NdFeB magnets**
   A decision to make regulation can be made in order to cover not only motors and generators from wind and automobile industry but from all the industries. Introducing a new regulation would imply that it would apply to all the Member States without being modified. In addition, if the EU really wants to be a circular economy and preserve the critical materials then it is imperative to introduce regulation. As part of the regulation, the EPR can be implemented. Which would potentially involve OEMs other than wind turbine and automobile OEMs in the EU to organise for the collection and recycling of the magnets within the PM motors and generators. This solution may also be helpful in making multiple industries more circular and sustainable.

Making the OEMs more responsible may enable collaboration between the OEMs and motor/generator recyclers in each of the EU countries. This may also lead the OEMs to develop

techniques in collaboration with motor/generator recyclers to disassemble the motors and generators efficiently and extract the magnets. In addition, the OEMs may also collaborate with research institutes to develop automated solutions for dismantling and extracting the magnets from PM motors and generators.
Automated solutions may be expensive to develop and buy initially; however, the number of motors and generators reaching EoL will increase significantly in the next ten years, which will lead to economies of scale (Expert 1, A.2.1; Expert 2, A.2.2). Moreover, making producers more responsible for their products would also force them to make their products and their components in such a way that they can be easily re-used and recycled at their EoL, thus increasing the chances of magnets getting extracted easily and, in turn, more economically which will make them available for direct re-use.

Requirements fulfilled: The solutions presented fulfil requirement *13- OEMs want more direction from legislation in place*. Furthermore, *8- The automobile and wind turbine OEMs should be responsible for organising and for collection and recycling of PM motors and generators present in EVs and wind turbines, respectively* which was only partially fulfilled earlier, is now fulfilled.

FM1. Scale up the collection process of NdFeB magnets

Make regulatory initiative targeting PM motors and generators which regulates collection of NdFeB magnets
To just have a collection target for PM motors and generators is not enough. It is also equally important to ensure that the neodymium magnets in them are extracted by the motor/generator recyclers or by someone else in the recycling value chain. Thus, it is important to regulate the collection of neodymium magnets after the PM motors and generators have been collected.

Requirements fulfilled: *4- The scale of collection and recycling should significantly increase by 2030 to process NdFeB magnets available from EoL EVs* can be said to be fulfilled by this solution.

7.4.2 Infrastructure development

FM1. Scale up the collection process of NdFeB magnets

Two solutions that can be implemented in the medium term to fulfil this function are as follows:

1. **Develop economical and efficient dismantling process of EV motors and generators**
   To scale up the collection process of magnets in PM motors and generators, an economical and efficient process of extraction of magnets from motors and generators needs to be developed. An EU funded project can be started to explore how dismantling and extraction of magnets can be automated to handle the upcoming volume of PM motors and generators. As mentioned earlier, the dismantling of EV motors is expensive due to the high labour charges in the EU, which compels them to sell the motors to third countries. Looking at the volume of neodymium magnets that would be available for collection and recycling just from Western Europe from EVs and Wind turbines (see figures 3.8a, 3.10a, 3.9a), it can be seen that the volume of magnets increases exponentially from 2027 for EVs, from 2031 for onshore wind turbines, and 2034 for offshore wind turbines. In the medium term, the more urgent need is to address the dismantling of the PM motor to get the magnets. Thus, if an automated solution is developed to dismantle the PM motors, then the motor/generator recyclers may be interested in buying such a solution due to the ease of removing the magnets, increased productivity and lower operating costs in the

long run due to economies of scale. For PM generators, removing the magnets is already comparatively easy. Thus, only a standard procedure may be needed to be developed. Implementing this solution can also make the price of the recycled magnets comparable to that of the Chinese-produced magnets.

2. **Encourage development of new waste stream for PM motor**
   Another solution that can be implemented with the first one is to create a separate waste stream for the rotors of the PM motor. As explained in section 3.3.2, the magnets are located in or around the rotor of the PM motors. It may happen that the motor/generator recyclers are not able to effectively handle the removal of magnets from the PM motor, as their main motive is to remove the copper wiring and iron from the PM motor. To avoid a case where the motor/generator recyclers are overburdened, which can eventually reduce the amount of magnets that are being extracted from the PM motors. The EU can encourage the development of an intermediate actor who would be responsible for collecting the rotor of the PM motor and removing the neodymium magnets from them. To encourage such businesses, the Member States can provide tax incentives to these businesses as proposed in the short term plan. Encouraging the growth of such businesses will be crucial to preparing for the high volume of magnets coming from EV motors. Furthermore, these businesses may even start sourcing EoL PM generators to extract the magnets. In the long run, this may help ease the pressure on motor/generator recyclers.

Requirements fulfilled: These solutions can be said to have fulfilled requirement *4- The scale of collection and recycling should significantly increase by 2030 to process NdFeB magnets available from EoL EVs.*

7.4.3 Material Flow

FR1. Develop design for recycling guidelines for Electric Motors and Generators

As mentioned in the short term plan, the design for recycling guidelines are essential to ensure that the magnets can be easily extracted without damaging them so that they can be reused or re-manufactured to be used again in wind turbines or in other applications. In context of PM generators, the PM generators are designed to be dismantled easily as per a major wind turbine OEM. However, it cannot be said with certainty that this is an industry wide practice. Thus it becomes important to develop the guidelines for 'Design for recycling' for wind turbine generators. This guideline may be developed in the following way.

Involving wind turbine OEMs into developing guide for dismantling of PM generators to extract NdFeB magnets.
The guideline can be developed by involving the wind turbine OEMs in the EU. They may be approached by the ERMA separately or can be reached out through an association like WindEurope[2]. If wind turbine OEMs come together then they may be able to discuss the guideline that should be industry standard in Europe for all wind turbine OEMs.
To ensure progress, the ERMA can form committee that would check on the progress of the development of such a guideline.

Requirements fulfilled: By this solution, the requirement *15- The design of motors and generators should be such that magnets can be easily extracted without being damaged* is now

[2]WindEurope has more than 400 members across the entire wind energy value chain and in 2021 it also called for a Europe wide ban on land filling of EoL wind turbine blades after many wind turbine manufacturers announced plans for blade recovery without any legislation forcing them to do so ("Wind industry calls for Europe-wide ban on landfilling turbine blades — WindEurope", 2021).

completely fulfilled.

FS1. Ensure that PM generators are tracked

Until there is an EPR scheme for wind turbines, the wind farm owners are responsible for deciding what happens to the PM generators and the magnets in them since it is their property (Wind turbine OEM, A.3.1). As discussed in section 5.2.3, the wind farm owners hire dismantling companies which are responsible for dismantling and also arranging for recycling of the wind turbine and its components. In order to ensure that the PM generators and the large amount of magnets are not lost due to improper recycling or due to being shipped to third countries, the following solutions can be implemented in combination in the medium term.

1. **Advice wind farm owners to track the movement of PM generators and the magnets within them**
   The EU, and more specifically the ERMA can advice the wind farm owners in the EU to actively track the movement of components like PM generators and the magnets within them at the EoL of the wind turbines. They may be able to do so by asking the dismantling companies to provide reports on the flow of the generators and the magnets in them. This would imply that the dismantling companies would need to monitor the flow of the magnets in the supply chain and present the report to the wind farm owners. Implementing this solution may lead to more transparent flow neodymium magnets.
   It is also important to mention that the other means that are presented for this functions are not selected as they can be argued to be resource incentive. Furthermore, the PM generator have a good business case due to very high amounts of neodymium magnets and other metals which make it attractive to recycle in the EU.

Requirements fulfilled: This solution fulfills the requirement *12- Wind farm owners should be advised to monitor the flow of magnets from EOL PM generators.*

7.4.4 Finance

The solutions related to finance that can be implemented in the medium term are discussed below.

FM4. Create incentive for Electric Motor and generator recyclers for extracting NdFeB magnets from assemblies

As discussed in the short term plan, there is a need to create incentive for motor/generator recyclers for extracting the magnets from the assemblies. In the medium term, the following solution can be implemented by the EU.

Provide Carbon credits on amount of magnets extracted
The Member States may give carbon credits to motor/generator recyclers in their states for saving the carbon emission that would have taken place if the magnets were to be produced by virgin materials. The carbon credit can be given based on the quantity of magnets that the motor/generator recycler salvages from the PM motors and generators and sells to the magnet recycler. Based on the quantity of magnets sold each year to the magnet recyclers in the EU, the motor/generator recycler can be given carbon credits. In addition, carbon credits can also be offered to magnet recyclers as the recycled magnets have much less carbon footprint than magnets produced from virgin material (Gauss et al., 2021). However, in order to implement the carbon credit system, the following will need to be looked into detail in another study:

1. What is the amount of $CO2$ emissions saved due to collection of scrap magnets from EoL motors and generators?
2. What is the amount of $CO2$ emissions saved due to recycling of scrap magnets?
3. How can the scrap magnet flow be monitored from motor/generator recyclers to magnet recyclers?
4. How can every motor/generator recycler can be a part of this system in each of the member states?
5. How can this be integrated in the EU Emission Trading System (ETS)[3]

Requirements fulfilled: This solution fulfils the requirement *12- Wind farm owners should be advised to monitor the flow of magnets from EOL PM generators*, also it can be argued that this solution would bring down the cost of collection and thus the cost of recycling will also decrease, which fulfils requirement *2- The price of recycled neodymium magnets should be competitive with the price of magnets imported by China.*

7.5 Long Term Plan

The long term plan can be implemented in 9-12 years time in order to ensure sustained collection and recycling of neodymium magnets. The morphological chart for long term plan with all the chosen means is highlighted in red in figure 7.2.

7.5.1 Legislation and Regulation

FM2. Scale up recycling of NdFeB magnets

In order to scale up recycling of neodymium magnets in the long run, two solutions that can be implemented are as follows:

1. **Regulating share of recycled magnet to be sourced**
   Another strategy that the EU can deploy is to enforce the purchase of recycled magnets by the wind turbine and automobile OEMs. For instance, the wind turbine and automobile OEMs must fulfill 20% of their magnet demand from recycled magnets produced in the EU. Implementing such a strategy would make sure that there is sufficient demand for recycled magnets. However, this kind of strategy may only be implemented once the industrial scale collection and recycling of neodymium magnets has started. Furthermore, the percentage of recycled magnets that can be sourced locally should increase with time as more EV motors and wind turbine generator reach EoL.
   The percentage of recycled magnet that a company should source can be gauged by equation 7.1:
$$\%\, R_{Motors\&Generators} = \frac{P_{NdFeB\ Magnets/year}}{D_{NdFeB\ Magnets/year}} X\ 100 \tag{7.1}$$
   Where,

   (a) $\%\, R_{Motors\&Generators}$ is percentage of recycled magnets to be sourced each year by automobile and wind turbine OEMs to be used in their motors and generators, respectively.

[3]"The EU ETS is a cornerstone of the EU's policy to combat climate change and its key tool for reducing greenhouse gas emissions cost-effectively. It is the world's first major carbon market and remains the biggest one" ("EU Emissions Trading System (EU ETS)", n.d.).

(b) $P_{NdFeB\,Magnets/year}$ is the amount of neodymium magnets (in metric tons) produced by magnet recyclers in the EU.

(c) $D_{NdFeB\,Magnets/year}$ is the demand of neodymium magnets (in metric tons) by the automobile and wind turbine OEMs each year in the EU.

As of now it is not known whether there will be any impact on the performance of motors and generators when recycled and virgin magnets are used in combination in the PM motors and generators. Therefore, if this particular solution is used then the EU should not push for a specific percentage of recycled magnets in one motor or generator. Instead, the EU should suggest a certain percentage of recycled magnets that need to be sourced each year by the automobile and wind turbine OEMs.

2. **Invest in different recycling technologies**
Other than the HPMS process, the EU and the Member States should invest in other recycling routes such as ionic liquid separation (Appendix C.2.2) which separates the constituent rare earth elements (Nd, Dy, Pr) from the magnet. In the long term, it is wise to invest in other recycling techniques in order to process those scarp magnets that cannot be recycled by HPMS process due to high degree of corrosion and or higher level of contamination but can be recycled by pyrometallurgical and hydrometallurgical processes which are less affected by contamination and corrosion (Expert 1, A.2.1). Furthermore, these recycling techniques are also useful in recycling magnetic scarp generated via production of permanent magnets, which may increase in the EU in the long run to ensure a secure supply chain for neodymium magnets.

Requirements fulfilled: Both the long term solution may contribute to fulfilling requirement *5- Collection and recycling setup should aim to process additional quantity of magnets from EoL Offshore and Onshore wind turbines from 2030* and *6- The scale of collection and recycling should further increase significantly to process large quantity of magnets from EoL Offshore and Onshore wind turbines in 2037 and 2040.*

7.6 Solutions that complement each other

Some of the solutions presented above should be implemented together in order to maximise their impact. The solutions that can work well together are as follows:

Ban the export of PM motors and generators to countries outside the EU and ***Provide tax incentives for extracting magnets from PM motors and generators***.
In order to keep the PM motors and generators in the EU so that the EU does not neodymium magnets the ban of export of PM motors and generators is essential. However, imposing a ban may cause backlash by motor/generator recycling companies who earn more profits by selling the EoL PM motors to third countries than by dismantling the motors themselves. In order to avoid backlash and to encourage the motor/generator recycling companies, a tax incentive can be provided by the Member States to them to disassemble and extract the neodymium magnets. In this way, the loss of neodymium magnets to other waste streams and to third countries can be prevented. Moreover, the incentive may also ensure that there is no illegal export of PM motors.

Ban the export of PM motors and generators to countries outside the EU and ***Develop economical and efficient dismantling process of EV motors and wind tur-***

bine generators.
Imposing a ban, especially on the export of PM motors of EVs may require a larger processing capacity in the EU as what may have been processes outside the EU now needs to be processed in the EU. To tackle this, it may be wise to invest early on in the research and development of economic and efficient dismantling processes of EV motor and wind turbine generators. Such processes will be helpful in processing the large amount of EoL motors and generators that will reach EoL in the near future.

Update the ELV Directive with PM motor take-back requirement, ***Make EoL wind turbine directive with PM generator take-back requirement*** and ***Regulating share of recycled magnet to be sourced***.
Increasing the scope of EPR by updating the ELV directive and making a EoL wind turbine directive will enforce the OEMs to be a part of the recycling of the neodymium magnets present in their products. However, EPR does not ensure that the OEMs would also generate demand for the recycled neodymium magnets. Thus to increase the demand for recycled neodymium magnets, regulating the amount of recycled magnets to be sourced by the OEMs will be a crucial step in increasing the collection and recycling of the magnets and simultaneously creating a stronger secondary market.

7.7 Conclusion

In this chapter, the *Design Activity: Design collection strategies for neodymium magnets present in end-of-life electric vehicles and wind turbines* was conducted. With the secondary functions defined in chapter 6, the means to each of these functions were generated using the morphological chart. The final set of collection strategies was divided into three phases- Short term plan (3-6 years), Medium term plan (6-9 years), and Long term plan (9-12 years). The short term plan focuses more strongly on the PM motors of EVs rather than on wind turbine PM generators due to the shorter lifespan of the EVs. Some of the urgent issue that are tackled in the short term plan are: the export of the EoL PM generators to the third countries, limited scope of EPR for automobile OEMs and a weak secondary market for neodymium magnets. The medium term plan focuses on the exponential upcoming volume of EoL PM motors and the start of EoL PM generators from the wind turbine. The urgent issues that are tackled in the medium term plan are the lack of EPR in the wind industry and the lack of efficient and economic dismantling process of PM motors. Finally, the long term plan focuses on further increasing the recycling rate by introduction of amount of recycled magnets that needs to be sourced by the OEMs.

CHAPTER 8

Design Validation

In this chapter, the validation of the conceptual design presented in the last chapter is provided. The chapter gives an overview of different ways in which the design can be validated.

8.1 Different ways of validating design

8.1.1 Stakeholder Consultation Sessions

The ideal way of validating the proposed collection strategy would be to organise a stakeholder consultation session with all the stakeholders that are identified as 'Subjects' and 'Players' in the stakeholder analysis presented in section 5.2. It may not be possible to invite each and every business and research organisation from the identified stakeholder groups (wind turbine OEMs, automobile OEMs, research projects, motor/generator recycling companies, car and wind turbine dismantling companies, and wind farm owners), thus one company/organisation of each group can be invited. Once the invitees have accepted the invitation, the session can be organised online or in person. To begin the session, an introduction can be given in which the background, the opportunity that has been identified in this thesis project, the objective of the collection strategies and a brief overview of all the requirements generated from the analysis are presented to the stakeholders. Next, the design that has been made (i.e. proposed collection strategies) can be presented. Furthermore, a copy of the proposed solutions can be handed out to the stakeholders for their reference and certain time can be allocated for them to go through the document. After the solutions have been presented, the stakeholders can be asked to share their thoughts, feedback and any questions that they have regarding the proposed solutions with everyone. Simultaneously, the questions, feedbacks, and criticism can be documented to be used for making a final version of the collection strategies. The session can end once every stakeholder has had the opportunity to either share their concerns, ask questions and make remarks.

To arrange such a stakeholder consultation session, a lot of time and resources have to be spent on making a team to organise for the session, designing the stakeholder consultation process, making a new data management plan and consent forms, documenting the entire process, analysing the outcome of the session and making a final version of the collection strategies. However, time and resources are very limited in the thesis project and this approach is not feasible.

8.1.2 Multi-disciplinary expert validation

The collection strategies have multiple aspects to it: legislative, financial, infrastructural, and informational. In order to get validation on the multiple aspects of the design. Different experts having different backgrounds can be approached to validate the design. The proposed collection strategies can be presented to different policy officers working under different policy departments (DGs) or different executive agencies in the EC. The policy officers may be able to validate legislative and financial parts of the design in detail. Similarly, researchers working in the field of recycling neodymium magnets can better validate the design from the point of view of recycling, reuse and information flow within the supply chain. Lastly, industry experts and the Rare Earth Magnets and Motors Cluster of ERMA maybe able to validate the overall design keeping in mind the different stakeholders that are involved. In order to organise this type of validation, various experts will first need to be identified and then be asked to participate in the validation process. The experts who have agreed to take part can be sent a consolidated document which explains the opportunity of collection of neodymium magnets from EoL wind turbines and EVs that has been presented in this study, the functions that have been formulated, and the short, medium and long term solutions that can be implemented by the EU.
The participants can be asked to validate the design based on the the following:

1. What are the general impressions about the design?

2. How feasible are the solutions (based on their perception and expertise)?
   The participants can be asked to judge each of the solutions presented in the short, medium, and long term plan based on two things: first, how practical is the solution? ; second, does the solution have the chance of being implemented in the specific phase that it has been put in? Both the questions together can be defined as feasibility. Furthermore, for both the questions a scale from 1-5 can be defined (presented in Table 8.1).

Table 8.1: Scale to judge the practicality of the solution and the time frame of implementation.

Scale	Practicality of solution	Time period of implementation
1	Not practical at all	Cannot be implemented within the time frame
2	May or may not be practical	May or may not be implemented within the time frame.
3	Practical with certain conditions* * - Specify the conditions	Can be implemented within the timeframe but with certain conditions* * - Specify the conditions.
4	Practical	Can be implemented
5	Very practical	Can be implemented very well within the time frame

3. Does the design meet the objectives of the collection strategies?
   The participants can be asked give a score from 1-5 (1 being 'the solutions cannot meet the objective' and 5 being 'the solutions perfectly meet the objectives') corresponding to each of the four objectives and one constraint that has been defined.

4. What can be improved in the design?

5. What elements are missing from the design?

These questions can be given along the consolidated document and through a semi-structured interview or a questionnaire, they can share their response and feedback. However, semi-structured interview will be a superior option because it allows for follow-up questions to be

asked, which can be more beneficial in improving the proposed strategies.
A more ambitious plan could be to organise a focus group after the participants have submitted their response to stimulate a discussion between multiple experts. Depending on the experts validation, the results can be analysed to further improve the proposed collection strategies.

8.1.3 Validation through participants of the study

Another validation approach could be through approaching the same experts and stakeholders that participated earlier in the study. They can be given a consolidated document and a score card as defined previously. However, this approach can induce bias in the results as two of the experts are working in the EU's Horizon 2020 project on neodymium magnet recycling. Furthermore, none of the experts are experts in policy matters, and they may not be able to judge the feasibility of the solutions. Also, including the stakeholders in the validation of the design is not ideal as only two stakeholders- a wind turbine OEM and a motor/generator recycler were part of the study, which do not accurately describe the representation of the main stakeholders that are identified. Moreover, there is a good chance that the response of stakeholders will be aligned with their own interests, which may affect the results.

8.1.4 Validation by researcher

This validation approach may be the least appropriate way to validate the proposed design because of researcher bias. However, in order to validate the design, the researcher can use the same scoring approach that has been defined earlier but with providing critical argument and presenting facts from grey or scientific literature where applicable. The researchers arguments can then be reviewed by the graduation committee to provide feedback.

8.2 Chosen approach to validate the design

The previous sections gave an overview of the different ways in which the proposed collection strategies can be validated. It was decided that the validation approach presented in section 8.1.2 will be used. However, due to poor response from identified experts and time constraints a different approach was taken where all the participants of the study and additional experts in the field of neodymium magnet recycling were reached out to. A document was prepared which consisted of context, thesis objective and the proposed collection strategies. The participants and additional experts were asked to share the following four things through email communication:

1. General thoughts on the strategies.
2. What is lacking in the strategies and what can be improved?
3. Thoughts on the practicality of the strategies in the proposed time frame.
4. Any questions that you might have for the researcher.

Only two participants (Expert 1, Expert 2) and an additional expert (referred to as Expert 4) who is part of Materials Science and Engineering faculty at TU Delft responded. Due to limited number of respondents, all the responses (comments and questions) have been clubbed below:

1. The overview of regulations and directives is impressive. The strategies identify how existing regulatory framework could incorporate measures to support magnet waste collection (Expert 1).

2. The problem of export of vehicles is not addressed which may be useful to do (Expert 1).
3. The labelling of rotors is a good idea (Expert 1).
4. **Using Carbon credits as a means to give incentive also means that the imported magnets are at a disadvantage (Expert 1)**.
5. The document reflects that the entire recycling industry is well understood (Expert 1).
6. Re manufacturing and reuse of the magnets is missing in the strategies (Expert 4).
7. Some of the functions overlap each other and can be clubbed. For instance, the function related to setting up collection targets and increasing scope of extended producer responsibility (Expert 4).
8. **The use of ProSUM may not be the correct way as it takes a top-down approach rather than bottom-up approach as it is suggested in the proposed strategies (Expert 1).**
9. **A lot of car manufacturers share information about their vehicle parts and materials through International Dismantling Information System, which can be used to share information about the magnets (Expert 4).**
10. Some of the solutions in the short term may extend to the long term (Expert 4).
11. **Will the solutions that complement each other be added (Expert 4)?**
12. Isn't the volume of magnets more decisive rather than the lifetime of EVs and Wind turbines? Don't we still have to act on short term, independent of the time until end of life (Expert 4)?
13. HPMS is not the only solution for recycling and there are other options which are also important (Expert 2).
14. PM motors are used in nearly 95% of the EVs as compared to 60% (Expert 2).
15. VALOMAG project should be mentioned as it is the biggest REE recycling project (Expert 2).

The critical points raised by the experts are important to be addressed. Some of the comments (in bold) were taken into consideration and updated to the design proposed in section 7.2. While other comments have either already been made clear through the analyses or will be addressed in the discussion.

8.3 Conclusion

This chapter answers the last sub-question, *SQ 3: What are different ways of validating the design and which is chosen?*. Four different approaches are described as part of this chapter. The ideal way of validating the design is by the means of stakeholder consultation process. However, due to limited time and resources this validation process cannot be used. The second way is to validate using the help of multiple experts- which may include policy officers working for European Commission, experts in the field of neodymium magnet recycling, industry experts and the Rare Earth Magnets and Motors Cluster of ERMA. The different experts can provide their point of view from their field of expertise which can prove to be an effective validation technique. The third way is to validate the design though the participants who were part of interviews conducted or respondent of questionnaire prepared during this thesis project.

However, this way of validation is not ideal as only a limited number of participants were part of this thesis. Furthermore, there may be an issue of bias as most the interviewees are actively working in recycling projects of neodymium magnets. The last method of validation can be self validation which is also not desirable as it can lead to researchers bias.
The chosen way to validate the design was a mix of reaching out to experts and participants of the study due to time constraints. The result of the validation was used to modify some of the solutions presented in section 7.2, while the others are highlighted in the next chapter. The result of the validation can be said to be on the surface due limited number of respondents and the respondents being part of recycling projects. Thus the depth that could have been achieved through validation is lacking. ree approaches are described in the chapter through which the collection strategies can be validated- validation through experts (ideal approach), validation through participants of the study, validation by researcher.

CHAPTER 9

Discussion and Conclusion

This final chapter concludes the thesis project by presenting the discussion, the limitations of the thesis, recommendations for future research. Furthermore, the thesis objective, different stages of the design approach and the sub questions are briefly answered along with practical recommendations and academic and societal relevance.

9.1 Discussion

The topic of neodymium magnet recycling is a relatively new topic. In the past, scientific articles have only touched upon the technical aspect (chemical recycling, pyrometallurgical process) of recycling of the neodymium magnets, and rightly so. First, the recycling methods should be developed and when those are well researched the other aspects like organising for collection should be focused on. In the case of neodymium magnet recycling, the recycling projects have been started to be established on a pilot scale. Thus it is important to now focus the attention towards other aspects such as markets, legislation, and stakeholders, which are equally important to establish a system that can be successful in recovering a major amount of neodymium magnets and be put back in the European market either directly or indirectly (in form of remanufactured product or in form of substituent elements). However, in order to put back a major amount of these magnets back into the market, they need to be collected from variety of sources. The sources considered in the thesis were limited to EVs and wind turbines, however, it should be noted that the neodymium magnets increasingly being used in the motors of E-scooters, and E-bikes. Both these products are gaining popularity in the Western Europe ("European Electric Scooter and Motorcycles Market 2021 — MotorCyclesData", n.d.) and have a shorter lifespan compared to EVs and wind turbines. When these e-bikes and scooters reach their EoL then it will add to the neodymium magnet scrap that is generated in the EU. Thus the volume of scrap neodymium magnets will be much more than what is estimated in thesis, which implies that the effort to increase the scale of collection and recycling should be much higher.

The collection strategies that are proposed as part of the thesis is not a prescription but a starting point for the European Union, the European Commission and the Member States. In addition, it is important to note that some of the solutions that are mentioned in the short term may even extend to medium term, this is due to the fact that the start date and the duration of these plans are dependent on the quantification model. Since the quantification model is rather static (i.e. different scenarios and assumptions have not been taken), it is plausible that there is delay in the volume of neodymium magnets that become available from EVs and wind turbines, and also the amount may vary as the assumption of % of EVs using PM motors is rather conservative in the thesis as pointed out by one of the experts during validation. Furthermore, the strategies are more oriented towards the recycling of the magnets rather than reuse and remanufacturing. This is mainly due to the fact that not enough concrete information could be found through scientific and grey literature, and even expert interviews. could be found on reuse and remanufacturing of the neodymium magnets present in EV motors and wind turbine generators, which in turn can be explained by the fact that not enough EVs and wind turbines have reached their EoL. This gap can be accounted for in the future when more information is available on the reuse or remanufacturing of the magnets.

9.1.1 Limitations

Limitations of thesis process methodology

The approach taken for this thesis was design approach which employed various methods of data collection such semi-structure interviews, questionnaires, desk research. Three semi-structured interviews were conducted with experts who have gained their expertise through working in the field of neodymium magnet recycling or have extensively studied about the recycling techniques. All three interviews contributed to different perspectives on similar questions that were asked to them. For getting insight into the stakeholder perspective from mainly the Players that were identified in the section 5.2, only one interview with motor/generator recycler present in the Netherlands was conducted. Furthermore, a questionnaire was shared with a major wind turbine OEM and a wind turbine dismantling company which has not responded to the questionnaire yet. In addition, multiple car dismantling companies, motor/generator recyclers, wind turbine dismantling companies, automobile OEMs were contacted via email or phone but unfortunately they either did not respond or did not want to participate. To overcome this issue, desk research was used to find more information about their positions and interests. However, this can be seen as an inferior data collection process compared to interviews or questionnaires. It can be concluded that the limited number of interviews were a limitation in the thesis, which may have affected the quality of data that was gathered.

Limitations of Quantification model

The quantification model for EVs and wind turbines which is used to make to make the requirements related to increase in capacity and scaling of collection and recycling has the following limitations:

1. The model only quantifies the amount of magnets that may be available for collection from only four countries. To estimate the amount from the entire EU, other EU countries should also be taken into account.

2. The assumption of lifetime of EVs and wind turbines is based on prior studies that have taken the same assumptions. However, in reality the lifetime of EVs and wind turbines may be less or more than assumed lifetimes.

3. The model is based on the assumption that the lifetime of PM motors and generators inside the EVs and wind turbines, respectively, is same as the assumed lifetime of EVs and wind turbines. However, in reality the lifetime of PM motors and generators may or may not exceed the assumed lifetime, which will result in different quantities of magnets that will be available for collection and recycling at different time than what is indicated.

4. For BEVs it is assumed that the average amount of neodymium magnets will be 2.1 kg and for PHEVs it will be 1 kg. However, the upcoming high performance EVs have multiple PM motors (for instance, Tesla Model S, Polestar 2, GMC Hummer EV etc.),

which increases the amount of neodymium magnets by 2-3 times the average amount. This is not captured in the model due to limited data on EVs which use dual motors and what is the share of EVs using dual motors.

All the limitations lead to the model being more static in nature rather than dynamic. In order to overcome this, different scenarios can be made where the assumptions of lifetime and the quantity of magnets in wind turbines and EVs can be changed. However, due to time constraints and limited data on the lifetime of PM generators and EV motors the model is kept rather simple.

Limitations of the Design

The design that has been proposed has several limitations:

1. The design does not take into account the logistics of collection of the neodymium magnets.
2. The proposed collection strategies are conceptual and a lot of practical details need to be considered in order to implement these strategies in the EU. Most of the solutions that are suggested may require coordination and cooperation between multiple actors and stakeholders and how to enable it is missing.
3. One of the solution that is suggested is the collection rate of the EoL PM motors and generators, however, the collection rate of the magnets within them is not considered. This is due to the fact that the collection rate of the magnets from the assemblies will involve taking into account the loss of magnets while extraction and the loss of magnets during transportation which could not be found.

9.2 Recommendations for future research

Some of the future research can be in the following areas:

1. As mentioned in section 3.5, the EoL EV motors are being sold to traders in the third countries, research can be done to find out about what happens to the neodymium magnets that are present in them.
2. If it is decided to setup a dismantling plant for dismantling the rotor of the motors to extract the magnets then research can be conducted to find the ideal location of the dismantling plant in the EU. A gravity model can be made to identify the location of this plant and factors such as labour charges, cost of setting up facility, cost of transportation to the location, policies supporting this industry can be some of the other factors that can be looked into while making a decision about the location of such facility.
3. The number of companies that recycle motor/generators and their processing capacities should be researched to find out whether they will be able to cope up with the amount of EoL motors and generators from EVs and wind turbines.
4. A feasibility study can be done on each of the suggested solutions to check the impact of the solutions and the cost related to these solutions that the EU and the Member States would need to bear.
5. Europe is the second largest market for e-bikes and scooters (which also use PM motors) after China ("E-Bikes and Rare Earths", 2015). Thus, a similar study can be done to quantify the amount of neodymium magnets that can be available for collection from e-bikes and scooters. The e-bikes and scooters also have less life compared to EVs and wind turbines and thus the possibility of collection can be earlier. Furthermore, doing so would

also give a more accurate estimate on how much collection and recycling capacity should be allocated to recover as much of these neodymium magnets.

6. Research can be conducted into making a semi automated or automated process to extract the neodymium magnets from the rotor of the PM motors. For PM generators, there is already a standard procedure being followed in the industry but it is not standardised.

9.3 Conclusion

The conclusion are presented as per the different stages of the thesis are as presented in this section.

9.4 Thesis Objective

The objective of the thesis was: ***Design of collection strategies for salvaging neodymium magnets from end-of-life electric vehicles and wind turbines in the EU.*** To fulfill the thesis objective, 3 sub questions and one design activity were formulated. The answers to the sub question and reflection on the design activity are presented below as per the five stages of the thesis.

9.4.1 Stage 1: Initial Opportunity

In this stage, the opportunity of collecting the neodymium magnets from the EoL EVs and wind turbines is identified by conducting a literature review. The neodymium magnets and the REEs within them are defined as critical raw materials by the EC as they have significant economic value for the EU and at the same time have a high supply risk. One way securing access to these materials is through mining which may be an essential part of building a supply chain that is less reliant on China. The other way to become less reliant is through accessing the secondary sources of neodymium magnets. EoL EVs and wind turbines are lucrative secondary sources of these magnets given the fact that they use significant quantities compared to other sources like hard drives, mobile phones, audio devices. However, to have access to these magnets for recycling them, the first step is to collect the devices containing them. In this case it was the PM motor from EoL EVs and PM generator from EoL wind turbines. Based on the literature review it was identified that existing literature that were reviewed and the literature that were read as part of the thesis do not fully explain how the collection of neodymium magnets will take place and how a high collection rate of magnets from secondary sources can take place. Furthermore, collection was identified as a weak link in the recycling value chain of neodymium magnets. And lastly, the supply chain of EoL devices including PM motors and generators of EVs and wind turbine were missing due to which the key actors in the supply chain were not identified. Thus, collection of these magnets from the EoL EVs and wind turbines in the EU was seen as an opportunity that could help secure the access to the neodymium magnets for the purpose of recycling.

9.4.2 Stage 2: Explicate Opportunity

In this stage the **SQ 1:** ***What is the current state of the system in which the collection strategies will be employed?*** was answered. A layered approach was taken to answer this sub-question, where four other sub-sub questions were formed and answered respectively. The output from sub-question 1 has been the basis for formulating the requirements that need to be fulfilled by the designed collection strategies.

SQ 1.1- What does the market of neodymium magnets look like?

The market of REMs, in particular the neodymium magnets is dominated by China due to their very early investment in the REE value chain, vertical integration of supply chain and heavy state subsidies, this strategy allows China to control the price of neodymium magnets. Furthermore, China provides tax incentive to its magnet manufacturers for exporting the magnets which is a big threat for the recycling industry in the EU as it can be difficult in the beginning to offer recycled magnets at similar prices without the intervention of EU. This directly affects the collection of the magnets as recycling and collection are interlinked operations. If the demand for recycled magnets is not there due to its high price point then it can translate down to the recycling value chain of neodymium magnets. Less demand can lead to poor rate of collection and recycling. On the other hand, if the collection rates are high then it can potentially lead to economies of scale, which may make the recycled magnets a good option for the customers. This point was further strengthened by the results of the quantification model which estimated the amount of neodymium magnets that may be available for collection from the EVs and wind turbines will increase exponentially.

However, in order to collect the neodymium magnets for recycling, the PM motors and generators containing them needs to be collected. It was found that the motor/generator collectors and recyclers were an essential player who deal with selling the EoL motors and generators, and dismantling and recycling of the EoL motors and generators, respectively. The motors and generators that are sold may also contain neodymium magnets depending on the type of motors and generators. Thus, it is essential to involve them in the collection process and so that the neodymium magnets can be collected and directed to the right recycling route.

SQ 1.2 What is the possibility of re-use and recyclability of neodymium magnets?

To prepare for the upcoming volume of magnets that will be present in EoL PM motors and generators, it is essential to figure out, how to extract the magnets from the motors and generators. By studying the dismantling of the PM motors and generators it was found that dismantling and extracting the neodymium magnets is a bigger concern for motors than for generators. It is difficult to extract the neodymium magnets from the rotor of the motor without damaging them due to their brittle nature. The extraction is especially difficult because the magnets are epoxied/glued in the slots of the rotor in case of IPMSMs, or on top of the rotor in case of SPMSMs. Due to difficult extraction of the magnets from the rotor and in general time consuming process of dismantling the motors, the motor/generator recyclers find it lucrative to sell the motors to third countries. However, this also leads to the loss of neodymium magnets in the PM motor. For PM generators, the process of removing the magnets is already established by the motor/generator recyclers, and the extracted magnets from PM generators are then sold to magnet traders who resell the magnets to Poland. However, what happens to the magnets is unknown. If the magnets from motors are extracted then they can be recycled but not re-used as they may suffer damage or the magnets are removed by demagnetising them. However, if the PM motors are designed to be recycled and dismantled then there is a possibility that the magnets can be reused. Even if they cannot be reused, the design of the PM motors should be such that the magnets can be easily extracted. For PM generators, the possibility of reusing the extracted demagnetised magnets could not be found, thus it is assumed that they will be directed to the recycling route. The most promising and popular recycling route that can be used for scrap magnets from PM motors and generators is turning the magnets into neodymium magnet powder and re-sintering them, this is a short loop recycling process and it saves significant amount of energy compared to producing magnets through virgin materials. Furthermore, even if the neodymium magnets are not used to make the magnets then it can be used as a secondary mine. However, in order to use the HPMS process efficiently, the different magnet grades, their chemical compositions, and their coatings should be identified early on in the process. This implies that this information needs to be passed on along the recycling value chain from the automobile and wind turbine OEMs.

SQ 1.3 What legislation are in place that governs the flow of EoL EVs, wind turbines and neodymium magnets?

Two directives (Waste Framework Directive, End-of-life Vehicle Directive), one framework (Extended Producer Responsibility), one action plan (Circular Economy) and a proposed regulation (battery regulation) are looked into. The general conclusion that was drawn after analysis was that they there are no legislative means currently that determine the route of the neodymium magnets present in EoL EVs and wind turbines. Furthermore, for wind turbines, there is no EPR in place which allows the wind turbine OEMs to be not involved in the collection and recycling of the components like the PM generators and the neodymium magnets within them. For EVs, the EPR applies to automobile OEMs which makes them responsible for the collection and recycling of the vehicles they put on market. However, since the recycling rate that is prescribed for the vehicles is mass based (i.e. focused towards materials that are present in bulk amounts in the vehicle like Copper, iron, aluminum etc.), the OEMs are not focused towards extraction of critical raw materials that are present in their vehicles. Thus these issues need to be addressed in order to make the collection and recycling of neodymium magnets possible just like the proposed battery regulation targets to collect and recycle the portable and EV batteries that are about to come in the future.

SQ 1.4Which stakeholders will be involved or affected by collection strategies?

The stakeholders that need to addressed in order to collect the neodymium magnets are of two types: The Players can either be involved in making appropriate polices for collection or in organising of the collection and recycling, or extracting the magnets from PM motors and generators assemblies. The Subjects can be indirectly involved in the process of collection by directing the PM motors and generators containing the neodymium magnets to the right recycling route. The coordination and cooperation from both Players and subjects would be needed to make the collection of the magnets possible.

9.4.3 Stage 3: Define Requirements

In this stage, sub-question:***SQ2: What are the requirements and functionalities for designing the collection strategies?*** is answered. The output of the analyses in the previous stage are used to formulate the objectives and constraint of the collection strategies, form requirements that must be met by the designed collection strategies and functions that the must be performed by the collection strategies in order to meet the requirements. A list of eighteen final 'Need-to-have' requirements were made that the collection strategies should meet. To meet these requirements three primary functions and corresponding secondary functions were formulated.

9.4.4 Stage 4: Design and Develop Artefact

In this stage, the secondary functions that were prepared in the last stage are put in a morphological chart to generate a solution space. The secondary functions that the collection strategies must perform were listed down in the leftmost column and across each of the secondary functions, different means of realising the functions were put in. Based on the generated solution space, the collection strategies that can be implemented by the EU were presented. Since it is not realistic and not necessary to meet all the functions urgently, three phases were defined in which the solution can be implemented- Short term (3-6 years), medium term (6-9 years) and long-term (9-12 years) plan. Furthermore, in each phase, the solutions were put into one or more of the five defined labels. The labels were: Legislation and Regulation, Information Exchange, Finance, Infrastructure development, and Material Flow. The short term plan is focused more towards the EoL PM motors coming from EVs. Furthermore the intent of the short term plan is to facilitate the process of collection of the neodymium magnets by laying out the necessary fundamentals like setting the rules, ensuring appropriate market conditions for collection and recycling, and addressing the necessary actors. In the medium term, more focus is placed on magnets that would start becoming available from EoL wind turbine generators and increasing the capacity of collection and recycling to deal with magnets that may be available from EoL PM motors. To do this, it may be important to make regulations that are specific to EoL devices containing neodymium magnets. Lastly, the long term solution is focused towards regulating the amount of magnets that should be sourced by the OEMs each year and the investing in other forms of recycling so that the REEs can become available for other applications as well.

9.4.5 Stage 5: Evaluate Artefact

In this stage, the last sub-question is answered: ***SQ3: What are different ways of validating the design and which is chosen?***. The chapter describes four alternative ways to validate the design- the ideal way to validate the design is by stakeholder consultation session, while the least desirable method for validation is validation by researcher. Due to time constraint a middle approach is taken to validate the design by including additional experts from field of neodymium magnet recycling and the participants who already took part in the thesis project. Some fundamental issues were raised by the experts regarding the proposed solutions which were partially addressed by updating the design.

9.4.6 Practical recommendations

In the short term, the first thing that the EC can do is to update the ELV directive to increase the scope of EPR to cover PM motors and the neodymium magnets in them. In addition, the EC should set concrete collection targets for the short, medium and long term. Increasing the scope of EPR would ensure that automobile OEMs are made responsible for financially organising the collection and recycling. The EPR may ensure that the Member States do not need to provide financial incentives to car dismantling companies and motor/generator recycling companies to remove PM motors and extract the magnets from the motor assembly, respectively.
Simultaneously, the EC can impose a ban on the export of both PM motors and generators outside the EU, as the export of motors and generators implies that the EU is losing critical raw material which has high economic importance and supply risk. Furthermore, awareness drives can be organised by Rare Earth Magnet and Motor Cluster of ERMA to make the motor/generator recycling companies aware of the importance and the economic value of the magnets present in the PM motors of not only EVs but also other types of motor that may contain neodymium magnets.
The increase in the scope of EPR may also motivate the OEMs to design their motors to be dismantled and recycled. However, this cannot be said with certainty, thus the EC should introduce a directive which guides the OEMs to make the motors easy to dismantle and recycle as it directly has an impact on the efficiency and economics of collection. Bringing down the dismantling costs may have a significant impact on the overall cost of the recycled neodymium magnets or REEs separated from them. In addition, the Member States like Germany, France, Denmark, Sweden who have high number of EVs and wind turbines should consider investing in HPMS process of recycling as it is the cleanest and shortest (i.e. less steps) way through which neodymium magnets can be recycled. However, other ways like hydrometallurgical and pyrometallurgical ways of recycling should also be encouraged as they are less sensitive to magnet scraps that are more contaminated and/or oxidised.

In the medium term, the EC should consider supporting or initiating the project of economic dismantling of the PM motors as the volume of PM motors will increase exponentially in the long term. Furthermore, the collection targets should also be increased to manage the large volume.
For wind turbine generators, the business case can be said to be stronger because of the large amount of magnets (in tons) in each PM generator. Furthermore, the generators being massive in size naturally demand the wind turbine OEMs to make them modular. Thus, for wind turbine generators, only implementing an EPR may be sufficient to ensure that the wind turbine OEMs are made responsible (financially and organisationally) for the collection and recycling of the neodymium magnets in the PM generators. Finally, in the long term, the EC can regulate the amount of recycled neodymium magnets to be sourced by the OEMs to create a stronger market for secondary neodymium magnets.

9.4.7 Academic and societal relevance

To the best of researchers knowledge, no studies have been conducted that take into account the market of neodymium magnets, the technical aspects of collection and recycling, the legal barriers and the stakeholders that should be involved together to make a set of collection strategies. Furthermore, this thesis project has mapped the supply chain of EoL PM motors, generators and the neodymium magnets within them which contributes to the body of knowledge. Another contribution that this thesis makes is the method taken to quantify the amount of neodymium magnets that may be available for collection and recycling. No studies that were reviewed or explored during this thesis have taken data from each of the wind farms in the Netherlands, Belgium, France, and Germany to estimate the amount of magnets that are in them. Moreover, for offshore wind farms in each of these countries, the individual turbine model and the type of generator in the model were taken into consideration before calculating the amount of magnets that are present in them. The thesis also contributes to adding value to the body of knowledge of design science research. The DSR framework by Johannesson and Perjons (2014) has been applied to a case which is not from Information Systems domain. Lastly, it can be stated that this thesis has laid down the barriers to collection of neodymium magnets from EoL EVs and wind turbines and how to potentially overcome them.

The societal relevance of the study is that it can help in starting the collection and eventually improving the collection rate so that more material can be recovered through recycling in the EU. This will contribute in making the EU more sustainable and circular as recycled magnets are much more sustainable compared to magnets produced from virgin materials. Furthermore, the dependence on other countries will reduce by establishing a good collection and recycling strategy. Additionally, the companies in the EU- automobile OEMs, wind turbine OEMs will become more sustainable. Last but not the least, the implementation of collection and recycling will create more jobs in the EU which will ultimately contribute towards the economic growth of the EU.

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APPENDIX A

Interviews

A.1 Consent form

The consent form used in the study is presented below.

Informed Consent Form

The information provided on Participant Information document accurately describes the risks and possible consequences of participating in the study.

Herewith I confirm, the undersigned, that I give permission to participate in the aforementioned study.

In connection with this, I declare the following:

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: Taking part in the study		
1. I have read and understood the information given about the study on dated [/ /], or it has been read to me.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I am sufficiently informed about the nature, purpose and procedure of the interview.	☐	☐
4. I agree to be video-recorded while taking part in the interview.	☐	☐
5. I understand that the interviews will be transcribed.	☐	☐
B: Use of information in the study		
6. I understand that the information I provide will be used in reports and presentations in an anonymous way (i.e. by hiding any personal information).	☐	☐
7. I agree that my information can be quoted in research outputs in an anonymous way (i.e. by hiding any personal information)	☐	☐
8. I understand that taking part in the study also involves collecting specific personal information, such as my name and my email address, and will not be shared beyond the graduation committee.	☐	☐
9. I understand that the original transcripts will be anonymised and only the summary of the anonymised transcripts will be made publicly available through TU Delft education repository and 4TU Data Centre (TU Delft)	☐	☐
C: Further use and reuse of the information		
10. I understand that the video recording of my interview will be deleted after 4 weeks of thesis defence.	☐	☐
11. I understand that the transcripts generated from the video-recorded interview will be stored till 1 year after thesis defence, and will be accessible only by the graduation committee.	☐	☐
12. I understand that, beyond 1 year of storage of original transcripts, I will be asked for permission to extend the storage.	☐	☐

Signature

I have read the Information Sheet carefully and understand what I freely agree with.

____________________ ____________________ ________

Name of participant Signature Date

For the researcher

I hereby certify, the undersigned, that I have fully explained to the above mentioned participant the nature, purpose and procedure of the interview by providing them a copy of the corresponding "Information Sheet" and that they have volunteered to participate in the study.

____________________ ____________________ ________

Name of researcher Signature Date

A.2 Interview Log

This section consists of the summarised and paraphrased version of the interview with experts. Any personal information mentioned by the participants during the interview has been removed and the identity of the interviewee has been made anonymous.

A.2.1 Interview with Expert 1

Expert 1 is a PhD researcher in a Leiden University in the Netherlands. His research is on rare earth magnets and in particular the sustainability impact of new technologies that are being developed by the European research project- SUSMAGPRO to recycle the magnets, recover the rare earth elements and upscale the operations. The European project is partnering with Leiden University and as a part of the partnership to find the answers to the sustainability-related questions related to the recycling technology and what can be expected in the future.
Arnav Kumar: Let me tell you something about the thesis. The idea of the thesis is to design collection strategies that would facilitate the collection of Neodymium magnets from End-of-life wind turbines and Electric Vehicle motors. I have chosen to focus only on Wind turbines and EVs because of their growing demand and because of the higher quantity of magnets in these technologies compared to a hard drive for instance. The idea of working on collection came from the fact that a lot of authors while quantifying the amount of Nd, Pr, Dy that can come from secondary sources assume that the collection rate of devices containing the Neodymium magnet would be more than 90% but there is no research on how such high collection rate would be possible in the first place. Moreover, the recycling rate of NdFeB magnets is less than 1% in the EU, I think this is partly due to the fact that there are still no industrial-scale recycling technologies and additionally, the magnets are not being collected in the first place for re-use and recycling. Most of the magnets are melted along with metals in higher quantities like Steel, iron and copper and then rare earth elements are removed as slag.
I am currently conducting a technical, institutional, and stakeholder analysis to get an overall

understanding of the waste management system where the collection strategy will be employed. The purpose of the interview is to get a richer understanding of the current system and simultaneously understand the needs, requirements and constraints of the collection strategies that I wish to design.

Arnav Kumar: Let me start with questioning you about the technical part first. What are the recycling technologies that you are currently working with?
E1: I am looking at the recycling technologies that are being used in the SUSMAGPRO project and they are mainly relying on hydrogen processing of the magnets, which means that you take magnets or scrap and the magnets are then placed in a large vessel where the hydrogen gas is applied. The hydrogen pulverizes the magnets which will turn the magnets into fin powder. The fine powder can then be used to process into new magnets.
What is important to understand here is that the magnets first need to be liberated from the device and then put in the vessel. Putting the device containing the magnets itself will take up a lot of space and it might not even work.

Arnav Kumar: Is Hydrogen processing the only technique that you are currently working with right now or is there any other chemical or hydrometallurgical method that's your analysis?
E1: I am aware of other approaches but those are outside the scope of my work. However, there is one process where you can remelt the magnets but you need even more pre-processed magnets because the magnets have a protective coating which needs to be removed before remelting them. The reason why this method is being investigated is because for some magnets that are more oxidized or for some reason they have been in contact with oxygen or the coating is damaged then the remelting route might be better suited. Moreover, you will get a higher purity alloy.

Arnav Kumar: Do you think that Hydrogen processing is a good recycling method for neodymium magnets present in electric vehicles and wind turbines?
E1: From a theoretical perspective, I would say that it's a very attractive approach because it uses limited amount of energy and it's a short loop recycling because you will recover the alloy and new magnets can be made from that.

Arnav Kumar: But I have read that the Hydrogen processing of magnets can be only used on sintered magnets and not polymer-bonded magnets.
E1: Yes that is true, but the magnets in EVs and wind turbines are sintered magnets.

Arnav Kumar: What aspects to do you think are important for the process of collection so that it can be recycled in the most efficient way?
E1: One of the drawbacks of the HPMS process is that it requires high requirements for collection and sorting process. First, the magnets need to be taken out of the device or its assembly. Second, you need to measure or know about the composition of the magnets that come in for recycling. As neodymium magnets have different elemental compositions and the composition of the magnets will determine the performance of the recycled magnets. So ideally you want to know what is this composition, what is the quality of the end-of-life magnets coming in? And there are various approaches to do that.

Arnav Kumar: Do you think the composition can be easily determinable? And does the grade of the magnets also matter?
E1: I am not a magnet expert but the grade and the composition of the magnet are linked but there are more aspects to the composition. For instance, it also has to do with the heat

resistance. While grade has to do with magnet strength.
Coming to the earlier part of the question, there are measurement techniques that determine the chemical compensation. But it's not a fast method. And I mean it does require some steps and it's not like like a scanner that you can simply scan the magnets and you know it's exactly so in that sense it's there are no methods yet for. Moreover, in practical setting, you need to ask yourself whether you need to measure every single magnet's composition since the wind turbines would come from the same wind farm and just checking one magnet would tell you the composition of the rest. For Electric vehicles, a certain type of car would likely have the same composition magnets as they were made identically by the manufacturer.
If we talk about solutions then there is Max cycle project going on which uses a small QR codes on magnets which can then be scanned to well to identify what is the magnet composition.

Arnav Kumar: You mentioned the QR code. Uh, but the QR code would be beneficial to use while inserting the magnets, right? Or in the design phase of the motors or the generators in which they're placed?
E1: Well, also in the take-back because then once you have liberated the magnets, you can scan the QR codes that would be imprinted on the magnets and then you would know it's properties. You could also think of ways of digitally registering the product composition.

Arnav Kumar: Do you think the HPMS would be industrially scalable? And do you have a duration in mind?
E1: It could be sooner than you think. Based on the business reports and what I see, there are several startup companies that really aim to implement recycling. In practice, there are have pilot projects that aim to upscale soon and in that sense it is already happening in Europe. There is a spin off in UK in the University of Birmingham, also in Germany.

Arnav Kumar: Do you think that it is a good idea to store the magnets in case the recycling technologies are not upscaled timely?
E1: From a resource conservation point, that sounds like a good idea but I am not sure about the business point of view.

Arnav Kumar: Ill now ask about the Institutional part. What is your perception on the current rules and regulations related to reuse or recycling of rare earth magnets in the EU?
E1: If you look at current legislations then there is nothing specific about targeting magnets. However, you do see that there is a high policy focus within the EU to secure rare earth magnets and rare earth materials. This awareness might lead to policy change.

Arnav Kumar: What policy changes do you think should happen?
E1: I am not a policy expert, but I think it should be something similar to the latest battery regulation, where they have specific targets for materials in the end-of-life battery. And policy tool like the Extended Producer Responsibility can be used to further facilitate collection.

Arnav Kumar: How do you think it can be applied in the case of wind turbines and electric vehicles?
E1: The collection could be quite favourable in the case of wind turbines and electric vehicles as there are limited number of car manufacturers and wind turbine producers so in that sense it is easy to regulate and the products are also quite large. However, there is risk of exports.

Arnav Kumar: Do you think that there should be export regulations on wind turbines and EVs?
E1: I don't really have an answer to that as I think it is a dilemma. However, the export of

waste should be prevented. There could also be monitoring and checks on what is actually exported but it might be cumbersome. But things can also be changed by incentives and financial incentives that can come from profits by selling the recovered materials, or there could be a take-back fee.

Arnav Kumar: Now I'll move onto the stakeholder part. What do you think will motivate the decommissioning companies or the Automobile recycling companies to start retrieving the magnets?
E1: One motivation could be the situation of rare-earth markets. If prices are very volatile or the supply is really uncertain then this will definitely motivate them to think about collecting the magnets and recovering the elements. Currently, the car manufacturers and wind turbine producers are aware of the supply risk of the magnets. The government can also motivate by introducing regulations on minimum recycling content and these government incentives do move the markets. In your case, this might be particularly interesting as the volume of magnets would be small but after few years it will rise and economies of scale can be achieved. Especially at the start of the recycling industry, such policies will help overcome the initial barrier.

Arnav Kumar: How should or would the Member States be involved in the collection and the storage?
E1: That can vary as per individual Member states, depending on their own geopolitical awareness and resource dependencies they will setup the regulations. France or Germany might take the lead in implementing such measures. Reducing the environmental impacts might be an incentive for such countries to act first. I am thinking of Denmark, which has been really proactive in starting up the Wind industry on shore and offshore and well for the same reasons they might want to pursue also the collection of magnets or other resources from the wind turbines.

Arnav Kumar: How would the recycling projects or upcoming recycling projects would benefit from the collection of these magnets?
E1: It all starts with the collection, so recycling or recovery companies will seek collaboration. I think with collection businesses and there is cooperation needed to do so. Moreover, these businesses can work with manufacturers for better design to enable collection by easy liberation of the magnets from the assembly of the products.

Arnav Kumar: What will be the requirement of future recycling companies from the perspective of collection?
E1: First would be a continuous supply of the magnets and second would be the quality of the magnets and depending on the quality it may be suitable for a different type of recycling methods.

Arnav Kumar: Is there specific information needed by recycling companies for doing their part efficiently?
E1: Indeed, the composition of the magnets would be the most important thing to know but also the type of coating that the magnet has. Because depending on what coating is on the magnet that well, a different way of processing might be needed. Some coatings can really easily be removed after the HPMS process because they just form large flakes and then they can be sieved off whereas other coatings have to be removed prior to the process.

Arnav Kumar: Do you think this information will be with product manufacturers?
E1: SUSMAGPRO project partners have found that most product manufacturers often do not know exactly what is the coating or composition of the magnet and it is really essential to know this. I am not sure whether this should be recognised during the collection or after it. But

depending on the quality of waste that comes in the prices of the final magnet will be determined.

Arnav Kumar: Thank you so much for giving your time for the interview. I think I have learned something new and this will be valuable for my study.

A.2.2 Interview with Expert 2

Expert 2 is a researcher in the metal and battery refining and recycling group in TU Delft which is lead by a professor who has a lot of expertise in rare earth recycling, especially the hydrometullurgical recycling of rare earths. Currently, he is working on project that deals with collecting, dismantling, pre-processing and then extracting, demagnetising and remaking the magnets. There are 3 different recycling routes that we use to make sintered and bonded magnets- Hydrometallurgy, Hydrogen decrepitation, HDDR process. Before the project, he did his PhD in Mari Curie Program and was working in the Project called DEMETER which was about the recycling and designing of the magnets for PHEVs and BEV motors. He was specifically looking into the shredder of the dismantling companies to track the magnets that have been shredded. In addition, he was working on the sorting of the magnets that are present in the EV. He had a Nissan leaf to work on which had different kinds of magnets in the entire vehicle and he did the categorisation. **Arnav Kumar**: Can you tell me more about the process of dismantling the motor of the Nissan Leaf?
E2: Yes, we dismantled a permanent magnet motor from 2013 Nissan Leaf. Firstly, it was difficult to remove the motor itself from the vehicle and then it was even difficult to dismantle the motor to access the magnets. The whole process took 2 days and I was with some dismantling experts. Once the motor was dismantled, another problem was to remove the magnets from the rotor of the motor. In this particular motor, the magnets were embedded inside the rotor and one would think that you can easily push out the magnets from the other end but they are glued in place using epoxy. Furthermore, the neodymium magnets are really strong and you need a lot of force to physically remove it and because it is brittle there is a high chance of breaking it. The magnets are not in line with the rotor because then there is generation of eddy currents which generate heat and then the magnets can get demagnetised. Epoxy which is used to stick the magnets is a pollutant when we recycle the magnets and the final strength of the recycled magnets lowers. So, ideally the surface of the magnets need to be clean in order to have a good product at the end. So this is one of the biggest challenges in the EVs.
From the point of collection, there is an advantage because collection rate of the end of life vehicles are already high but then there is a problem with end of life vehicles being exported outside of Europe and then you loose valuable resources. Apart from that, you have the problem of illegal export which needs to be looked into if we want to close the loop. From there, you just need to remove the motor of the Electric vehicles. Right now, there is legislation on removing pollutants like the battery and the fluids from end of life vehicles, similarly, there needs to be legislation on removing EV motors so that they do not enter the shredder where these magnets will be impossible to recover.

Arnav Kumar: From a collection point of view, then who do you think should take out these magnets from the motor? Would it be the dismantling company or would it be someone else in the supply chain?
E2: Firstly, I think the dismantling companies are not prepared for EVs. Currently, one dismantling company tries to send the EV to another dismantling company which has some experience in doing that. At the moment, these companies are trying to focus on battery of EVs because they are a safety hazard. For motors, I am not sure how would they do it but "it would be difficult for them to remove the magnets you know, the maximum they could do is to remove the motor just like you know how they remove the catalyst and then they sell the catalyst to the company that deals with them."

I think they also will be forced to remove the motor from the EV before it reaches the shredder because the motor damages the blade of the shredder. So it can be a good thing. Moreover, "the case of the motor is full of steel and that they could, you know, make money out of that. So I don't know, depends on the technology. If it would be possible to easily open the more the case to remove the stator would be a big step and then send the stator for to someone else who gonna remove the magnets from the stator."

Arnav Kumar: Lets say that there's a recycling company which recycles magnets. Do you think it should be their job to get these motors and extract the magnets or would it be someone else?
E2: Ideally the people making the magnets from end of life magnets should not be concerned with collection and just focus on getting the magnets and testing them. Because they are experts and material engineers who check grain boundaries and other things associated with material science.

Arnav Kumar: How do you think the legislation should change then for making collection and recycling possible?
E2: Like the proposed battery regulation, they should impose some recycling rate and collection rate for the magnets. Or they should increase the scope of producers to collect and process these magnets. For catalytic converters this was the same, and the legislation came in which made it obligatory for dismantling companies to remove the catalytic converters.
For wind turbines, it should be easy to set up collection because they are big and have lot of magnets. They can also be directly re-used by reshaping and putting a protective coat on top of it again. But it is important to know the composition of the magnets.

Arnav Kumar: Who should then classify these magnets as per their composition?
E2: They are already classified, as the designer of these motors and generators go to the magnet manufacturers with a set of requirements and the magnet manufacturers then give them the magnets of the particular specification. So there is already information available but somehow this information needs to be passed on.

Arnav Kumar: "So there needs to be an information flow from the producers to the collectors and then forward in the supply chain about the composition, so that it, yeah, it reaches the right place with the reuse or recycling."
E2: Yes, the composition of the magnet is like a signature of the magnet which does not change even if you cut them into pieces and reuse them for other application like electric scooter. Because the life of magnets itself is long, and they can be re-magnetized.

Arnav Kumar: From a market perspective, do you think that the collection and recycling will be profitable?
E2: Both in Motors and generators there are significant amount of copper and iron which can be recovered and sold to smelters. For magnets we need to think if it is cheaper or strategically safe to collect and recycle. "Because if you have like 100% of production in the hands of lets say the Chinese Government then you have a risk associated to that. So perhaps, if have another source that where you pay a bit more then I think you should diversify your portfolio."
"I believe that European Union is stepping in now and like, give subsidies to this companies that are doing a these things, like in a premium price to be competitive with Chinese magnets." Moreover, it is all about volumes, when the volume of the EOL magnets increases, the price of collection and recycling will go down because of economies of scale. "There is a company that's called Urban Mining CEO. They got like 20 millions now from the pentagons, you know, from the Pentagon to to develop the the the process in the larger scale recycling of magnets."

Arnav Kumar: Can you think of anyone who would be opposed to the idea of collection and recycling?
E2: Maybe the mining companies as they want more funding from the EU and the miners try to undermine the recycling. Sometime even automobile companies as the designers are not aware about the critical raw materials because they are under the perception that materials are available and we can order them in huge quantities. "So there's there are few initiatives to educate the designers you know and the Mechanical Engineers in the different industry."

Arnav Kumar: Then it makes design of the generators and motors very crucial right?
E2: Yes, the design is essential, you should be able to dismantle easily and fast.
"I think the Tesla Model 3, they are doing the dismantling of the motor within 45 mins- 1 hour so we need to learn from that."

Arnav Kumar: I have read that Hydrogen Processing of Magnetic Scraps is a suitable recycling technique for magnets in wind turbines and EVs. I would like you to comment on that.
E2: "I think it's very suitable and I think it's the the the favorite method that should be incentivized because it's clean and it's a low energy tense, so like doesn't spend much energy, doesn't produce a pollutant. It's a a very nice method. The there are some problems like to get the material very clean. You don't want to have a box coating around, you want to to remove the like all the coatings and and so on to have a better."
I hope I was helpful in clarifying a lot of your questions.
Arnav Kumar: Yes, I think this was very productive and helpful and I will share my thesis with you. Thank you!

A.2.3 Interview with Expert 3

Expert 3 is an assistant professor in TU Delft and is working on circular product design. He has a background in rare earth elements and resilience of the rare earth supply chain.

Arnav Kumar: How do you think we can achieve a high collection rate or even start collecting the magnets that are present in the wind turbines and electric vehicles?
E3: The ideal way to do it is by introducing legislation where you make it mandatory to recycle the magnets and then you can achieve a high collection rate relatively easily. Secondly, the price of these magnets are quite high which makes them attractive commodity to collect and recycle.
Wind turbines have a huge amount of these magnets and if they get dismantled then someone in the supply chain will try to get a hold of them and make money off of them. But its more of a question of how you build the wind turbines because if they are not build for recycling then it is very difficult to collect them. Moreover, for wind turbines it is an ownership problem, like who will own the wind turbine and the magnets in 20-30 years (lifetime of wind turbines), which is a theoretical question.

Arnav Kumar: There are a price fluctuations for the rare earth elements and thus for the magnets as well, how do you think we can put an incentive on recycled magnets so they would be demanded by the industry?
E3: There can be incentives given via carbon tax for instance and then the recycled magnets will be lot cheaper than the new magnets because of how much lower the impact of the recycled magnet is on the environment. Or there could be laws in place which say that there should be at least 50% recycled content for example and then you force the market to exist. You can look

into general tax incentives schemes that currently exists because recycling is generally legislated.

Arnav Kumar: Do you think exports of the wind turbines and EV should be monitored if we want to salvage the magnets in them?
E3: Monitoring can be a good idea because then you can make good decisions based on that but at the same time there should not be excessive control on where and how much Neodymium can go to a certain place because firstly it is too complicated to do and secondly it can arrange itself if we have strong policy like a high CO2 tax.

Arnav Kumar: From the perspective of recycling, what kind if information do you think needs to be passed on in the supply chain for efficient collection?
E3: The quantity of the magnets and how to get access to them. So first and foremost, the design of the products should be such that people can have access to it and then you need to have information on how to do it. It needs to be passed on if you have product like wind turbine which have a really long life time of 25 or 30 years. Furthermore, you need to know the grade and composition of the magnets. If there is no information or little information on how to dismantle the wind turbine and get access to the magnets then recycling will be difficult to do.
For electric vehicles, the issue of accessibility becomes more important because there are only a couple of kilograms of magnets present in the motors.

Arnav Kumar: From a stakeholder perspective, what do you think will motivate companies or actors in the supply chain to start collecting and recycling?
E3: There is one incentive only and that is money. If you have well designed products that can be taken apart and recycled easily then it allow people to make money. "The amount of money you can earn is kind of set by the amount of material that's in there". The more difficult it is to access the material, higher will be the costs and costs will lower the profit. So either you need something to reduce the costs or you need legislation which means everyone needs to comply. Moreover, "I think businesses understand they can invest into the future if they see big volume coming down there. So I'm not actually not in not concerned about that either. I think what's concerning is that the EU is investing in maybe the wrong things to say, now we invest in recycling capacity but ten years ago they should have invested in design for recycling, and then you get a huge amount of stuff that you cannot recycle, like that's the real problem here."

Arnav Kumar: I have some specific questions about recycling through HPMS process. Can you tell me something about the cost of recycling through HPMS process?
E3: I have no idea about the cost of HPMS process.

Arnav Kumar: Do you think we can directly reuse these magnets somehow for the wind turbines?
E3: Maybe yes, but in practice probably not because again you need to design the products for recycling and reuse. They need to be "designed in a way that you can take them out without destroying."

Arnav Kumar: When do you think we will have an industrial setup for recycling of the magnets?
E3: People are already working on it and in a couple of years we may have a first industrial scale recycling of the magnets.

Arnav Kumar: Thats all the questions I had for you, thank you for your time. **E3**: Good luck and send me your thesis, I am curious to hear what it is!

A.3 Interview with Motor/generator recycler

The company is an electric motor and generator recycling company in the Netherlands. The company buys end-of-life cables, electric motors, generators, and transformers and dismantles them to extract copper, iron, aluminium and even magnets for motors.

Arnav Kumar: Can you tell me something about the kind of motors you buy and in particular motors of EVs?
S1: We buy a lot of motors and cables and once in a while we also get electric car motors. The EV motors are not always from scrap yard but also from warranty motors which are not working anymore due to some fault. The motor usually has an aluminium housing and then you have the stator which contains copper (nearly 5-15% of the weight of the motor) and then you have rotor made of Steel which have the magnets inserted in them at strange angles.

Arnav Kumar: Do you source these motors from car dismantling companies?
S1: No, the motors are sourced from bigger companies which have good connections with various car dismantling companies, and other industries and then we buy it from them. "At the end, the company which pays the most money for the motors can buy them." Depending on the market we either take them for ourselves or to resell them.

Arnav Kumar: How many EV motors and generators that you get contain permanent magnets in them or are permanent magnet synchronous motors?
S1: We buy nearly 50 tons of electric car motors each year and they all have permanent magnets.

Arnav Kumar: What do you do with the magnets that are present in these motors then?
S1: We take some of them apart, for instance from Wind turbine and then there are traders in London who buy them from us and then they go to Poland. But sometimes the generators from wind turbine can be packed and shipped to third countries where they can be recycled as it is expensive to take them apart because it takes time and the labour cost in the Netherlands is high. Sometimes we split the stator and rotor of the motor and we get different prices for that. However, if we really have to take apart the steel plates in the rotor then it becomes too expensive to do so here in the Netherlands and it will not be competitive. For wind turbine generators, the magnets are really big and heavy and it is not easy to just extract them from the rotor so the rotor is then placed inside an oven where they are heated to 350 degrees Celsius. The magnets then get demagnetised and we can pull the magnets out easily.
The magnets can be really dangerous to work with if you are not care full because if you walk near them with your phone in the pocket or someone with a pacemaker walks near them then it can be very dangerous.
The demagnetised magnets are then bought by some magnet traders here in the Netherlands and they are sent to Poland but I dont know what happens to them once they are in Poland. The traders paid €5000/metric ton for the scrap magnets a few years back but now we get roughly €25000/metric ton for good quality magnets, like the ones in wind turbines.

Arnav Kumar: Ones the generator rotors are placed in the oven, is it easy to take apart the magnets then?
S1:Yes, it is easy to pull them out.

Arnav Kumar: Do the wind turbine generators come from end-of-life wind turbines or wind farms that are dismantled?
S1: The generators come from end-of-life wind turbines and but we mainly get generators that were taken out because they were not working anymore. The faulty wind turbine generators can be really expensive to repair and the wind turbine manufacturer really needs to be sure if the generator of the wind turbine will run for the long time or not.
For EV motors, we generally get motors that are relatively new because they have stamps on them which tell the year of manufacturing and we have seen motors that are from 2018, 2019, also 2021. For Wind turbine I am not aware of the age.

Arnav Kumar: What will motivate your company or others to extract these magnets from the motors and generators? Will the government incentives motivate recyclers?
S1: "I am sure that a lot of companies don't even know about that there are magnets in the products." "We know it because we take them apart, and I am sure a lot of the magnets are being lost in the iron furnaces".
We are a commercial company and in the end if we can make money out of it then we can take them out, keep it and sell them to someone. In the market, it is not so common to get magnets out and it is mainly the old stuff like copper, Iron, aluminium that is being taken out. "I think right now only specialised companies are buying motors with magnets in them".

Arnav Kumar: Apart from magnets, do you know how much copper and Iron is there in the motors and generators, and what is the rotor made off?
S1: There is 5-15% copper, the casing is aluminium and 1-2% is material like sealant and other stuff and the rest is iron. The rotor is made of steel and then you have magnets inside them.
Arnav Kumar: How easy is it to dismantle the motor and take the magnets out?
S1: Yes, its a lot of work. But for bigger motors it is very easy but for small motors it is a lot of work.

Arnav Kumar: Are you the biggest motor and generator recyclers in the Netherlands?
S1: No, there are other companies in the Netherlands gathering these motors and generators but they are mostly separating the Iron, copper and aluminium but not magnets. However, there are very few electric car motors coming in the market. In future, there will also be motors coming from electric bikes and right now people are more interested in getting out the iron, aluminium and copper from it.

Arnav Kumar: Thank you so much for agreeing for the interview on such short notice. This was really helpful. I will send you the thesis report when I am done. **S1**: Good luck!

A.3.1 Response to questionnaire prepared for Wind turbine OEM

1. How does Extended Producer Responsibility work in the case of wind turbines? What components are recovered at the end of life of wind turbines? And does that include Generators of the wind turbine?
   Response: No EPR is present for wind currently. Only battery directive requiring OEMs to take back batteries.

2. Are you and/or other wind turbine manufacturers aware of the issue/opportunity that end-of-life wind turbines (with Permanent magnet synchronous generators) can be a huge source of neodymium magnets?

Response: Yes, we have also recycled several prototype generators.

3. Do you have a plan to collect the neodymium magnets present in wind turbines with Permanent magnet synchronous generators (PMSG)? If not, how will it happen (which actors will be involved, who will pay for collection and recycling, what information will the actors need from you and vice versa)?
   Response: The owner of the generator (our customers) will decide as it is their property.

4. What will motivate you to start the collection of neodymium magnets present in their wind turbines? Can you comment something about the wind industry in general?
   Response:I am sure this will happen, since the magnets have big value. We expect first magnet-containing turbines to be decommissioned from 2035 and on wards.

5. During the sourcing of the magnets, do you know the chemical composition of the NdFeB magnets or is it just the grade of the magnets?
   Response: Both

6. If the chemical composition is known to you, do you think this information can be somehow passed on to the recyclers? If not, then why?
   Response: Yes

7. Do you design your generators for recyclability, and does that include easy retrieval of the magnets? If not, will you do so in the future and what can motivate your company to make their generators more recyclable?
   Response: Yes

8. How much influence will the wind industry have in the collection and recycling of the neodymium magnets present in their wind turbines?
   Response: The owner of the turbine, not the OEM, will decide the collection and recycling route.

9. How accurate is the assumption that a direct drive wind turbine with PMSG contains 650 kg/MW of NdFeB magnets? Does SG know the amount of magnets (in kgs/tons) present in each of their Wind turbines? Can you share this? If not, can you give me a range for direct drive and other drive trains that use PMSG? And is this range similar across all wind turbine manufacturers?
   Response:We know exactly the amount yes, and it is confidential information (for IP considerations), but 650kg/MW is not completely off. The range is similar for NdFeB permanent magnet based direct drive turbines, not geared DFIG machines, which do not rely on NdFeB permanent magnets for the generator design.

A.3.2 Questionnaire for Wind turbine dismantling company

Material Flows and Administrative Questions

1. What kind of transaction takes place between the dismantling company and wind farm owners? Do the wind farm owners sell the wind turbines to you and then they are responsible for its dismantling, recycling or relocation?

2. Why do wind farm owners decide to dismantle the wind turbines?

   (a) How often do they re-sell it before the wind turbine reaches the end of life?

(b) Do wind farm owners write off their wind turbines? If so, then do you know why? Do they get financial benefit? Or they plan to repower the wind farm with smaller number of wind turbines but with larger individual capacity?

3. What happens when the wind turbines need to be dismantled and recycled? What happens to the different components of wind turbine?
   (a) Specifically, what happens to the generator of the wind turbines? Do you dismantle it or it is shipped as a whole? Who dismantles it and recycles it, if it is not you then can you give me the name(s) of the company who is responsible for it?
   (b) If you dismantle the generator of the wind turbine then what happens to individual components? Specifically what happens to the magnets that are present in the generator if any.
   (c) Does any component go back to the wind turbine producer or the Original equipment manufacturer (OEM) . If so, then what are they and do you sell it back or just give it to the OEM?
   (d) Are different companies contacted for recycling different components of wind turbine? And are these recyclers present in the same country as that of the dismantled wind turbine or do you have fixed recycling companies in the EU who take care of it?
   (e) Do you need to submit recycling data to the wind farm owners? Or do the wind farm owners demand a report on what is recycled and how much is recycled?
   (f) What kind of information is required by you and other dismantling companies like you when the wind turbines need to be dismantled for recycling?

Information and Financial Flows

1. What kind of information do you need to give to the recyclers, is any of that information related to the materials used in the wind turbines?
2. Do you get any information related to dismantling from the wind turbine producers and materials ?
3. Do the wind farm owners get money from the wind turbine parts they sell (assuming that the wind turbines are being dismantled for recycling)?
4. How much does dismantling cost? Can you indicate this in '%' of initial investment of wind farm?

Regulatory aspects

1. How does dismantling vary in different countries in the EU? For example, does France have the same or similar rules compared to Netherlands or Germany for wind turbine dismantling?
2. Does dismantling of wind turbine come under construction and demolition waste?

Questions related to future

1. What will be the role of dismantling companies if the EU requires that the neodymium magnets that are present in wind turbines need to be collected and recycled?
2. In the next 20 years, it is expected that there will be huge amounts of magnets that will be coming from end of life wind turbines. What would motivate you to collect the magnets and then dispatch them to the necessary recycling facilities (At present, no such recycling facility for magnets is present but in the coming future this will be setup)?

APPENDIX B

Methodology

B.1 Search Scheme for literature selection

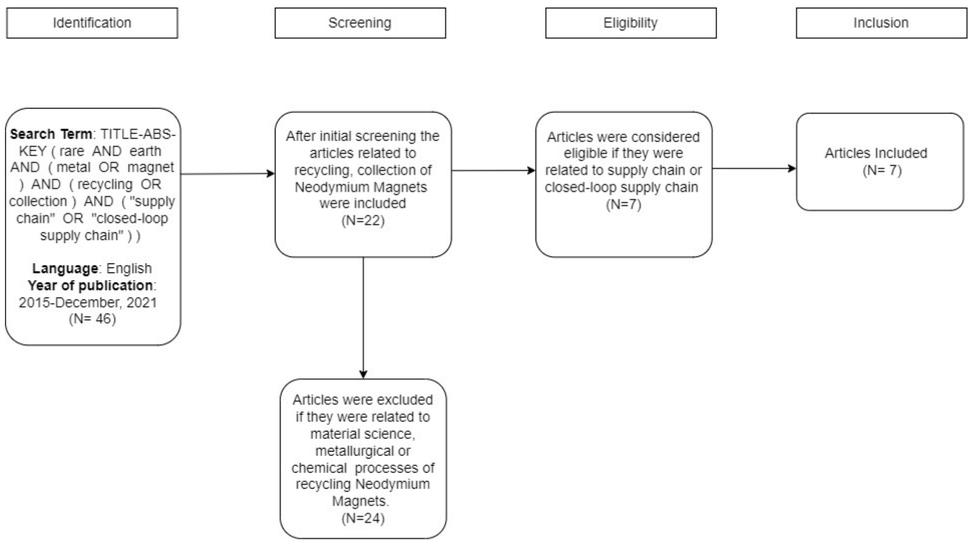


Figure B.1: Literature selection scheme

Table B.1: Overview of Literature

Authors	Theme	Method
Ciacci et al. (2019)	Recycling potential of NdFeB magnets in Europe.	Dynamic Material Flow Analysis
J. Li et al. (2020)	Mismatch in demand from wind turbines and supply of Rare earth elements.	Dynamic Material Flow Analysis
München et al. (2021)	Recycling potential of NdFeB magnets obtained from Hard drives and mobile phones in Brazil.	Quantitative analysis
Bonfante et al. (2021)	Investigates the type of sustainability that is being studied in rare earth magnet supply chain and how the studies contribute to achieve the Sustainable Development Goals (SDGs).	Literature Review
Ferron and Henry (2015)	Highlights the uses of rare earth metals in different products and based on that identifies scrap sources for recycling.	Qualitative analysis
Løvik et al. (2018)	Reviews the ongoing government funded research in the area of critical metals for Europe	Qualitative analysis
Sprecher et al. (2015)	Supply chain resilience framework for NdFeB magnets	System Dynamics Modeling

B.2 Search Scheme for dismantling of wind turbine generator

Table B.2 below presents the search terms that were used to find the literature on dismantling of wind turbine generators. Scopus and Google scholar were used as the databases to find the relevant articles. The search was refined by checking "Review Articles" on Google Scholar and by English on Scopus. After the search results, the titles of the articles were read, if the articles were relevant then the abstract was read to check if the article(s) contain information about dismantling or disassembly of permanent magnet synchronous generator or electric generators in general. However, no articles were shortlisted as none of the articles contained information about the dismantling of the generators.

Table B.2: Search Scheme for finding literature on the dismantling of wind turbine generators.

Search Terms	**Database**	**Number of results**	**Filters**
(disassembly OR dismantling) AND ("electric generator" OR "permanent magnet synchronous generator")	Scopus	20	Articles in English
"material recovery" AND "electric generators"	Scopus	0	Articles in English
"disassembly" AND "permanent magnet synchronous generator"	Google Scholar	4	Articles in English Peer reviewed articles
(dismantling OR disassembly) AND ("permanent magnet synchronous generator") AND "wind turbines"	Google Scholar	8	Articles in English Peer reviewed articles
"material recovery" AND "electric generators"	Google Scholar	5	Articles in English Peer reviewed articles

APPENDIX C

Analysis

C.1 Market Analysis

C.1.1 Additional information about the quantitative model

The tables below show the raw data that was used to derive the graphs present in section 3.4. Data on the registration year, number of BEV and PHEV registered in the particular year were gathered from “Homepage — European Alternative Fuels Observatory” (n.d.) for Germany, Netherlands, Belgium, and France. Based on the assumption about lifetime of EV as 10 years, the ’EOL Year’ was determined. In addition, the amount of magnets in BEV was assumed to be 2.1 Kgs and in PHEV it was assumed to be 1 Kgs.
To calculate the amount of neodymium magnets (in metric tons) present in BEV and PHEV in a particular EOL Year, equation C.1 and C.2 were used.

$$PM\ BEV = \frac{BEV \cdot (\%\, of\, Vehicles\, that\, use\, PM) \cdot 2.1}{1000} \tag{C.1}$$

$$PM\ PHEV = \frac{PHEV \cdot (\%\, of\, Vehicles\, that\, use\, PM) \cdot 1}{1000} \tag{C.2}$$

EV Data

Germany

Registration Year	EOL Year	BEV	PHEV	Sum of BEV and PHEV reaching End of life/1000	PM-BEV	PM-PHEV	Sum of PM	% of vehicles that use PM
2008	2018	0	0	0				
2009	2019	15	0	0.015	0.0189	0	0.02	0.6
2010	2020	144	0	0.144	0.191016	0	0.19	0.631666667
2011	2021	1828	266	2.094	2.546404	0.176446667	2.72	0.663333333
2012	2022	2555	1232	3.787	3.7290225	0.85624	4.59	0.695
2013	2023	5464	1656	7.12	8.338064	1.20336	9.54	0.726666667
2014	2024	8379	4401	12.78	13.3435575	3.337425	16.68	0.758333333
2015	2025	12097	11111	23.208	20.068923	8.77769	28.85	0.79
2016	2026	11243	13383	24.626	18.82921425	10.6729425	29.50	0.79750000
2017	2027	24438	29124	53.562	41.312439	23.44482	64.76	0.80500000
2018	2028	35238	31041	66.279	60.1248375	25.2208125	85.35	0.81250000
2019	2029	61555	44303	105.858	105.99771	36.32846	142.33	0.82000000
2020	2030	191369	199606	390.975	329.537418	163.67692	493.21	0.82000000
2021	2031	351327	322320	673.647	604.985094	264.3024	869.29	0.82000000

Figure C.1: Germany- Raw data for EV (BEV and PHEV)

Netherlands

Registration Year	EOL Year	BEV	PHEV	Sum of BEV and PHEV reaching End of life/1000	PM-BEV	PM-PHEV	Sum of PM	% of vehicles that use PM
2008	2018	0	0	0				
2009	2019	28	2	0.03	0.03528	0.0012	0.04	0.6
2010	2020	86	0	0.086	0.114079	0	0.11	0.631666667
2011	2021	849	15	0.864	1.182657	0.00995	1.19	0.663333333
2012	2022	828	4326	5.154	1.208466	3.00657	4.22	0.695
2013	2023	2441	20164	22.605	3.724966	14.65250667	18.38	0.726666667
2014	2024	2853	12466	15.319	4.5434025	9.453383333	14.00	0.758333333
2015	2025	3168	41280	44.448	5.255712	32.6112	37.87	0.79
2016	2026	4029	18846	22.875	6.74756775	15.029685	21.78	0.7975
2017	2027	8007	1184	9.191	13.5358335	0.95312	14.49	0.805
2018	2028	23938	2829	26.767	40.8442125	2.2985625	43.14	0.8125
2019	2029	61668	4934	66.602	106.192296	4.04588	110.24	0.82
2020	2030	73132	15938	89.07	125.933304	13.06916	139.00	0.82
2021	2031	64420	31083	95.503	110.93124	25.48806	136.42	0.82

Figure C.2: Netherlands- Raw data for EV (BEV and PHEV)

France

Registration Year	EOL Year	BEV	PHEV	Sum of BEV and PHEV reaching End of life/1000	PM-BEV	PM-PHEV	Sum of PM	% of vehicles that use PM
2008	2018	0	0	0				
2009	2019	10	0	0.01	0.0126	0	0.01	0.6
2010	2020	184	0	0.184	0.244076	0	0.24	0.631666667
2011	2021	2630	0	2.63	3.66359	0	3.66	0.663333333
2012	2022	5663	668	6.331	8.2651485	0.46426	8.73	0.695
2013	2023	8779	863	9.642	13.396754	0.627113333	14.02	0.726666667
2014	2024	10560	2070	12.63	16.8168	1.56975	18.39	0.758333333
2015	2025	17268	5518	22.786	28.647612	4.35922	33.01	0.79
2016	2026	21751	7429	29.18	36.42748725	5.9246275	42.35	0.7975
2017	2027	25271	11614	36.885	42.7206255	9.34927	52.07	0.805
2018	2028	30989	14556	45.545	52.87498125	11.82675	64.70	0.8125
2019	2029	42925	18581	61.506	73.91685	15.23642	89.15	0.82
2020	2030	110909	74587	185.496	190.985298	61.16134	252.15	0.82
2021	2031	162107	141394	303.501	279.148254	115.94308	395.09	0.82

Figure C.3: France- Raw data for EV (BEV and PHEV)

Belgium

Registration Year	EOL Year	BEV	PHEV	Sum of BEV and PHEV reaching End of life/1000	PM-BEV	PM-PHEV	Sum of PM	% of vehicles that use PM
2008	2018	0	0	0				
2009	2019	0	0	0	0	0	0.00	0.6
2010	2020	34	0	0.034	0.045101	0	0.05	0.631666667
2011	2021	288	16	0.304	0.401184	0.010613333	0.41	0.663333333
2012	2022	585	326	0.911	0.8538075	0.22657	1.08	0.695
2013	2023	494	319	0.813	0.753844	0.231806667	0.99	0.726666667
2014	2024	1169	852	2.021	1.8616325	0.6461	2.51	0.758333333
2015	2025	1358	2451	3.809	2.252922	1.93629	4.19	0.79
2016	2026	2052	7338	9.39	3.436587	5.852055	9.29	0.7975
2017	2027	2709	11951	14.66	4.5795645	9.620555	14.20	0.805
2018	2028	3728	9750	13.478	6.3609	7.921875	14.28	0.8125
2019	2029	8886	8832	17.718	15.301692	7.24224	22.54	0.82
2020	2030	14996	33001	47.997	25.823112	27.06082	52.88	0.82
2021	2031	21975	48447	70.422	37.84095	39.72654	77.57	0.82

Figure C.4: Belgium- Raw data for EV (BEV and PHEV)

Wind Turbines and type of generators in them The wind turbine models presented below in figure C.5 contains neodymium magnets.

Manufacturer/Turbine Name	Generator
Areva Multibrid M5000	PMSG
Haliade 150-6.0MW (GE Energy)	**PMSG**
Vestas V164-8.0	PMSG
Vestas V164-8.0	**PMSG**
Siemens SWT-6.0-154	PMSG
Areva Multibrid M5000 5.0MW	**PMSG**
Areva Multibrid M5000 5.0MW	PMSG
Siemens SWT-6.0-154	**PMSG**
WinWind-3-100	PMSG
Siemens SWT-6.0-120	**PMSG**
Vestas V112 3.0MW	PMSG
WinWinD-3-100	**PMSG**
WinWinD-3-100	PMSG
Siemens SWT-3.3-130 (onshore?)	**PMSG**
Siemens SWT-6.0-154	PMSG
Samsung 7.0 MW	**PMSG**
AD 5-135 (Adwen)	PMSG
Vestas V164-8.0	**PMSG**
Siemens SWT-6.0-154	PMSG
Vestas V164-8.0	**PMSG**
Vestas V112-3.0MW	PMSG
Siemens SWT-7.0-154	**PMSG**
GE Energy Haliade 150	PMSG
Siemens SWT-7.0-154	**PMSG**
Siemens SWT-6.0-154	PMSG

Figure C.5: Wind turbine with PMSG

The wind turbine models presented in figure C.6 have generators that do not use neodymium magnets.

Manufacturer/Turbine Name	Generator
Enercon E112 4.5MW	EESG
Nordex N90/2500	DFIG
BARD 5.0MW	DFIG
REpower 5M	DFIG
Siemens SWT-2.3-93	SCIG
Siemens SWT-3.6-120	DFIG
GE3.6s	DFIG
Siemens SWT 3.6-120	DFIG
BARD 5.0MW	DFIG
Vestas V90-3MW	DFIG
REpower 5M	DFIG
Vestas V90-3MW	DFIG
Vestas V112-3.3MW	SCIG
Vestas V66-2MW	DFIG
Siemens SWT-3.6-120	DFIG
Siemens SWT-4.0-120	SCIG
Siemens SWT-3.6-120	DFIG
Siemens SWT 3.6-107	SCIG
Siemens SWT-3.6-120	DFIG
Siemens SWT-3.6-120	DFIG
Vestas V90-3MW	DFIG
Siemens SWT-3.6-120	DFIG
Senvion 6.2(6.15)M126	DFIG
Vestas V90-3MW	DFIG
Nordex N90 2.3MW	DFIG
Siemens SWT-2.3-82	PSCIG
Siemens SWT-4.0-130	SCIG
Senvion 6.2M(6.15)126	DFIG
Senvion 6.2(6.15)M126	DFIG
Siemens SWT-3.6-107	SCIG
Siemens SWP-3.6-107	SCIG
Siemens SWT-3.6 107	SCIG
Siemens SWT-4.0-130	SCIG
Vestas V80-2MW	DFIG
Siemens SWT 2.3-93	SCIG
Siemens SWT-3.6-107	SCIG
Vestas V90-3MW	DFIG
Siemens SWT 2.3-93	SCIG
Siemens SWT-3.6-120	DFIG
Siemens SWT-3.6-120	DFIG
Siemens SWT-3.6-107	SCIG
Bonus B76-2MW	PSCIG
Vestas V80-2MW	DFIG
REpower 5 MW	DFIG
Siemens SWT-4.0-130	SCIG
Vestas V80-2MW	DFIG
Siemens SWP 3.6-107	SCIG
Vestas V90-3MW	DFIG
Siemens SWT-2.3-82	PSCIG
Siemens SWT-2.3-93	SCIG
Siemens SWT-2.3-93	PSCIG
Vestas V80-2MW	DFIG
Siemens SWT-2.3-82	PSCIG
Vestas V80-2MW	DFIG
Siemens SWT-3.6-107	SCIG
Vestas V90-3MW	DFIG
Siemens SWT-2.3-93	SCIG
Vestas V90-3MW	DFIG
REpower 5 MW	DFIG
Senvion 6.15MW	DFIG
Senvion 6.15MW	DFIG
Enron EW70-1.5MW	DFIG
Siemens SWP 3.6-107	SCIG
Siemens SWP 3.6-120	DFIG
Siemens SWP 3.6-120	DFIG
NEG Micon NM72-2MW	PSCIG

Figure C.6: Wind turbines with no magnets

C.1.2 Results of EVs

C.1.3 Results-EVs

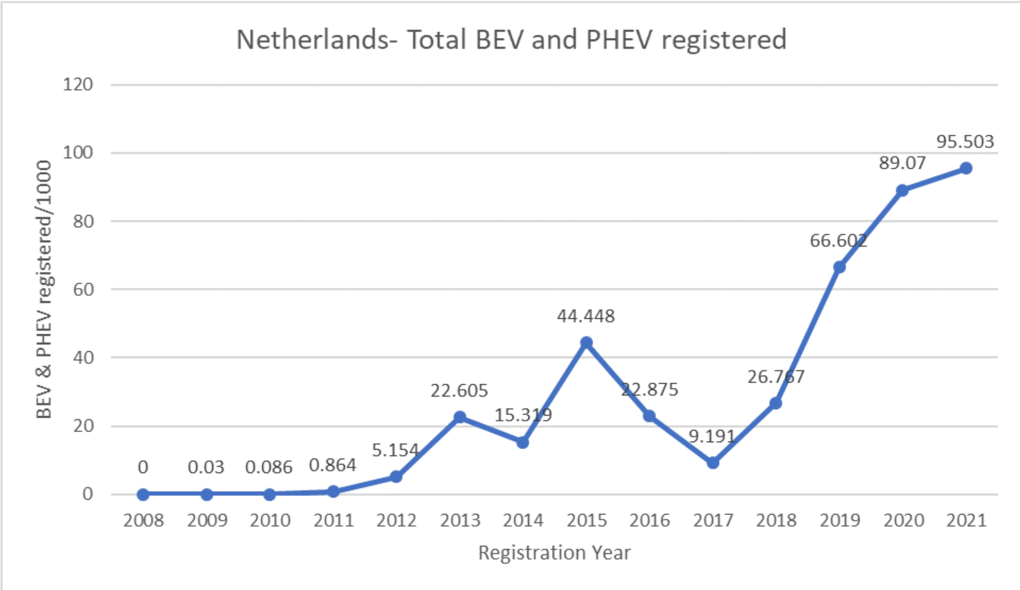
The graphs presented below are a result of the calculation done on the basis of data gathered (shown in table 3.2) and the assumptions taken for EVs. The graphs show the amount of neodymium magnets that may be available from EoL EVs (BEVs and PHEVs) in the Netherlands, Belgium, France, and Germany. Two graphs are presented per country:

1. The graphs on top shows the number of BEVs and PHEVs that have been registered from 2008 till 2021 in each of these countries.
   The x-axis shows the registration year of the BEVs and PHEVs, and the y-axis shows the number of registrations in each year divided by thousand.

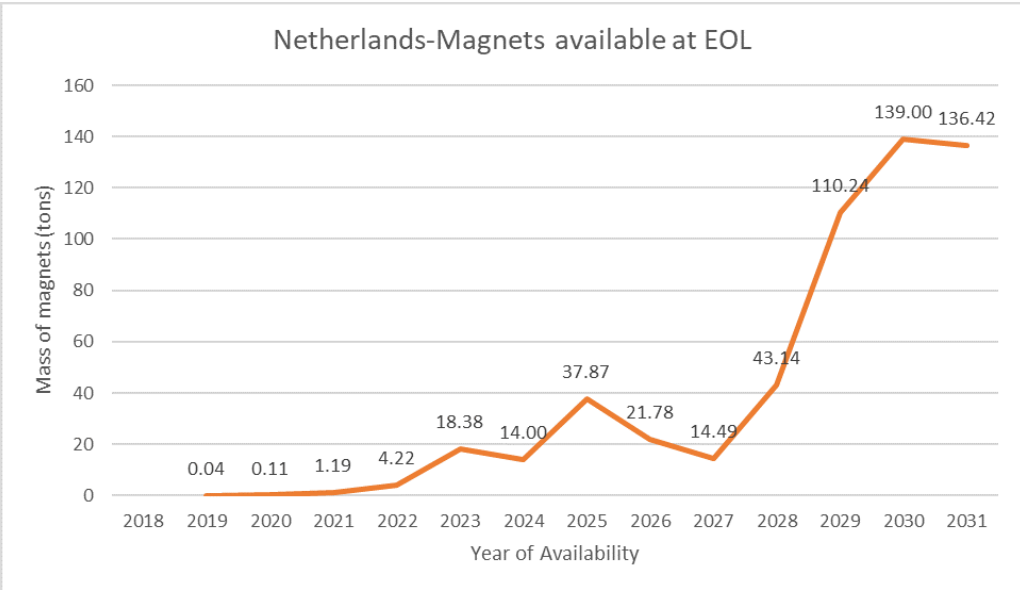
2. The graphs on the bottom present the mass of neodymium magnets that may be available each year for collection once the BEVs and PHEVs have reached their EoL.
   The x-axis shows the year of availability of the magnets and the y-axis shows the mass of magnets (in tons) in each year.

Since the number of assumptions taken for calculating the amount of neodymium magnets is only a few, and the graphs for each country are relatively easy to understand. Therefore, a common explanation is given in the end.

Netherlands



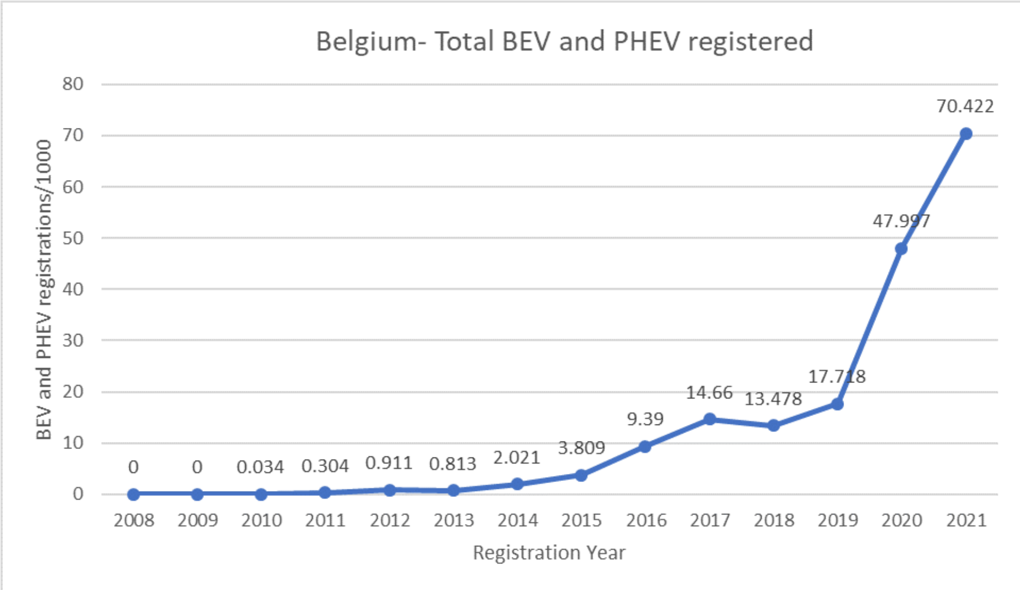
(a) Total BEV and PHEV registrations in the Netherlands



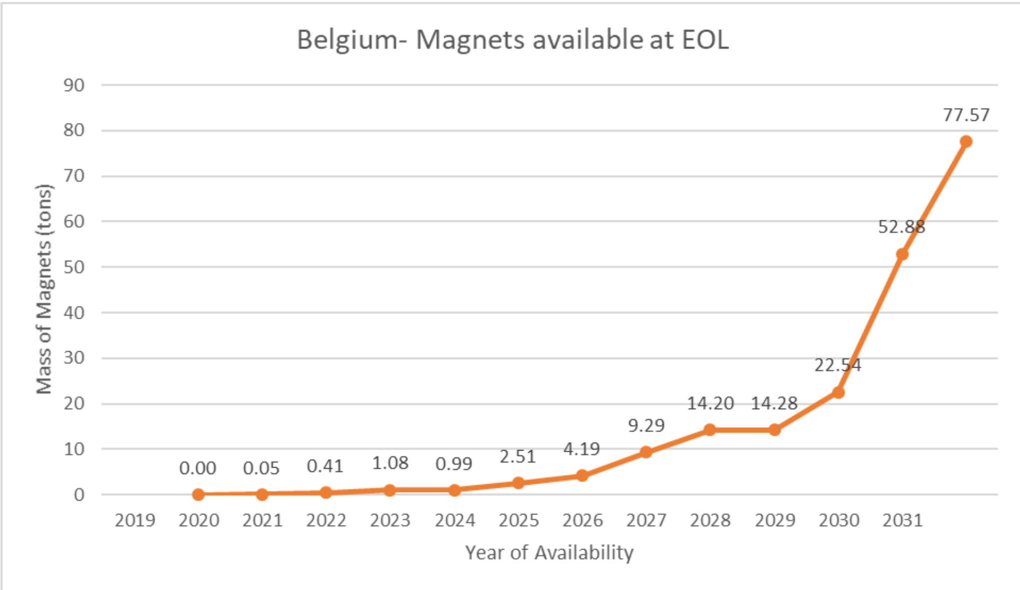
(b) Mass of magnets available for reuse/recycling from EVs in the Netherlands

Figure C.7: EV registrations and corresponding mass of magnets available at EoL in the Netherlands

Belgium



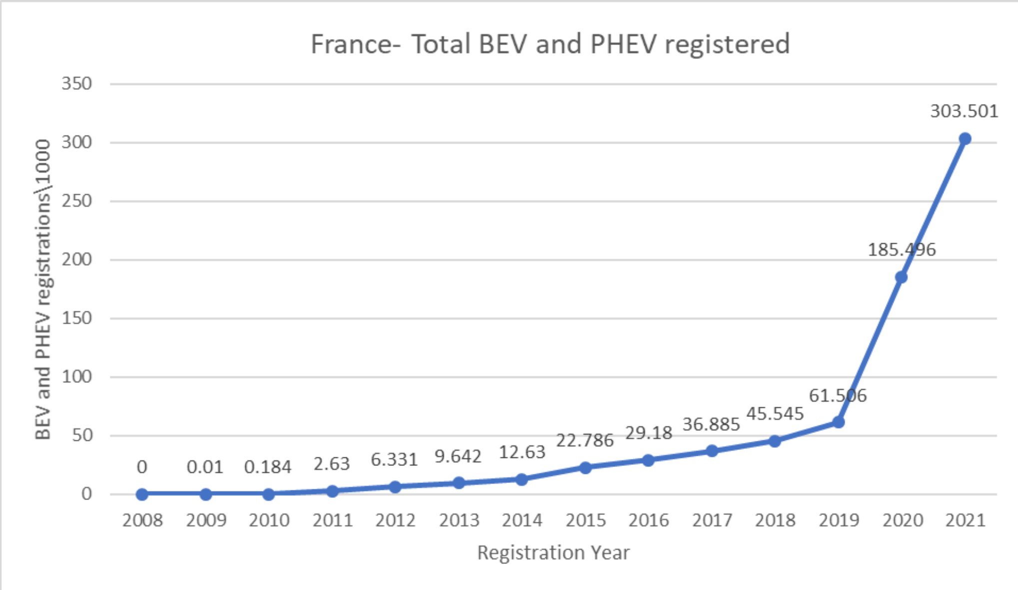
(a) Total BEV and PHEV registrations in Belgium



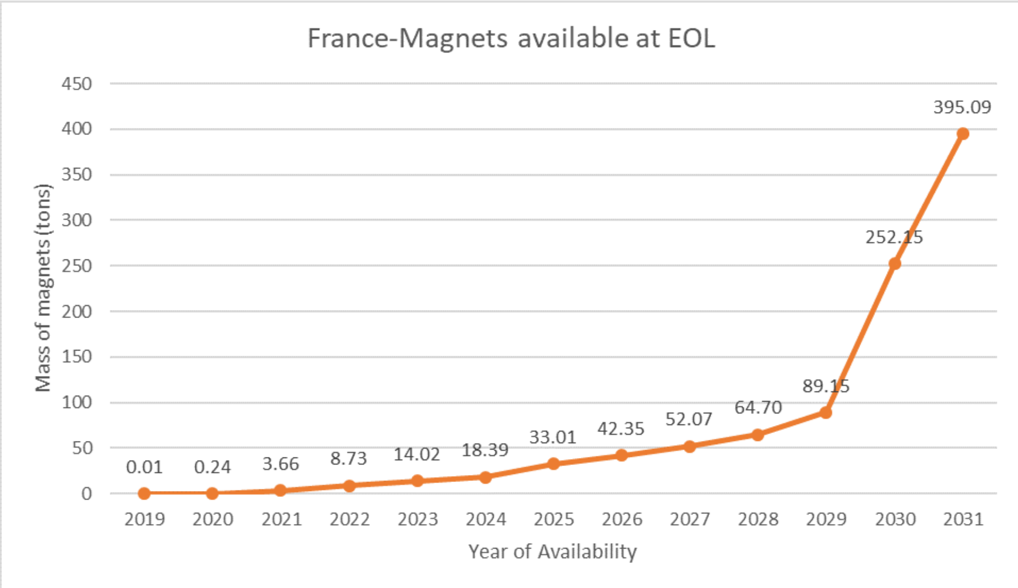
(b) Mass of magnets available for reuse/recycling from EVs in Belgium

Figure C.8: EV registrations and corresponding mass of magnets available at EoL in Belgium

France



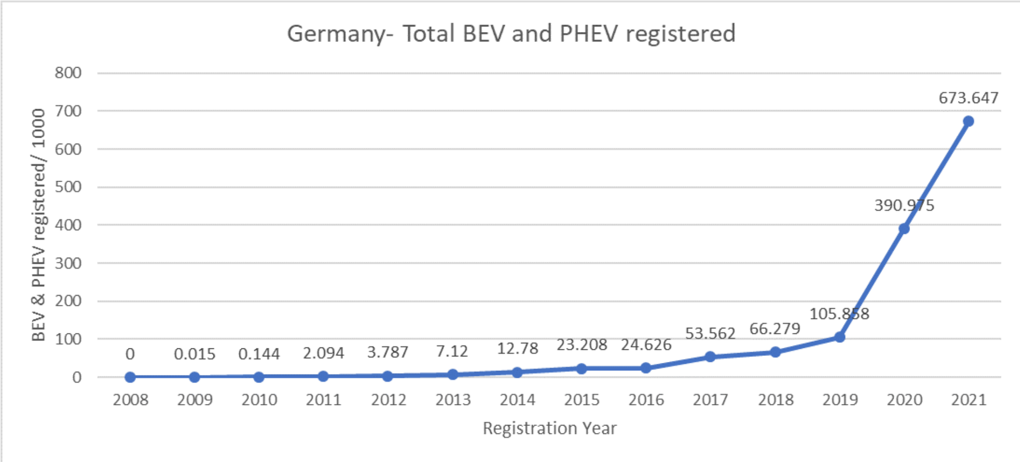
(a) Total BEV and PHEV registrations in France



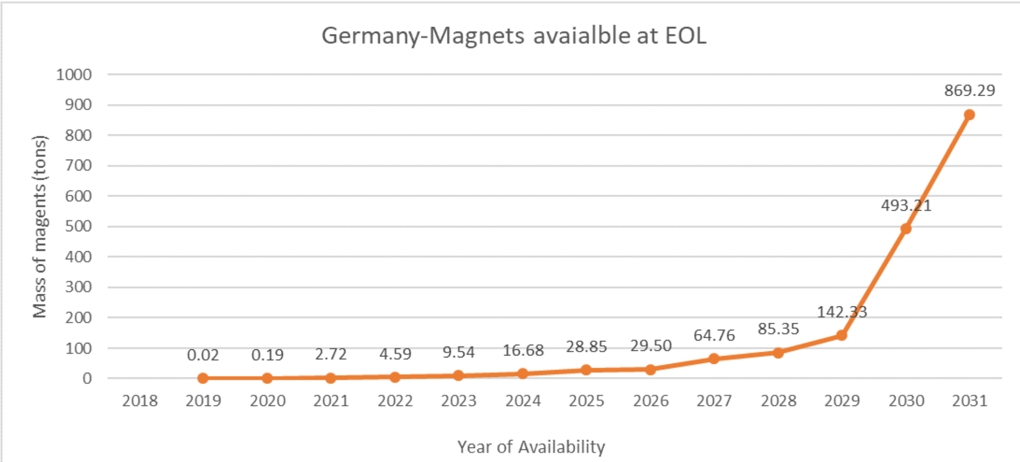
(b) Mass of magnets available for reuse/recycling from EVs in France

Figure C.9: EV registrations and corresponding mass of magnets available at EoL in France

Germany



(a) Total BEV and PHEV registrations in Germany



(b) Mass of magnets available for reuse/recycling from EVs in the Germany

Figure C.10: EV registrations and corresponding mass of magnets available at EoL in Germany

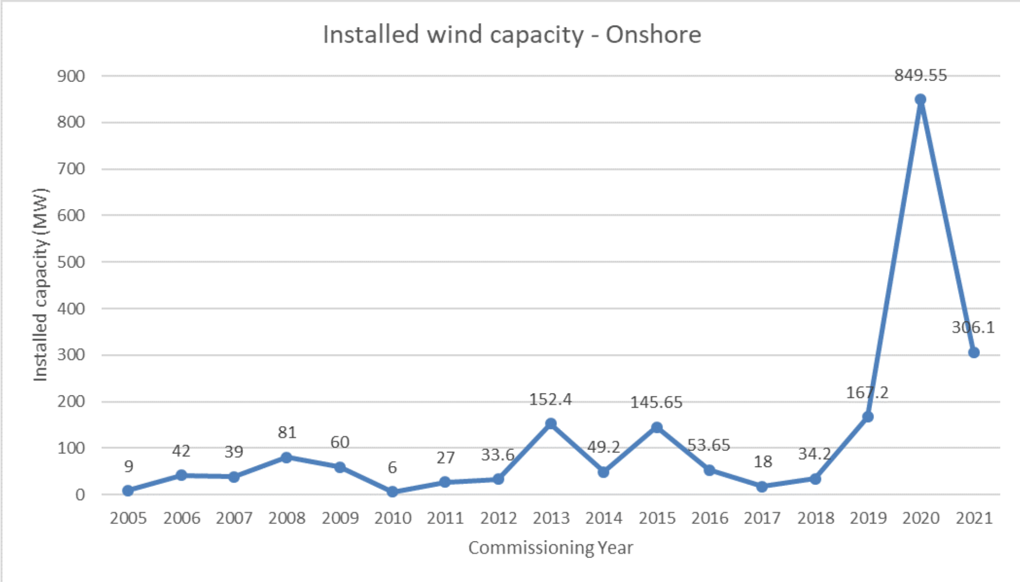
It can be seen from all the graphs (C.7, C.8, C.9, and C.10) that there is a common trend of increasing number of EVs being registered in all four countries. The increasing trend may be explained by the fact that more consumers in all these countries are buying EVs at an increasing rate which may be a consequence of the incentives that the governments in all these four countries are providing for EVs ("Belgian government pushes electrification of company cars", 2021; "France extends EV incentives until July 2022 — Automotive News Europe", 2021; "German EV subsidies more than doubled in 2021", 2022; "The Netherlands reaches impressive 69% all-electric market share", 2021). As a consequence of the increasing number of EVs in these countries and in general in the EU, the amount of neodymium magnets in-stock in these EVs is increasing which may go to waste at the EoL of the EVs if the magnets are not collected for re-use or recycling.

Out of the four countries, Germany has the highest amount of neodymium magnets stock in the EVs, followed by France, the Netherlands, and finally Belgium. This can be explained by the fact that Germany and France are the bigger and have more population compared to the Netherlands and Belgium ("European Countries by Population (2022) ", n.d.; "Largest Countries in Europe 2022", n.d.). Furthermore, it can be seen that in Germany (figure C.10b), France (figure C.9b) and the Netherlands (figure C.7b), the amount of neodymium magnets available for collection starts to increase from 2022, and for Belgium (figure C.8b) it starts to increase from 2025. This indicates that the effort to collect these magnets should have already started, but that is not the case. Furthermore, the amount of magnets available for collection will start to increase exponentially from 2029 in Germany, France, and Belgium, and from 2027 in Netherlands. This suggests that there should be sufficient collection and recycling capacity by then to salvage the magnets.

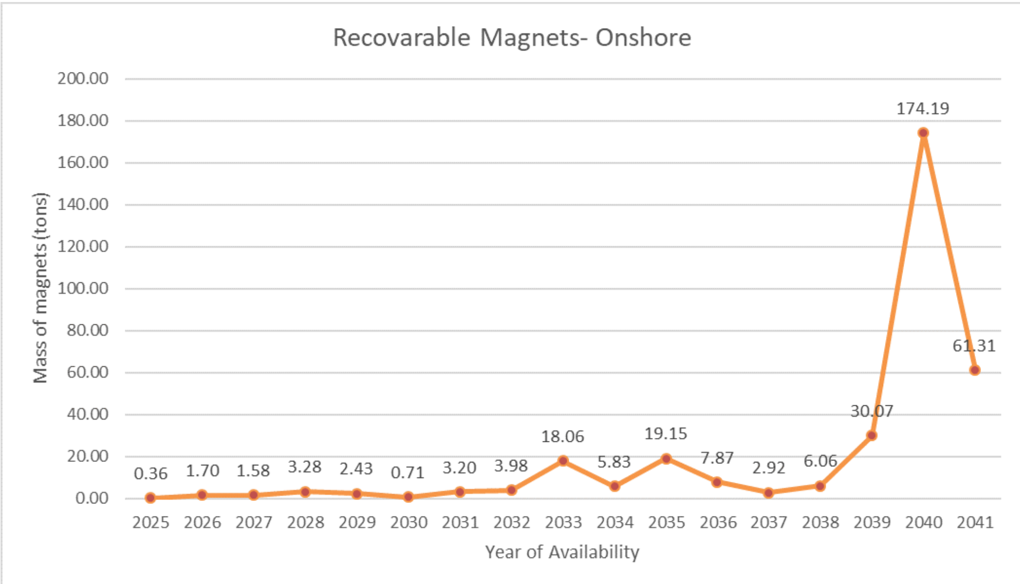
On the basis of the assumption taken to quantify the amount of neodymium magnets that may become available for collection and recycling from EoL EVs, it can be observed that very small amounts of magnets have already entered the waste stream from 2019 in all four countries. This is confirmed by the fact that the motor/generator recyclers have already started to get the PM motors from EVs in their facility for recycling (Motor/generator recycler, A.3).

C.1.4 Results- Wind turbines

Netherlands-Onshore



(a) Total onshore capacity installed in the Netherlands



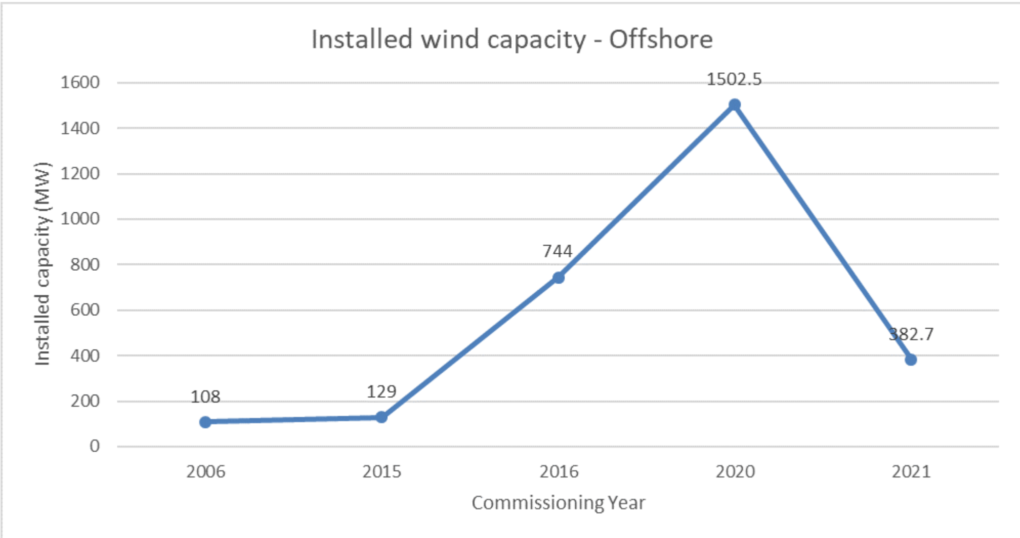
(b) Quantity of magnets available for reuse/recycling from onshore wind turbines in the Netherlands

Figure C.11: Installed capacity and magnets available for recycling from onshore wind turbine in the Netherlands

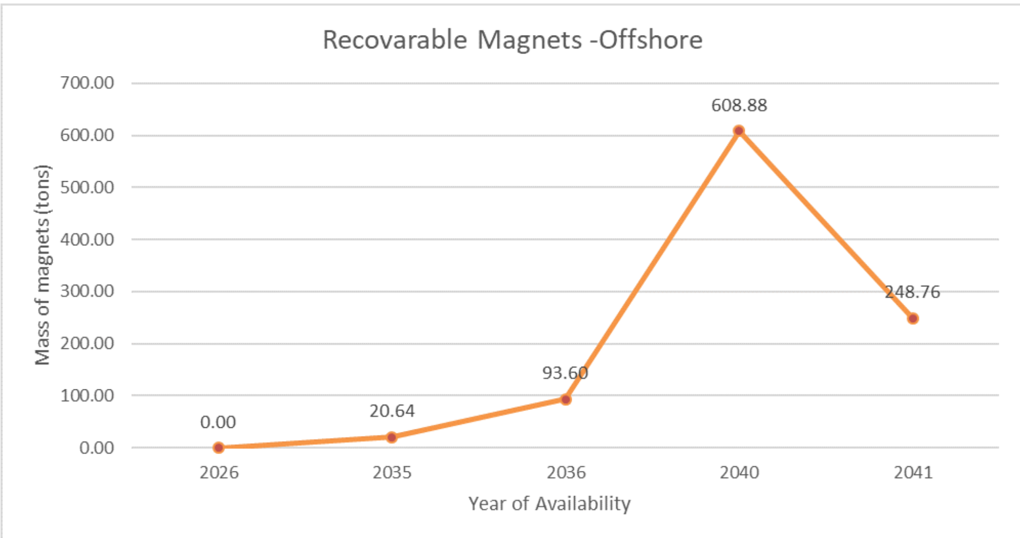
The total onshore capacity in the Netherlands from 2005 till 2021 is 2696.37 MW. However, the graph C.11a shows the capacity that comes from wind turbines that are greater than or equal to 3MW in capacity. This is according to the assumptions 3 and 4 that has been taken for calculating the amount of neodymium magnets that are present in the onshore wind turbines. The x-axis represents the year in which the onshore wind turbines were commissioned and the y-axis shows the capacity that was installed in the corresponding commissioning year. Graph C.11b shows the amount of neodymium magnets that will be available at the EoL of onshore wind turbines. The x-axis shown in the graph shows the year in which the magnets will be

available for collection and subsequently re-use or recycling. The 'Year of Availability' is based on the assumption that the lifetime of wind turbines is 20 years (assumption 1). The y-axis in graph C.11b shows the mass of the magnets (in tons) that will be available from the wind turbines that have reached their EoL.
By comparing the graphs C.11a and C.11b, it can be seen that the amount of magnets available at the EoL is proportional to the wind capacity installed. For instance, in graph C.11a it can be seen that in the year 2013 a total of 152.4 MW of onshore wind capacity was installed and in graph C.11b it can be seen that after 20 years, in 2033, 18.06 tons of magnets will be available for re-use or recycling from the 152.4 MW of wind capacity that was installed. However, it should be noted that the magnets are only available from 22% (17% from Direct Drive wind turbines and 5% from Medium Speed Wind turbines) of the wind capacity of 152.4 MW, this is based on the assumption 8.

Netherlands-Offshore



(a) Total offshore capacity installed in the Netherlands

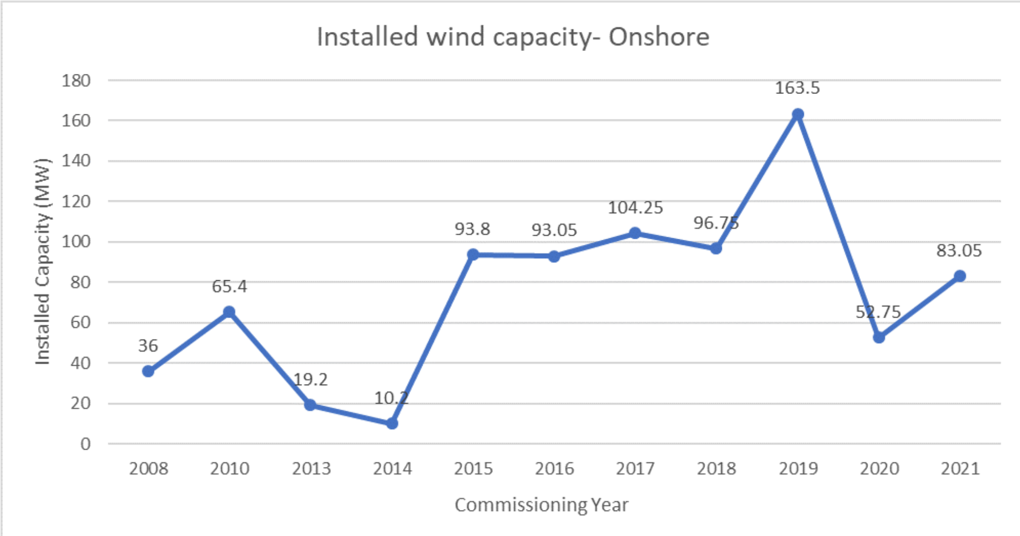


(b) Quantity of magnets available for reuse/recycling from offshore wind turbines in the Netherlands

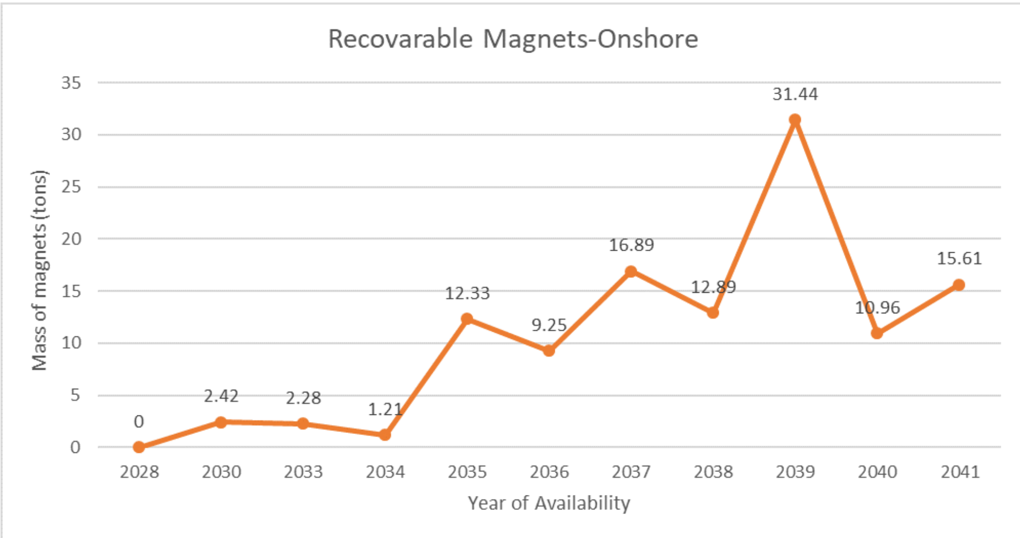
Figure C.12: Installed capacity and quantity of magnets available for recycling from offshore wind turbine in the Netherlands

The total offshore wind capacity in the Netherlands from 2006 till 2021 is 3003 MW. However, the graph C.12a shows the wind capacity from the turbines that are greater than 3MW in capacity. This done to be in line with the assumption 5 that has been taken for calculating the amount of neodymium magnets that are present in the wind turbines. It can be seen that the installation is not as uniform as onshore capacity since offshore wind capacity installation takes much more planning and finance ("Offshore Wind Farm vs Onshore Wind Farm: the Advantages", n.d.). Which can be explained by the fact that the installing offshore wind is more complicated than installing wind turbines in the sea. This implies that the magnets present in these wind turbines will also be available sporadically. By comparing both graphs C.12a and C.12b it can be seen that the amount of magnets available for collection is proportional to the capacity that is installed. However, on a careful inspection it can be seen that in graph C.12a in 2006 the installed wind capacity is 108 MW but the amount of magnets available from that capacity is 0 in 2026 in graph C.12b. This can be explained by the fact that the type of wind turbine installed in 2006 did not use PMSG (since the data of offshore wind turbines was smaller, the exact model and type of generator was determined), thus no neodymium magnets will be available at their EoL. A list of wind turbine types and specific information about the type of generator and drive train present in them can be found in the Appendix C.1.1.

Belgium-Onshore



(a) Total onshore capacity installed in Belgium

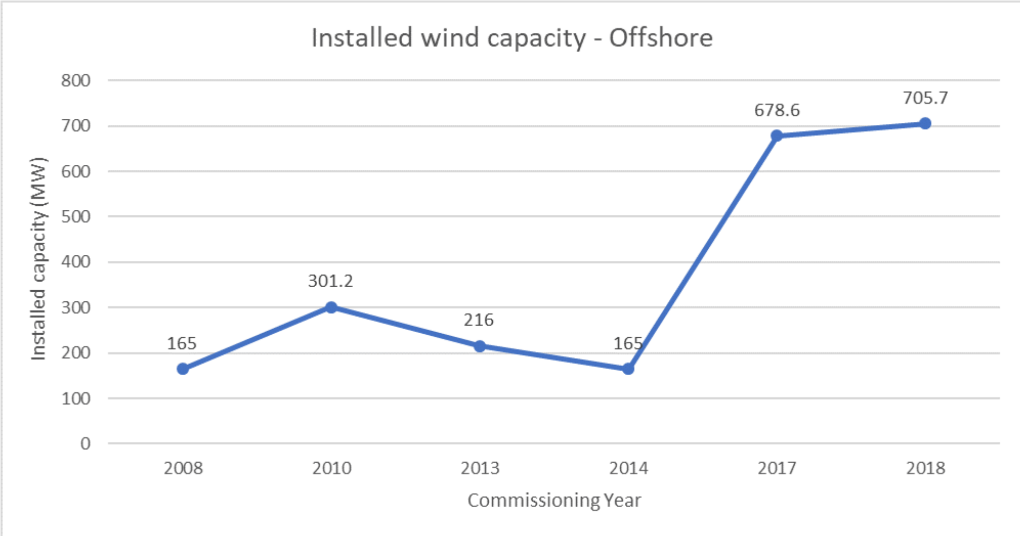


(b) Quantity of magnets available for reuse/recycling from onshore wind turbines in Belgium

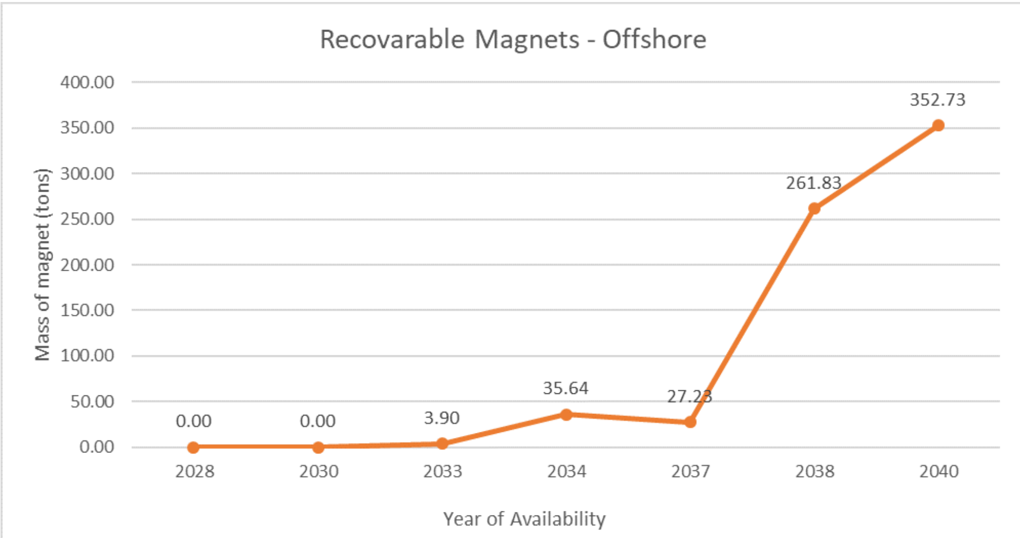
Figure C.13: Installed capacity and quantity of magnets available for recycling from onshore wind turbines in Belgium

The total onshore wind capacity from 2005 till 2021 in Belgium is 2857.5 MW. However, the graph C.13a starts from 2008, this is due to the fact that each of the onshore wind turbines installed in Belgium in the period of 2005 to 2007 were smaller than 3 MW and were assumed to have no PMSGs thus containing no neodymium magnets (assumption 5). Like previous graphs, graphs C.13a and C.13b also exhibit similar pattern to each other. However, the anomaly here is that corresponding to the wind capacity installed in 2008 (in graph C.13a) no magnets are available in 2028 (in graph C.13b) from that installed capacity. This can be explained by the fact that the installed wind turbines were manufactured by Enercon which do not use PMSG in their wind turbines thus no neodymium magnets can be collected from those wind turbines (assumption 7).

Belgium- Offshore



(a) Total offshore capacity installed in Belgium

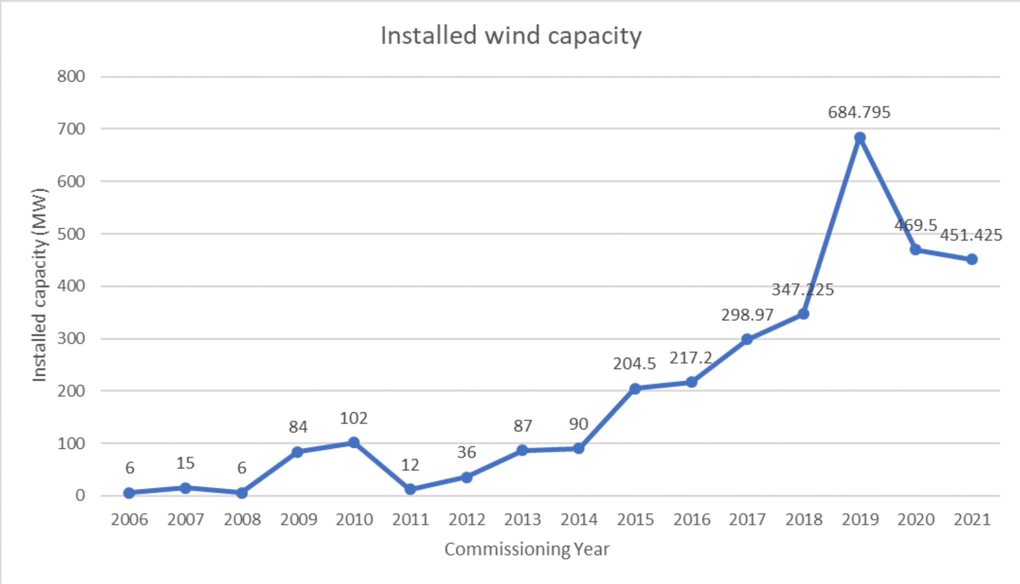


(b) Quantity of magnets available for reuse/recycling from offshore wind turbines in Belgium

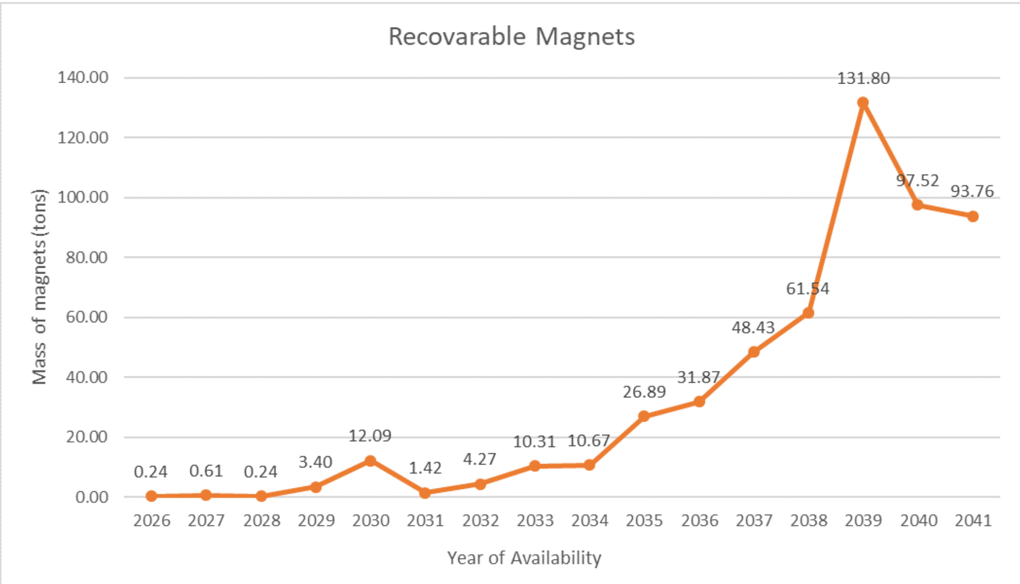
Figure C.14: Installed capacity and quantity of magnets available for recycling from offshore wind turbines in Belgium

The total offshore wind capacity of Belgium is 2696.37 MW from 2005 till 2021. The graph C.14a shows the wind capacity that comes from wind turbines that are 3MW or higher. For the years, 2008 and 2010, it can be noticed that there is 165 MW and 301.2 MW of installed capacity, respectively. However, the corresponding amount of neodymium magnets is 0 in graph C.14b, this is due to the fact that the wind turbines installed in these two years did not use PMSG and thus contain no neodymium magnets (C.1.1). From 2014, the trend in both the graphs C.14a and C.14b are proportional. However, one thing to notice here is that the wind capacity installed in 2018 compared to 2017 is not considerably higher but the mass of the magnets that can be potentially recovered is considerably more. This can be explained by the fact that in 2018, more wind turbines with Direct Drive drive train were installed which use much more neodymium magnets (3).

France- Onshore



(a) Total onshore capacity installed in France

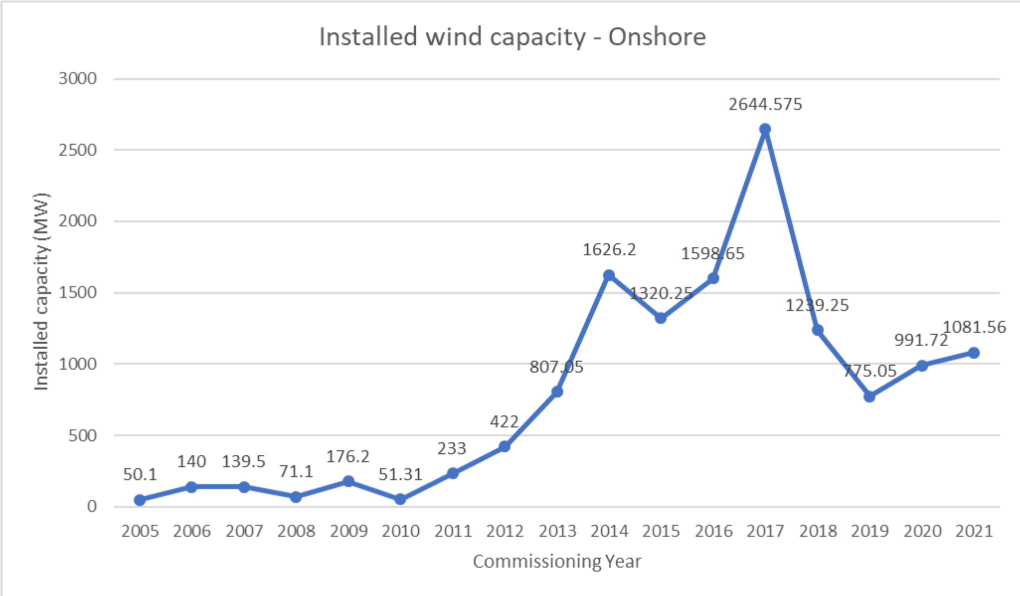


(b) Quantity of magnets available for reuse/recycling from onshore wind turbines in France

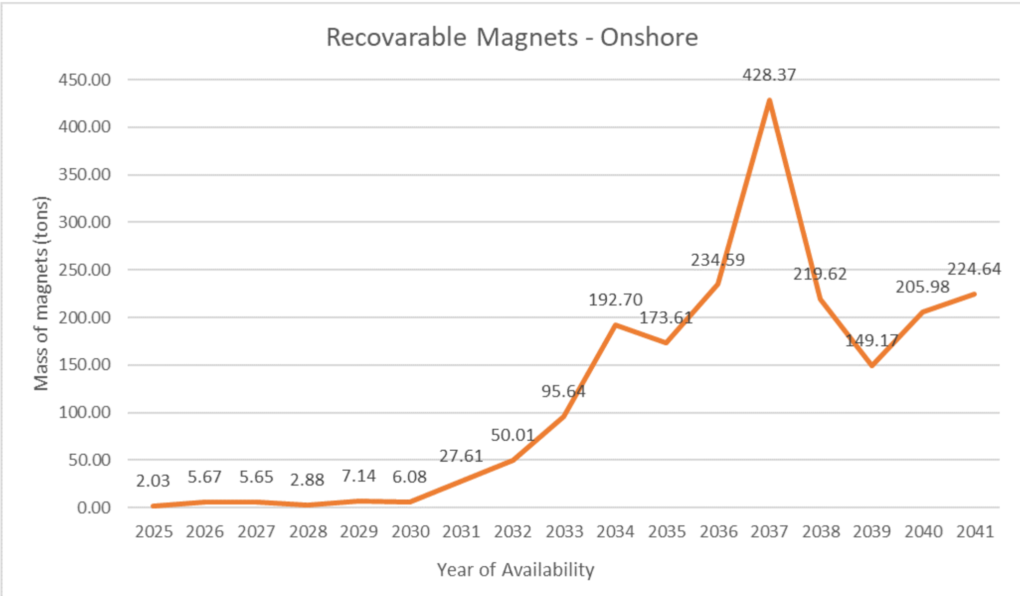
Figure C.15: Installed capacity and quantity of magnets available for recycling from onshore wind turbines in France

The total onshore capacity in France from the period of 2005 till 2021 is 12811.17 MW. France does not have any offshore capacity till now, however, offshore wind farms have been planned and are under construction (Komusanac et al., 2022). Out of 12811.17 MW of wind capacity only 3123.615 MW of the capacity comes from Wind turbines that are equal to or higher than 3MW, this can be seen in the graph C.15a. Corresponding to the installed capacity, the neodymium magnets that can be recovered 20 years later can be seen in graph C.15b.

Germany- Onshore



(a) Total onshore capacity installed in Germany

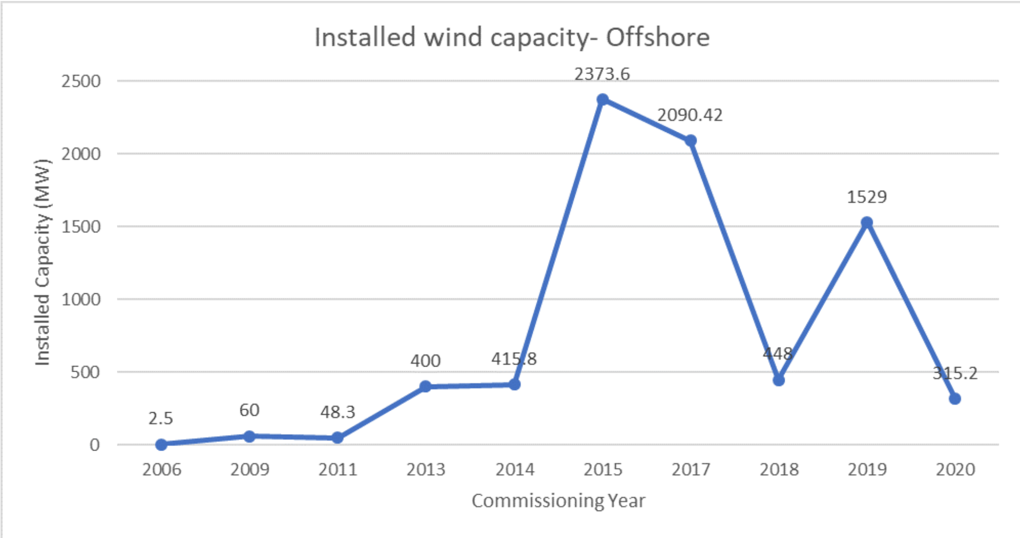


(b) Quantity of magnets available for reuse/recycling from onshore wind turbines in Germany

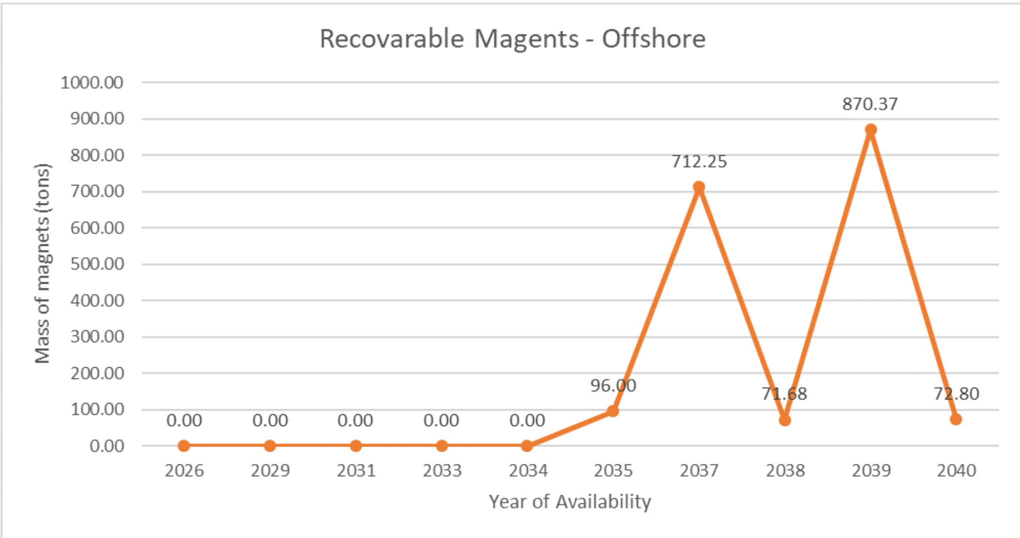
Figure C.16: Installed capacity and quantity of magnets available for recycling from onshore wind turbines in Germany

Germany has a total onshore wind capacity of 42,101.39 MW from 2005 till 2021. Out of 42,101.39 MW only 13367.515 MW (represented in the graph C.16a) of capacity comes from wind turbines that are greater than or equal to 3MW in capacity. By comparing the two graphs (C.16a and C.16b) it can be observed that the trend of mass of magnets that can be recovered from these wind turbines follows a similar trend as shown in graph C.16a.

Germany- Offshore



(a) Total offshore capacity installed in Germany



(b) Quantity of magnets available for reuse/recycling from offshore wind turbines in Germany

Figure C.17: Installed capacity and quantity of magnets available for recycling from offshore wind turbines in Germany

The total offshore wind capacity in Germany is 7682.82 MW for the period of 2006-2021. All the wind turbines in offshore farms in Germany have individual capacity of 3MW or higher, this is represented by the graph C.17a. Corresponding to graph C.17a, graph C.17b shows the amount of neodymium magnets that can be recovered from the wind turbines. It can be observed that from the period of 2026 to 2034, no neodymium magnets can be recovered, this is because the wind turbines that were installed in the period of 2006 to 2014 either were from Enercon GmbH or did not use PMSG and thus do not have any neodymium magnets that can be collected.

On the basis of the assumptions, it can be observed that some amount of neodymium magnets present in onshore wind turbines will be available for reuse/recycling starting from 2025 in all four countries, while a significant amount of the magnets will be available from the year 2033 in the Netherlands, 2035 in Belgium, 2032 in France, and 2031 in Germany.
The maximum amount of magnets being available for re-use/recycling will be between the year

2037 to 2041 for all four countries. This is due to increasing amount of wind capacity being installed in all four countries around 2017 to 2020. The amount of neodymium magnets that will be available for re-use/recycling from offshore wind turbines will be available from the year 2035 in the Netherlands and Germany, and from 2033 in Belgium. No magnets will be available from offshore wind turbines in France till the year 2041 since France does not have any installed offshore wind capacity till now. The maximum amount of magnets that will be available for re-use/ recycling will be from the year 2037 in Germany and from 2038 in Belgium and from 2040 in the Netherlands.

C.2 Analysis of reuse and recyclability of neodymium magnets

C.2.1 Horizon 2020 Projects- Neodymium magnets

The project EREAN(European Rare Earth (Magnet) Recycling Network) started in the year 2013 and ended in 2017, the aim of the project was to research the development of efficiently extracting rare earth metals from electronic waste, experiment with different methods of making rare earth concentrates, look into separation techniques, and prepare new magnets ("EREAN - European Rare Earth (Magnet) Recycling Network - a FP7 Marie-Curie Initial Training Network", n.d.). Two routes of recycling were studied , direct and indirect recycling. The researchers were able to develop a process through which more than 95% of the Neodymium magnets in the automotive assemblies was extracted with the help of hydrogen gas. The use of hydrogen gas on the neodymium magnets demagnetized the magnets and turn them into powder. The powder was then used to produce a new magnet with similar magnetic properties compared to neodymium magnet made from virgin materials. This method of recycling is called as direct recycling and is suitable for magnets that are bigger in size and have not oxidised. (ALL Paraphrased through the CORDIS page of EREAN) On the contrary, indirect recycling is seen as an ideal method for all other types of neodymium magnets where the REEs are extracted through the process of hydrometallurgy or pyrometallurgy. Then the REEs were turned into rare earth oxides and then finally to magnet alloys. Another project related to recycling of rare earth magnets was DEMETER which started in 2015 and ended in 2019. The aim of this project was to recover large neodymium and samarium magnets from automotive assemblies by developing "eco-efficient" direct and indirect recycling routes and ultimately making new magnets through innovative processes (https://etn-demeter.eu/project/). Similar to EREAN, DEMETER used hydrogen gas to extract the neodymium magnets, they also explored the use of ammonium-based ionic liquids to extract the magnets (report from CORDIS). Furthermore, the researchers also developed an EV motor that contained recycled neodymium magnet which can be easily slid out at the end of life of the motor.

C.2.2 Recycling techniques for Neodymium magnets

1. **Organic Solvent Separation technique** The most commonly used method to separate the REEs present in the neodymium magnets is by the use of organic solvents but that results in flammability, toxicity and volatility thus making the process environmentally unfriendly (Riaño and Binnemans, 2015) .

2. **Ionic Liquid Separation technique** Another recycling technique is to use ionic liquid to separate the REEs which then are converted into REOs which are required to form the neodymium magnets. Ionic liquids are known for their thermal and chemical stability, high conductivity, low flammability and low vapor pressure and thus are called environmentally friendly solvents (Riaño and Binnemans, 2015). In order to extract the REEs (Neodymium and Dysprosium) from the magnets. First, the iron is separated from the

magnets by reacting nitric acid with the magnets. Then, cobalt is separated from the magnets with the help of ionic liquid called trihexyl(tetradecyl)phosphonium chloride. Later, neodymium and dysprosium are separated using EDTA (ethylenediaminetetraacetic acid) in the presence of same ionic liquid (Riaño and Binnemans, 2015). During the entire process various separation techniques like time, temperature, and shaking were used optimally. The process allows for removal of three elements which are precipitated with oxalic acid and then subject to thermal treatment to remove any moisture, this results in three oxides- neodymium oxide (purity- 99.6%), Dysprosium oxide(purity- 99.8%) and Cobalt Oxide (purity- 99.8%) (Riaño and Binnemans, 2015).

More about EOL Vehicle Directive.
"Directive 2000/53/EC on end-of-life vehicles (ELVs) focuses mainly on the prevention of waste from used vehicles as well as on its recovery, and aims at the limitation of the use of hazardous substances in vehicles and the reduction of such use as soon as possible "so as in particular to prevent their release into the environment, make recycling easier and avoid the need to dispose of hazardous waste".Footnote25 In this context, the collection of end-of-life vehicles must be ensured by economic operators, which inter alia include for the purposes of the Directive producers, distributors as well as "other treatment operators of ELVs" (Art. 2.10). These **economic operators** must set up systems for the collection of all end-of-life vehicles, their transfer towards collection facilities adequately available within a Member State's territory and then to an authorised treatment facility (Art. 5). According to Article 5 of this Directive, the delivery of end-of-life vehicles to such authorised facilities must occur without any cost for the last holder and/or owner and it is, therefore, for the producer to bear such costs or, alternatively, to take the end-of-life vehicles back directly. This was explicitly confirmed by Court of Justice case law,Footnote26 highlighting the fact that this would act as an incentive to producers to prevent or limit the production of waste as early as at the design phase or else to minimise the costs of reuse and recovery by improving the recyclability of their vehicles.Footnote27" (Pouikli, 2020)

How is a producer defined in EPR?
"The Directive text states that "in relation to packaging 'economic operator' shall mean suppliers of packaging materials, packaging producers and converters, fillers and users, importers, traders and distributors, authorities and statutory organizations". Member states have been given some flexibility in defining which of the economic operators should be obliged to take part in collection and recovery systems for packaging, and, considerable flexibility in how they implement the provisions of the Directive, resulting in some countries introducing policies and instruments, such as packaging taxes and advance disposal fees which exceed the Directive baseline requirements"- Waste Packaging (Cahill et al., n.d.)

C.3 Stakeholder Analysis

Individual goals and measures for Germany, France, the Netherlands, and Belgium are discussed below with relation to neodymium magnet collection and recycling of rare earth elements.

Germany
Germany's announced its first raw material strategy in 2010, the latest revision to that was made in 2020 as the previous version was outdated. The new strategy focuses on supply of raw materials and future markets for raw materials and is much more aligned with circular economy. The strategy is built on three pillars: "Increase domestic production, Support the import of raw materials, Increase recycling activities" (Schmid, 2021). The relevant pillar for this study is the third pillar; increase in the recycling activities. Out of the seventeen total measures that are part of the strategy, only two measures are related to the third pillar. This indicates that there is plenty scope for improvement and revision (Schmid, 2021).

The two measures that are part of the third pillar are related to circular economy and utilising the secondary source of raw materials. As part of the measures, the strategy emphasises on the increase of research and development on recycling of new technologies, and overcoming the challenges of circular economy by addressing industry, science and administration. Although, there is no specific mention of rare earth magnets or REE the revision indicates the step in the right direction.

France

France has generated a road map for circular economy. The road map consists of fifty measures that France wants to implement in order to become a circular economy As part of the measures, twenty four measures are part of managing the wastes in a better way. Some measures that can be related to recycling and re-use of neodymium magnets are as follows:

1. Manage resources more sustainably
   This measure discusses about making a plan for recovery of the most strategic critical metals. Rare earths in the neodymium magnets are strategic critical metals as listed by the EU Critical Raw Materials list.
2. Combating the illegal trade of end-of-life vehicles
   A large amount of EOL vehicles get exported illegally to third world countries (Same Source). Not only this means loosing important secondary raw materials available in the vehicles but also putting burden on the countries with poor recycling infrastructure. In context of electric vehicles, this becomes really important measure as it contains more critical raw materials than a gasoline or diesel powered vehicles.
3. Extend the scope of Extended Producer Responsibility Scheme
   Through the extension of EPR schemes, the measure is trying to eliminate the side effects of EPR scheme where certain important raw materials are lost in EOL vehicles (same source).
4. Better collaboration between actors in supply chain
   In order to have a circular economy, ultimately the actors in the supply chain need to collaborate with one another. This measure promotes the collaboration between waste management companies and producers so that necessary information can be passed between the two for efficient recycling and product design that is based on recycling and re-use.

The proposed measures will create a positive environment for the collection and recycling of neodymium magnets in future in France. **Netherlands**

The Netherlands aims to be a circular economy by 2050. As part of the Government wide programme for a Circular Economy in the Netherlands, the cabinet wants to reduce the dependence on primary raw material by 50% by 2030 (CE Document, NL). In context of rare earth magnets, the cabinet realises the importance of rare earths in the new technologies that are essential for tackling with climate change. At present, there are no specific policies that focus on the rare earth magnets and rare earth elements mainly due to lack of focus on rare earths at EU level policies. However, the vision for 2050 developed by the cabinet for rare earth metals is to re-use and recycle by exploiting the urban mines (CE Document, NL).

Belgium

Belgium adopted a Circular Economy strategy in 2014. The strategy comprises of 21 measures which focus on sharing of products, repairing, and sustainable waste management (https://hollandcircularhotspo content/uploads/2020/06/Belgium-2-pager-24-juni.pdf). Belgium has selected three priority areas that need to be attended to- construction and demolition, sustainable design for packaging and finally circular offshore wind farms. In context of the study, the circular offshore wind farms is interesting to look into. Through this priority area, it can be concluded that Belgium is aware of the problem of rare earth supply for the exponential growth of wind sector. The importance of design of modular wind turbines is discussed in this priority area for the re-use and recycling of wind turbines (Same source as above). This indicates that there is necessary awareness and now action is required to facilitate the collection of rare earth magnets from the wind turbines and electric vehicles in a few years.

A common measure proposed by all four countries in their circular economy documents was related to the collaboration of actors in the supply chain for better information flow to create transparency and efficiency in recycling value chain (all 4 sources).

APPENDIX D

Conceptual Design

D.1 Elaboration of means that were not chosen

All the solutions that were not used in the Proposed Collection Strategies are explained below.

FI1. Establish a collection target for PM motor, generators

Assigning collection rate based on comparison
Another alternative to assign a collection rate can be take a look at the collection rates of portable batteries in the proposed battery regulation(EU COM(2020) 798, 2020) discussed in section 5.1.5. The collection rate that is proposed for portable batteries to be achieved by 2023 is set to 45% and 70% by end of 2030. However, it can be argued that the collection rate of PM motors can be set at a higher level from the very beginning due to a well developed collection infrastructure for vehicles in each of the Member States.
For instance, in the short term, the collection rates can be set to 70%, for medium term the collection rates can be set to 90% and in the long term the collection rate can be set to 100%. The collection rates that will be assigned could either be updated in the current ELV directive or a new directive specifically focusing on PM motors and generators can be developed.
For PM generators, the collection rate from the very beginning can be set high since the wind turbines are industrial products and they can be better tracked than EVs. This solution was not selected because it takes a rather rudimentary approach and a more detailed approach is presented in the section 7.3

FI3.Prevent export of PM motors and generators

Allow export of PM motors and generators only when receiving country has necessary recycling technology
This solution may allow be suitable from a resource conservation point of view but is not very beneficial for the EU if these these REMs are going outside the EU for recycling as the EU ultimately would need to buy these magnets from countries like China. This does not aid to the process of developing a less reliance on China for the magnets.

FT4. Mandatory flow of information about magnets in Supply Chain

Blockchain to share information: The OEMs can be sensitive about sharing information about the chemical composition and grade of the magnets used in their components (Wind turbine OEM, Burkhardt et al., 2020) as it may have an impact on their competitive edge. However, a wind turbine OEM expressed that they can share this information with magnet recyclers. A solution to sharing sensitive information like the composition, grade, and coating type of neodymium magnets in the supply chain while maintaining transparency and traceability is through Blockchain. Blockchain is a digital ledger that stores data which is encrypted and unchangeable and any changes or mistakes can be tracked and traced (Shrestha et al., 2020). The Blockchain technology can be used in combination with labelling of the magnets, the OEMs can input the data in the code and generate a scannable code which then can be linked to the Blockchain (digital ledger). When the EOL PM motors and generators move to motor/generator recyclers and the magnets are extracted, the scannable code can be scanned to gain access to the important information about the magnets which will help in sorting of the magnets. Once the code is scanned a permanent digital timestamp will be created indicating the access of data (Shrestha et al., 2020) and ownership of the magnets by motor/generator recyclers. Then, the sorted magnets can be sent to magnet recyclers who will then scan the codes to gain access to the necessary information and simultaneously creating a permanent timestamp implying access to information and ownership of the magnets.
It can be argued that the scannable code may get destroyed in the attempt of extracting the magnets from the motors and generator. Thus an alternative can be to print the code on the stator of the motor and generator instead of individual piece of magnet. The solution also may not work if all the OEMs have their own scannable code and different way of present the necessary information as this would not only make it incompatible with the both the motor/generator and magnet recyclers but also lead to confusion and thus make the process of collection and sorting inefficient. In order to overcome this challenge, the code generated and the information stored should be standardised across all wind turbine and automobile OEMs. However, the use of labelling and Blockchain to share information about the magnets needs to be studied further to find out the following:

1. The interoperability of Blockchain technology across OEMs and various motor/generator recyclers and magnet recyclers.
2. The cost of usage of Blockchain to resolve the issue of information sharing.
3. Who will bare the costs if any for using Blockchain?
4. How can additional information (weight of magnets extracted, level of contamination or damage, amount of losses while recycling etc.) be shared by motor/generator recyclers and magnet recyclers using Blockchain.
5. What is the ideal location to place the label?
6. Will be label last as long as the lifetime of motors and generators?

The use of Blockchain cannot be enforced by the EU but the EU can strongly advise the actors in the Supply Chain to use Blockchain to share information. The EU however can and should enforce the sharing of important information like the production type of magnets (sintered or bonded), the chemical composition, the grade of magnet and the type of protective coating on the magnet with the motor/generator recyclers and the magnet recyclers in the supply chain.

OEMs share data about magnets in ProSUM and motor/generator recyclers access it through the ProSUM database. Prospecting Secondary Raw Materials in the Urban Mine and mining wastes (ProSUM) is a knowledge base which provides data on various secondary raw material (including Critical Raw Material) that are present in stock, and that are generated as waste, this "allows the recycling industry and policymakers to make more informed investment and policy decisions to increase the supply and recycling of secondary raw materials" (Huisman et al., n.d.). ProSUM has developed an open access platform for the EU called Urban Mine Platform which gives access Flow, Compositions, and Urban mine data about vehicles, batteries, and WEEE ("Urban Mine Platform", n.d.). Thus an important addition to this list can be the necessary information related to neodymium magnets (production type (sintered or bonded), chemical composition of the magnets, the grade, and the type of coating present on the magnets) used in wind turbines generators and EV motors. In order to do so, the data first needs to be shared by the OEMs with ProSUM which in turn can provide access to motor/generator recyclers and magnet recyclers. However, in order to provide access select motor/generator recyclers across the EU, motor/generator recyclers will need to be identified and possibly get registered with ProSUM, which can lead to high transaction costs. Despite of the transaction costs, this solution can be very useful in passing necessary information in the neodymium recycling value chain.