Master's Thesis – Master Energy Science
March 2019

Future material resource demand under 2 ^{o}C climate policy

Determining the material resources needed for green technologies

Author:
N. Visser
Student Number: 5534291
Study: Energy Science
University of Utrecht
n.visser2@students.uu.nl

Supervisor:
Dr. Birka Wicke
University of Utrecht
Copernicus Institute of Sustainable Development

Summary

To reach the climate goals that were set in the Paris Agreement, i.e. keeping global temperature increase below 2 ^{o}C, significant renewable electricity generation capacity has to be installed. Wind turbines and solar PV are expected to supply a major share of the future energy demand. These technologies however require certain material resources that are not infinitely available. For the different solar PV technologies these material resource are tellurium, indium and silver. For wind turbines the most important material resources are neodymium and dysprosium. To determine whether problem will occur in the supply of those material resources, their future demand from all applications should be mapped. The current research maps the part of the demand that comes from the wind turbine and solar PV industries. In doing so, it takes into account three points of improvement to current research. Firstly, demand for multiple material resources in wind turbines and solar PV is analysed on basis of the same projections for development of the whole energy system. Secondly, distinctions are made between different types of wind turbine and solar PV technologies. Thirdly, to serve as an example, demand from a technology outside the electricity generation industry is addressed.

Future demand is determined on basis of the market share of technologies, the material intensity of the material resources within the researched technologies and the future installed capacities. The market share and material intensity are determined on the basis of an elaborate review of existing literature. Scenarios were created to take into account the different visions on future developments. The future installed capacity is taken from data generated by the IMAGE model. This model determined the best installation pathway to obtain an energy system by 2050 that results in meeting the climate targets. On the basis of these three variables, projections for the future yearly demand of tellurium, indium, silver, neodymium and dysprosium were made.

The highest projected cumulative demand for indium by 2050 (4.7 ktonne) is only 42% of the lowest estimates for indium reserves. The other material resources show even lower shares for their cumulative demand in estimated reserves. For indium, silver, neodymium and dysprosium their highest yearly demands are no more than 40% of current production levels. Yearly demand for tellurium from solar PV (already responsible for 40% of tellurium demand) could possibly exceed current yearly production (estimated between 0.4 and 0.7 ktonne/year). This would however only be the case in the most tellurium intensive scenario, with a projected demand of 0.6 ktonne. Looking only at demand from renewable electricity generation technologies thus does not seem to give reason for great concern about availability of material resources.

Adding indium demand from the TV industry however raises indium demand to 10 ktonne, close to the lowest estimates for current reserves of 11 ktonne, indicating the importance of including demand from other industries. Furthermore, comparison of the results with results from previous research that did not take technological differences and market shares of different technologies into account shows big differences in material resources demand, indicating the importance of addressing those factors. Additionally, the moment of installation (i.e. the installation path) proves to have a great influence on the material resource demand. Changing the installation pathway of IMAGE to a linear installation path results in a large shift in demand between the different material resources under investigation.

The current research addresses a part of the demand side. Further research on the rest of the demand side and the supply (and source) of material resources is needed before solid conclusions on whether problem in the supply of the material resources under investigation will occur can be drawn.

Acknowledgements

The author would like to express his gratitude to his supervisor from Utrecht University, Birka Wicke. By providing detailed and supportive feedback she significantly contributed to creating a well-structured and to the point report. She also kept the author critical towards his own work which helped to improve the quality and reliability of the research.

Furthermore the author would like to thank Sebastiaan Deetman from Leiden University, who was willing to help despite any direct gains or benefits. His knowledge on the topic of material resource demand really helped to steer the research. His feedback and suggestions throughout the process were very useful and the data he provided from his own research was of great value.

Table of content

List of abbreviations

Solar PV	Solar photovoltaïc
EV	Electric vehicle
Dy	Dysprosium
Nd	Neodymium
Te	Tellurium
Cadmium tellurium	CdTe
BEV	Battery electric vehicle
SSPs	Shared socioeconomic pathways
MW	Mega watt
MI	Material intensity
c-Si	Crystaline Silicon
a-Si	Amorphous Silicon
TCO	Transparent conductive oxide
AG	Asynchronous generator
SG-E-DD	Synchronous direct drive generator without permanent magnets
SG-PM-MS	Synchronous middle speed geared generator with permanent magnets
SG-PM-HS	Synchronous high speed geared generator with permanent magnets
SG-PM-DD	Synchronous direct drive generator with permanent
HTS-DD	High temperature superconductor direct drive generator
O&M	Operation and Maintenance
NdFeB	Neodymium-iron-boron
Pr	Praseodymium
Tb	Terbium
LCD	Liquid Crystal Display
QD	Quantum Dot
OLED	Organic LED

List of Figures

Appendix

List of Tables

Appendix

1. Introduction

As mankind keeps increasing its consumption, more and more of the earth's natural resources are used up. Because we live in a finite world the chances to run out of some of the material resources we extract within the next few decades to a century are very real (Henckens et al., 2014). The limited amount of material resources on the planet might constrain supply of certain material resources in the future. Therefore research is focussing on limiting the extraction of the most scarce resources (Henckens et al., 2014, Henckens et al., 2016, U.S. Department of Energy, 2011).

At the same time, agreements were made in the Paris Agreement to limit global warming to a maximum worldwide temperature increase of 2 ^{o}C (United Nations, 2015). This led to what is generally referred to as the 'energy transition'. We should significantly reduce energy use and increase energy efficiency, while moving away from the current energy system based on finite fossil fuels that results in the emission of greenhouse gasses. Scenarios have been developed that show how we can reach the target of the Paris Agreement. Although there are some significant differences between the scenarios, all scenarios show that we need to shift towards a system based on renewable energy production (e.g. solar and wind energy) and decarbonize the transportation sector (Greenpeace, 2015, O'Neill et al., 2017, Van Vuuren et al., 2017, Deetman et al., 2018).

The technologies that are projected to develop most are wind, solar photo voltaic (solar PV) and electric vehicles (EVs). Despite the fact that these technologies appear to be very different technologies at first sight, they have at least one thing in common: significant amounts of material resources are needed to produce them. Next to the bulk materials like steel for the tower and concrete for the foundation of wind turbines, they require different kinds of material resources that are less common. Examples of these less common materials are dysprosium (Dy) and neodymium (Nd) that are used for the permanent magnets inside wind turbines (Hoenderdaal et al., 2013). Another example are specific materials for thin film solar cells like tellurium (Te). Tellurium is one of the main components of cadmium telluride (CdTe) based solar PV (Bustamante & Gaustad, 2014).

In 2011 the United States Department of Energy found that some material resources needed for 'green energy technologies' might face supply constraints in the foreseeable future (U.S. Department of Energy, 2011). This possible supply risk indicates the need to take a closer look at the future demand for these material resources. It is thus important to look into the material resources needed for each technology and the availability those resources.

Various studies have already addressed the future material resource demand. A selection of them is discussed in this paragraph and an overview is given in Table 1. Already in 2001 Andersson & Råde looked into problems related to material resource demand that might occur in the development of thin-film PV and battery-electric vehicles (BEVs) (Andersson & Råde, 2001). They did so assuming that 2 to 7% of energy would be supplied by thin-film solar PV in 2050. For both solar PV and BEVs they find that material availability will constrain development. Given recent scenarios their assumed solar PV share is however too low. Furthermore, although an elaborate analysis was done for thin-film solar cells, the assessment of BEVs has only limited detail. About a decade later, Kleijn & Van der Voet (2010) looked into materials needed to supply 95% of worldwide energy demand with solar (80%) and wind (15%) with hydrogen as the main fuel for transportation. They find that for both solar and wind, as well as for hydrogen in transport, limited availability of material resources will constrain development. The assumptions made on the amount of solar and wind and the hydrogenization of transport however are unrealistic given recent scenarios and current developments. Jacobsen & Delucchi (2011) looked into land and resource needs and availability for a system based on wind (50% of energy production), water and solar (20% solar PV, 20% concentrated solar power (CSP)) with BEVs and hydrogen fuel cell vehicles for transportation. The timeline of this study however runs only until 2030 and, as the article indicates itself, the review is somewhat limited.

Table 1: Overview of literature on resource constraints for multiple technologies.

References	'Green' technologies					Materials		Assumptions on development				Limitations
	Solar PV	Wind turbines	EVs	Hydrogen transport	Water power	Bulk materials	Other materials	PV energy share	Wind energy share	Other	Time-frame	
Andersson & Råde (2001)	X		X				X	2 - 7%	-	All PV is thin film	2050	Low share of solar PV, little detail for EVs
Kleijn & Van der Voet (2010)	X	X		X		X	X	80%	15%	Transport hydrogen based	2050	Unrealistic assumptions given current situation
Jacobsen & Delucchi (2011)	X	X	X	X	X	X	X	40%	50%	-	2030	Time frame only till 2030, limited detail, especially for solar PV
Deetman et al. (2018)	X	X	X				X	25%	15%	50 % of transport by EV	2050	No distinction between different variations of technologies

Though research exists that is more detailed and built on assumptions based on more recent developments, this research often focusses on only one technology category, e.g. solar PV. However, energy generation from solar PV takes place in a larger energy generation system. To adequately determine the developments of one of the technologies of the future energy system, one should also be aware of developments of other technology categories, e.g. the development of wind turbines. Solar PV and wind turbines are both expected to replace a large share of the current fossil fuel based energy generation capacity in order to reach the climate targets. To know the amount of solar PV capacity that is needed, it is also necessary to know the amount of wind turbines that will be installed and vice versa. Only when analysing both technologies with the same basic assumptions, their individual demand for material resources can be adequately determined.

Next to the specific limitations, one general limitation can be identified. All of the discussed papers only look at the amount of material resources that is needed for the specific technology(ies) under investigation. Many of the material resources are however also used in other technologies/industries. When determining possible constraints in the supply of a certain material resource, the demand for that material resource in all of its applications should therefore be taken into account.

A significant share of the material resources used in the green technologies is also used for other applications. Cadmium, that is used in solar PV, is mainly used for rechargeable batteries in electric appliances (USGS, n.d.). Neodymium based permanent magnets, that are used in wind turbines, are also used for many other purposes. Neodymium is additionally used for making certain types of glass. If we want to determine whether and when problems in the supply of cadmium and neodymium may occur we can not simply look at the cadmium and neodymium needed in future solar PV and wind turbines. We also have to take into account the developments in all the other applications of the two materials. This of course holds for all materials, and not just for cadmium and neodymium.

To set a first step in developing a comprehensive image of the total future demand for material resources, Deetman et al. (2018) made projections for the use of 5 material resources (cobalt, copper, lithium, neodymium and tantalum) in 'green energy technologies' (renewable electricity generation technologies and electric cars) AND electronic appliances. The appliances under investigation were amongst others cooling appliances, washing appliances, personal computers and laptops. The projections were made under the assumptions of so called Shared Socioeconomic Pathways (SSPs). On basis of these SSPs the future capacity of green energy technologies was determined from a modulation of the *whole* energy system. According to the projections solar and wind will produce about 25% and 15% of global energy, respectively, by 2050. 50% of cars on the road by that year are some type of EV. The amount of electric appliances more than doubles while the share of different appliances remains more or less constant. This all happens under assumptions of climate policy that is aimed at reaching the climate goals of the Paris Agreement. However, the research only covers 5 material resources and 3 demand groups (electric appliances, transportation and electricity generation). Deetman is currently focussing on mapping the demand for a number of material resources in buildings to increase the amount of *demand groups* taken into account (S. Deetman, personal communication, November 2018). There is however thus also still a significant potential to improve and enrich the data on the different *material resources* needed in electric appliances, transportation and electricity generation.

In Deetman et al. (2018) distinctions are made between different technology categories in each demand group. But although on- and offshore wind turbines and different types of EVs are taken into account, solar PV is taken as one group. There are however many different types of solar PV technologies that require different material resources. For wind turbines and EVs further differentiations can also be made, regarding the composition of the generator and the battery, respectively. To determine the material resource demand for each technology category average values of their material resource content are used. This entails that two different solar PV cells are seen as one group with similar material resource demands. Looking at the material resources needed for specific technologies within a technology category will thus increase the level of detail and the accuracy of the results found by Deetman et al. (2018).

Based on the review of past research above, three main areas of improvement to existing research can be distinguished:

- Improve detail within the researched technology categories
- Add more material resources to the analysis
- Determine the total material resource demand by taking demand from other technologies and industries into account.

The current research tries to improve on each of these areas by **determining the demand for material resources from the wind turbine and solar PV industry until 2050, while taking into account the different possible technologies within those industries.** The current research thus contributes to creating insight into the total material resource demand in the future and problems that might occur in their availability. Furthermore it shows the added value of taking into account that different technologies exist within an industry. In addition, the demand from a non-energy-generation technology for one of the material resources under investigation is taken into account. This is done to show the importance of addressing demand from other technologies and industries. The full range of demand from all applications of a material resource should however be taken into account before drawing a conclusion on whether sufficient material resources are available for each of the future energy generation technologies. This is however too complex to cover in one paper. The current research therefore does not provide such a conclusion. Rather, it answers a small piece of the question and further research is needed in order to give the full answer. The current research buils partly on the work of Deetman et al. (2018) that is discussed more elaborately in the next section of this proposal.

2. Background

To better understand the rest of the research at hand, it is important to have some knowledge about the terms and concepts that were used. Therefore it is first explained more elaborately how 'material resources' are defined in this research. Then, some general insight into recent research into material resource use in green energy technologies is presented.

2.1. Material resources

The term 'material resources' is often used in the current research. For the current research, this term indicates all the materials that are used as input in the production process of the technologies under investigation. This can include raw materials that occur naturally in the environment (metals, wood, sand), or products that are made from those naturally occurring materials (alloys, glass and other processed materials). The European Commission divides raw materials into four categories: mineral resources, metal ores, biomass and fossil energy materials/carriers (European Commission, n.d.). The most important categories for this research are mineral resources and metal ores. The material resources that are investigated in this paper are (made from) materials in these two categories. Taking the example of neodymium and cadmium: neodymium is extracted from raw materials in the mineral resources group, cadmium is mainly a by-product of metal production and thus comes from the metal ores group.

2.1.1. Critical material resources

In 2011 the United States Department of Energy published the Critical Materials Strategy (U.S. Department of Energy, 2011). In this study sixteen elements, important to green technologies, were assessed for criticality. Criticality was defined as a combination of supply risk and importance of the material to green technologies. Five elements were found to be critical (dysprosium, europium, neodymium, terbium, and yttrium). Four more elements were found to be near-critical (cerium, indium, lanthanum and tellurium. The (near-)critical material resources are presented in Table 2.

Table 2: (Near-)critical material resources (U.S. Department of Energy, 2011).

Critical material resources	Near-critical material resources
Dysprosium	Cerium
Europium	Indium
Neodymium	Lanthanum
Terbium	Tellurium
Yttrium	

2.2. Previous research

Some previous research was already discussed briefly in the introduction. Since the current research is partly based on findings from Deetman et al. (2018), their work is discussed more elaborately here. A general description of the research is given along with background on the methods and concepts used.

To determine the material resource demand in the years until 2050, Deetman et al. (2018) build on projections that show the developments that are needed to obtain an energy system that keeps global warming within the 2 ^{o}C climate target. A scenario for the composition of this future energy system was developed on the basis of SSPs. This scenario was modelled with IMAGE. First the usefulness of scenario analysis is briefly addressed. Then the SSPs and IMAGE are discussed to get an idea of how the scenario was created.

2.2.1. Scenario analysis

Scenario analysis contributes to gaining insight into possible futures. Under certain input conditions the possible developments of a variable under investigation can be identified. This shows what we can expect in terms of problems or constraints that might occur in the development.

2.2.2. Shared Socioeconomic Pathways

The SSPs describe possible futures under different assumptions on the development of for example demography, economy and concern for the environment (O'Neill et al., 2017). 5 different storylines have been developed, conveniently termed SSP1 to SSP5. SSP1 (significant effort to reduce both environmental impact and inequality), SSP3 (business as usual scenario) and SSP2 (in between SSP1 and SSP3) are often used in environmental research. This research usually aims to determine the efforts that are necessary to reach the climate target. The other two scenarios, SSP4 (reduced environmental impact but inequality remains) and SSP5 (reduced inequality but no effort to reduce environmental impact) are used less often. This is probably because they are seen as less likely scenarios because of their extreme nature. An overview of the main assumptions in each SSP is given in Figure 1. For a more elaborate description, see O'Neill et al. (2017).

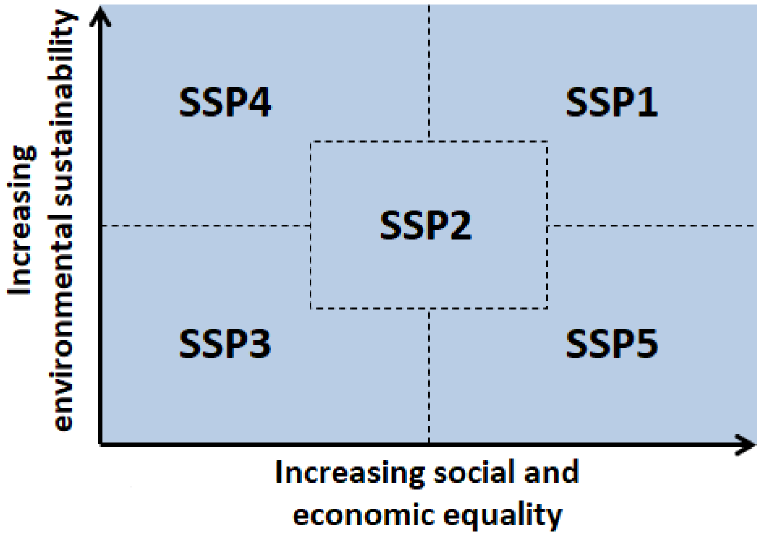

Figure 1: Overview of the SSPs, based on Fig. 1 from O'Neill et al. (2014) and Fig. 1 from O'Neill et al. (2017).

Multiple studies developed scenarios under the characteristics of the SSPs. Under the conditions of the most environmental sustainability oriented storyline, SSP1, Van Vuuren et al. (2017) developed projections on the development of energy production for different climate policies. One of these policies aimed at limiting radiative forcing to 2.6 W/m^2. This is consistent with the 2 ^{0}C target. If we want to achieve this target, it is projected that about 75% of electricity should be produced in a renewable way. Of that 75% about one-third comes from solar and wind. Deetman et al. (2018) assumed the more moderate SSP2 for their calculations on the material requirement for electricity generation technologies, cars and appliances. They project about 2300 GW of solar and 1500 GW of wind power to be added by 2050, together representing about 40% of global installed energy generation capacity. The characteristics of SSP2 are given in Table 3.

Table 3: Overview of the characteristics of SSP2 (Riahi et al., 2017 in Deetman et al., 2018).

	Year			
	2010	2020	2030	2050
Population (billion people)	6.87	7.61	8.26	9.17
GDP (trillion US$	67.5	101.2	143.1	231.3

per year, in 2005 PPP)				
Energy (total primary energy, EJ/yr)	501	580	667	842

2.2.3. IMAGE

To obtain the data for the share of different energy generation technologies in the future energy system, Deetman et al. (2018) use the IMAGE model. Since the current research builds partly on those results, it is important to understand how the IMAGE model functions. The model is however not directly used and is therefore not discussed in large detail. To understand how the model functions, only the most relevant concepts behind the model are explained.

The IMAGE model is a model that aims to determine future greenhouse gas emissions. To do so, it combines the developments in several drivers (e.g. income and population growth) to assess their impact on the environment. This impact is modelled through different impact categories by IMAGE. The most important category for the current research is the composition of the energy generation system, in terms of newly installed power generation capacity, divided over 27 technologies. Included in the IMAGE model are increasing efficiencies of the energy generation technologies.

The IMAGE model can be used in two ways. It can be used to model what *would* happen under certain trends that can be provided as input. In this way a business as usual development could be modelled. Furthermore, it can model what *should* happen in order to reach a goal that is set at some point in the future. This is for example the case when the characteristics of SSP2 with Climate Policy are used as input. In that case there is a limit on the radiative forcing (the scientific 'phenomenon' that is behind global warming). IMAGE can describe the necessary future developments while taking into account both economic development and efforts to sufficiently decrease greenhouse gas emissions.

When IMAGE is used to describe what *would* happen in a business as usual future, IMAGE takes current trends and extrapolates them. In IMAGE, investment decisions are based on costs. In a business as usual situation, additional investments in green energy technologies are thus only made when those technologies are the cheapest option. If however IMAGE is used to determine what *should* happen, investments in technologies that are not the cheapest might be necessary. Because IMAGE discounts future costs, those (from an economic point of view) non-rational investments are postponed as long as possible.

2.2.4. Methods used

On basis of the outcomes of the scenarios, developed using IMAGE and SSP2, Deetman et al. (2018) determined the future demand for the material resources under investigation. To do this a database was constructed with information on the material resource content of electronic appliances, electricity generation technologies and cars. To determine the composition 36 sources from scientific and grey literature were used. From these sources Deetman et al. (2018) created three 'scenarios' for the material content of the technologies. They took the highest and lowest value for the material content from literature to serve as a high and a low estimation. The third scenario is the average of the high and the low estimation. Combining the estimations of the amount of material resources per unit (for cars and electric appliances) or per capacity (in MW, for electricity generation technologies) with the amount of units and the installed capacity gives the total material resource demand. The material resources considered were cobalt, copper, lithium, neodymium and tantalum, selected on the basis of availability of information.

3. Method

The aim of the current research is thus to determine the demand for material resources in wind turbines, solar PV and a non-energy-generation technology while taking into account the different compositions of those technologies. In doing so, three point of improvement compared to existing research, that were identified in the introduction, are taken into account. To improve the detail within the technology categories a distinction is made between different variations of a technology. Deetman et al. (2018) focussed on five material resources present in a wide range of technologies. To increase the range of material resources the current research looks at material resources that are specifically needed within the green energy technologies under investigation. To determine the total demand for material resources the use of those resources outside the green energy technology industry is discussed.

The results of the current research will contribute to identifying whether problems will occur in the supply of the material resources that are necessary to produce wind turbines and solar PV cells. To provide a comprehensive insight into the way material resource demand will develop, it is necessary to find the yearly demand for the material resources needed in green energy technologies in the years up to 2050. To create this insight, three aspect of the development of the green energy technologies under investigation should be known. The first one is the specific types of a technology that are installed. The second one is the amount of certain material resources required in the technologies. The third one is the yearly installed capacity of the technologies. The demand for a specific material resource in a certain year can then be determined with Equation 1.

Equation 1:

$$Demand\ for\ X\ in\ year\ Y = Newly\ installed\ capacity\ of\ T_X\ in\ year\ Y * share\ of\ T_X\ in\ year\ Y * material\ intensity\ of\ X\ in\ T_X\ in\ year\ Y$$

With:
X = material resource under investigation
T_X *= technology under investigation that contains material resource X*
Year Y = the specific year under investigation

Combining information on the yearly installed capacity, the technology shares and the material intensity gives the yearly demand for the material resources under investigation. This yearly demand in turn provides different insights. First of all it shows the absolute amount of a material resource that is needed in a certain year. Adding the demand in individual years gives the cumulative demand in the investigated period. It can thus be determined what the total amount of a material resource is in the investigated period. Other information that can be drawn from the yearly demand is the relative increase in demand. It is important to have this information to determine whether supply can keep up with demand. An example of the importance of this relationship can be found in the solar PV industry. Here is was not the physical availability of a material resource but the inability of the material resource suppliers to keep up with increasing demand that caused problems with supply (Kuypers et al., 2018).

To put the material resource demand in perspective, yearly demand is compared to current annual production. Furthermore, cumulative demand is compared to current estimated reserves. This comparison is often used to determine availability of a material resource (Davidsson & Höök, 2017).

In the next section of the method, first the timeframe of the research is set. Then it is explained which green energy generation technologies are under investigation in this study, followed by an elaborate discussion of the material resources that are taken into account. Subsequently, it is clarified how the yearly installed capacities are determined. On the basis of the review of the green energy technologies, it was determined which non-energy-generation technology was analysed. This is therefore explained in more detail after the green energy generation technologies are discussed.

3.1 Research Scope

3.1.1. Timeframe

This research looks at the needed developments in solar and wind energy generation technologies to reach the climate targets and the development of a non-energy-generation technology during the same period. The climate targets are set for the year 2050. Therefore this research, like the research of Deetman et al. (2018), looks at the developments until the year 2050.

3.1.2. Technologies

Deetman et al. (2018) focus on a number of different technology categories in electronic appliances, electricity generation technologies and cars. Because of the limited time available for this research not all categories could be investigated. The research was therefore limited to two electricity generation technologies and one non-energy-generation technology from the electronic appliances group. Of these groups the most important (renewable) technology categories in terms of share were investigated. For energy generation technologies these were wind turbines and solar PV. The non-energy-generation technology is discussed in section 3 of the method.

Variation in technologies

For wind turbines and solar PV different variations of the technologies exist. For example, solar PV cells can be silicon based but also CdTe based. A breakdown of the different levels of detail is presented in Figure 2. The first step of this research was to determine which technologies will possibly constitute the future composition of a technology category. Therefore it is necessary to create an overview of the most important variations of the technologies. 'Most important' here means that it is expected that the technology has a meaningful share in the future energy system. This selection was made to take into account the greatest possible sources for material resource demand. Also, for these technologies sufficient detailed information and data was expected to be available to perform a solid analysis.

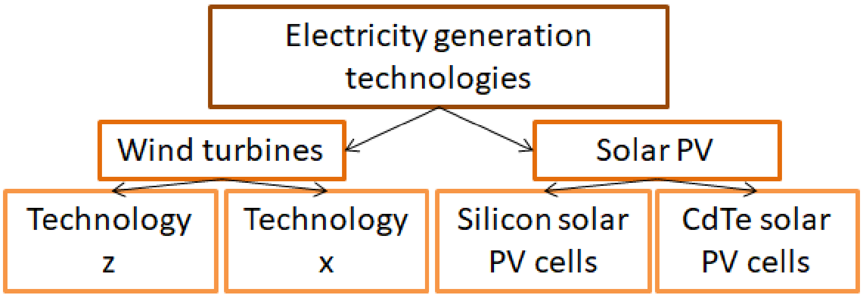

Figure 2: Breakdown of energy generation technologies.

After determining the most promising technologies, the division of the different technologies in the technology categories had to be determined. This was done on the basis of more detailed scenarios of the future energy system and projections on development of the different technologies. The contribution of these scenarios and projections was to find the relative amount, i.e. the share, of each technology within its technology category. The absolute amount could then be determined by multiplying the share of a technology with the expected size of the technology category as defined by Deetman et al. (2018). This will be further explained in section 1.4 of the Method.

Despite the research into the green energy technologies, market developments remain uncertain. This shows in the large range of estimates that can be found in literature. Furthermore, most studies focussed on one technology tend to assign a larger share of the future market to that single technology than studies focussed on multiple technologies. Because it is still uncertain what technology or which technologies will dominate the future market, no decisive picture of the future division of the technology categories can be created. Therefore three different scenarios for the future developments within each technology category were created. By doing so an approach similar to that of Nassar et al. (2016) was taken to account for uncertainty in the composition of the future market. Nassar et al. (2016) assume linear increases for the market share of the technologies they investigate. The current study took the same approach.

3.1.3. Material resources

The material resources that were considered in the current research are the material resources that characterize the selected technologies. A characterizing material is a material that can not be substituted without changing the physical properties of the technology. Jean et al. (2015) state that substitution of a characterizing material would lead to a different kind of technology. Taking again the CdTe solar PV cells as an example, cadmium and tellurium are the materials that characterize this technology. For CdTe solar PV these two materials were thus investigated. A further selection for the materials that were finally used in the analysis was made on the basis of availability of data on the prevalence of the characterizing materials in the selected technologies.

Many papers discuss the material resources content, or material intensity (MI), of the currently available models of a technology. Some assume this MI to be constant over time (Valero et al., 2018). However, there is significant potential for reducing the use of material resources in green energy technologies (Worrell et al., 2016; Shahbazi et al., 2016; Hjortsberg, 2016). A decreasing MI has a limiting effect on the demand for material resources. It is therefore necessary to know how the MI will develop in the years up to 2050. Studies that take this decrease into account indicate that the MI will become significantly lower (e.g. Viebahn et al., 2015, Davidson & Höök, 2017, Houari et al., 2014, Brumme, 2012). There is agreement on the way the MI will develop. Most studies describe the development as exponentially decreasing (e.g. Davidson & Höök, 2017; Bustamante & Gaustad, 2014). To determine the yearly demand for a material, an exponential curve was fitted to the data using the GROWTH function in Excel.

Despite the agreement on the development path, the magnitude of the decrease is still uncertain. Future estimates for the MI differ. To tackle this problem for solar PV and wind turbines, Nassar et al. (2016) create a conservative, neutral and optimistic scenario for the MI. The values for the MI in each scenario are set by varying the factors that determine the MI. To account for variations in the estimates for the future material intensity of the different technologies a similar approach was used in this research. Different values for the MI were fitted to the scenarios that were created to account for uncertainty in the future share of the technologies.

It must be noted that this paper exclusively focusses on the amount of material resources that is needed. No distinction is made with regard to the source of these materials. The aim is to determine the absolute amount of material resources that is needed. It is thus possible, and even likely, that a part of future demand is met by recycled material resources. Recycling has a smaller impact on the environment than the extraction of raw materials. It is however beyond the scope of this research to take the sources of the material resources into account.

3.1.4. Scenarios for installed capacity

Two main cases were discussed in Deetman et al. (2018). Both cases are based on the characteristics of SSP2. The first case (Baseline) shows the business as usual developments. The other case (Climate Policy) shows the development that is needed to reach the climate targets. The ultimate goal of this research is to contribute to a clear understanding of the material resource needs to achieve the climate targets. It is however also useful to see how material resource demand changes when climate policy is implemented. Therefore this research took both the Baseline and the Climate Policy case into account. The development of the two technology categories in the two cases set the boundary for the total development of the technologies. This means that the total amount of wind turbines and solar PV by 2050 was the amount given by IMAGE in Deetman et al. (2018). The amounts are shown in Table 4.

In the Climate Policy case especially the installed capacity of solar PV increases significantly. A greater increase in installed capacity might result in greater developments of a technology. This in turn might lead to reduced MIs. This difference in development between the two cases is however not taken into account. The scenarios that were created for the development of the market share and MI of the technologies already take a comprehensive range of possible developments into account.

Table 4: Amount of wind turbines and solar PV by 2050 (Deetman et al. (2018)).

Technology	Unit	Capacity in 2050 (Baseline)	Capacity in 2050 (Climate Policy)
Wind turbines	GW globally installed	1,130	1,467
Solar PV	GW globally installed	1,394	2,319

The aim of this research is to create an overview of the yearly demand for the material resources under investigation. Data on the yearly installed capacity of each technology in the years till 2050 is therefore necessary. This data was generated by Deetman et al. (2018) with the IMAGE model and obtained through personal communication with S. Deetman. The data is presented in Figure 3 and Figure 4. Figure 3 presents the yearly installed capacities under the Baseline case. Figure 4 gives the yearly installed capacities when climate policy is implemented. These installed capacities include both the 'absolute' new capacity (mainly until 2035) and the replacement of existing capacity (mainly after 2035) (Deetman et al., 2018).

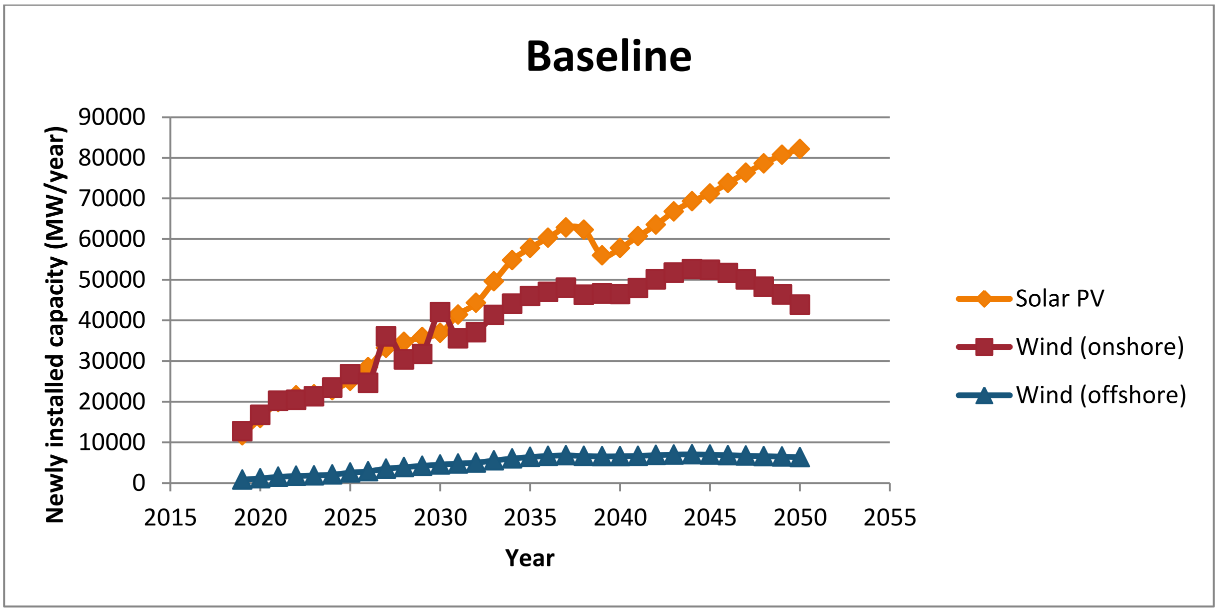

Figure 3: Newly installed capacity in Baseline case.

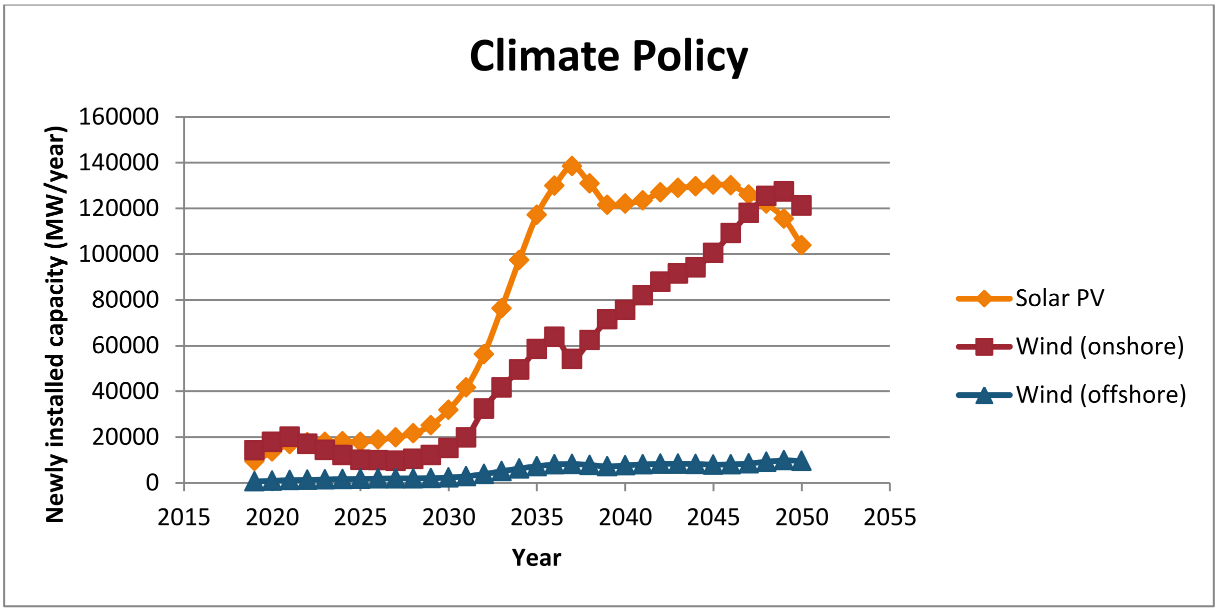

Figure 4: Newly installed capacity in Climate Policy case.

3.3 Non-energy-generation technology

Detailed information on the expected future purchases is available for certain electronic appliances from the IMAGE model used by Deetman et al. (2018). Therefore one of these appliances was used for analysing the material resource demand in a non-energy-generation technology. The exact technology was determined on basis of a review of the material resources that were analysed for wind turbines and solar PV. This review is presented in chapter 4.3 and contains an overview of the uses of the material resources outside the energy generation sector. On basis of this review televisions were selected to serve as an example of material resource demand in a non-energy-generation technology. Next to being the appliances with the largest market share in the electronic appliances, the television industry is currently the largest source for indium demand.

To determine the indium demand in televisions, the same steps were taken as for the energy generation technologies. First the variations of the technology and the expected market shares of these different variations were investigated. Then it was determined what the MI of the technology is. The yearly purchases were available from the IMAGE model. To acquire the yearly material resource demand a slight variation of Equation 1 was used, with yearly purchases instead of yearly installed capacity.

An important remark to make regarding the electronic appliances is that there is no difference between the amount of purchases in Baseline and Climate Policy case. Electronic appliances do not (directly) contribute to lowering greenhouse gas emissions and their purchases are therefore not affected by the policy that is in place in the Climate Policy case.

3.4 Sensitivity analysis

The current research uses the IMAGE model to determine the yearly installed capacity of the technologies under investigation. The results therefore depend partly on external data. To show how this data might influence the results, two sensitivity analysis were performed.

The first analysis looks at the installation path that IMAGE projects. Because of the cost orientated decision model of IMAGE, installations occur as late as possible, as future money is cheaper than current money. To see how a different development path influences the results, a sensitivity analysis was performed with a linear increase of installed capacity.

The second analysis treats the market share of on- versus offshore wind turbines. Currently the amount of wind turbines installed offshore is only about 3% (Hernández et al., 2017). As becomes clear from Figure 3 and Figure 4, the share of offshore wind is expected to remain relatively low compared to the share of onshore wind. The main reason for this is that the IMAGE model that determined the amounts of capacity installed on- and offshore strongly prefers onshore capacity because it is cheaper. However, most of the reviewed papers expect a larger market share for offshore turbines. Brumme (2012) assumes 33% of turbines to be installed offshore and Elshkaki & Graedel (2014) project a maximum of 50% of wind capacity to be offshore. To see how a higher offshore market share would affect the results a sensitivity analysis was performed. In this analysis, the change in demand for neodymium and dysprosium as a result of a different on- vs. offshore distribution was investigated. The total capacity thus remains the same but the division is changed. For the sensitivity analysis it was assumed that the share of offshore wind will increase linearly from the current 3% to 50% by 2050.

Furthermore, a sensitivity analysis was performed for the MI of the material resources in wind turbines. For the main analysis an average value was used to obtain the results because estimations from literature displayed only a small range. By taking the highest and the lowest value from this range it was analysed how the results would change when this range had been used to perform calculations.

4. Literature review and scenario definition

4.1 Solar PV

4.1.1. Technologies

To date, many different types of solar PV technologies are available. A comprehensive and elaborate overview is given in Jean et al. (2015), see Figure 5. They distinguish between wafer based solar PV and thin film solar PV. The main difference between wafer and thin film solar PV is their thickness. Wafer based solar PV is several times thicker than thin film solar PV and therefore more rigid. Thin film solar PV is thinner and more flexible which allows for application on non-flat surfaces. Furthermore, thin film cells can be transparent (to a certain degree) which allows for the use of thin film technologies in windows. Within thin film solar PV, commercial technologies are distinguished from emerging 3rd generation technologies.

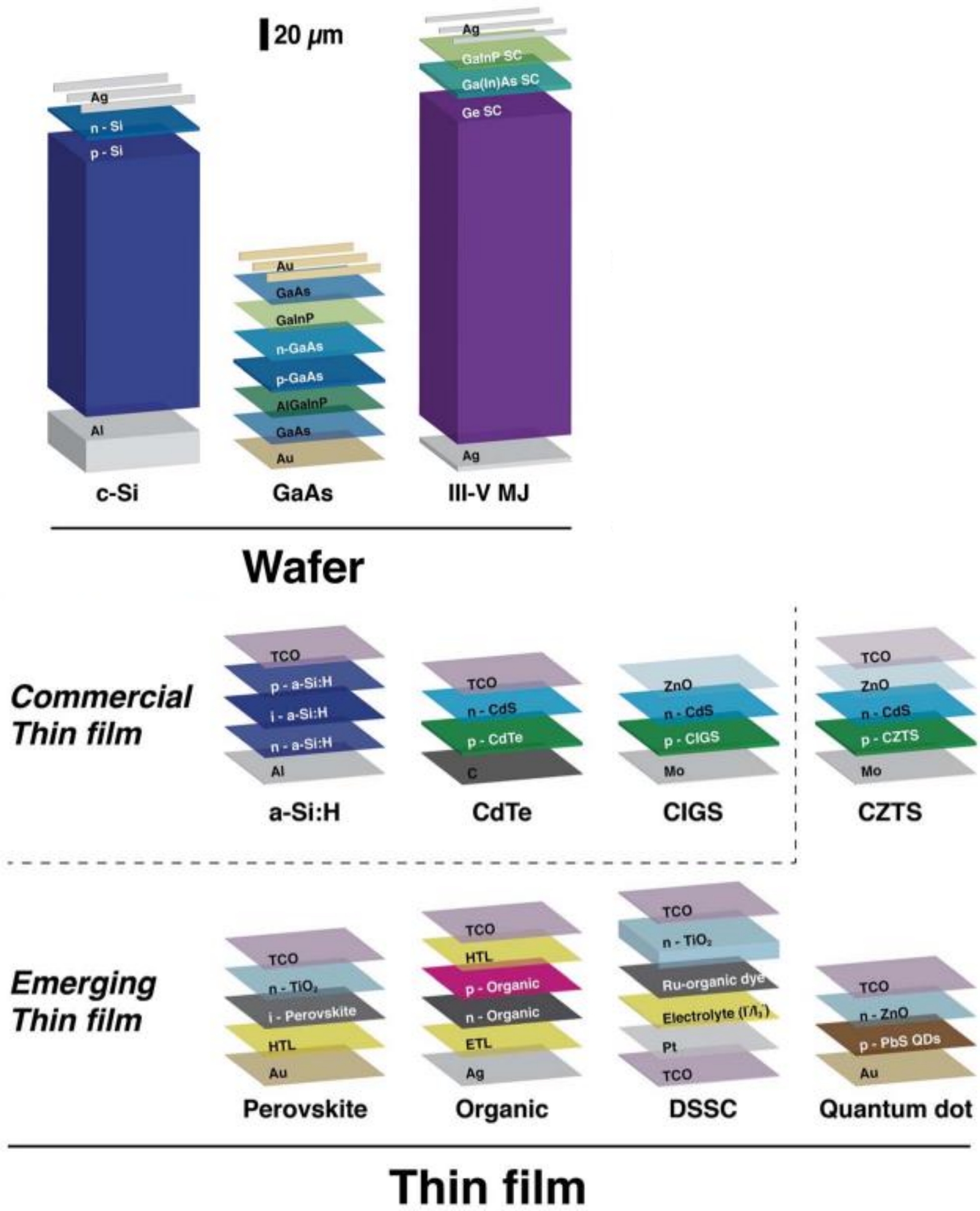

Figure 5: Different types of solar PV technologies (taken from Jean et al., 2015). The characterizing layers are indicated in white letters.

Past developments in the solar PV market

Before discussing the role each of the solar PV technologies might play in the future energy system it is useful to have an insight into the past developments of the market. From the year 2000 onward, considerable amounts of solar PV cells started to be produced. Crystaline silicon (c-Si) cells dominated the market until around 2008, at which point c-Si solar PV production reached such levels that demand for very pure (solar grade) silicon exceeded supply (Kuypers et al., 2018). This was not caused by limited availability of the material resource, silicon, but by a shortage in suppliers that could produce it at the purity required for solar PV. The shortage led to a steep rise in the costs of c-Si solar PV. Till 2008, thin film solar PV had been more expensive than c-Si solar PV. This increase in costs thus offered a change for thin film technologies to gain market share. Until 2010 thin film gained significant market share (amounting to 15% (Speirs et al., 2011). Therefore Tanaka (2008) believed that thin film would have taken over the market almost completely by 2050, obtaining a market share of 85%. After 2010 however, dedicated solar grade silicon production increased and the price of c-Si fell below that of thin film again. This in turn pushed the share of thin film down. The current share of thin film solar PV is estimated around 5% and has been decreasing in the past years. Based on the trend of the last years, thin film would have a total market share of 1.5% by 2050 (Viebahn et al., 2015).

Future developments in the solar PV market

Of the wafer based solar PV technologies, Jean et al. (2015) expect c-Si to be (and remain) the only technology with a significant market share. This is the case because GaAs and III-V MJ cells are too expensive for large scale application. Their high cost mainly result from their complex manufacturing processes and the expensive material resources that are required. Of the thin film cells, Jean et al. (2015) expect CdTe and copper-indium-gallium-diselenide (CIGS) cells to be the two technologies that constitute the thin film market. Already commercial amorphous silicon (a-Si) cells suffer from light induced degradation and have low efficiency. These two factors limit large scale adoption in the solar PV market. Emerging, 3rd generation thin film technologies have the advantage of using relatively abundant materials. However, their efficiency is low compared to the efficiency of their commercial relatives. At the moment this limits the large scale application of these emerging technologies. If however R&D succeeds in increasing the efficiency of those technologies they could become important in the long-term. According to Jean et al. (2015) the technologies that will constitute the future solar PV mix are thus c-Si, CdTe, and CIGS cells. This view is shared by most other authors that allocate most of or the full market share to these three technologies (Bustamante & Gaustad, 2014; Stamp et al., 2014; Choi et al., 2016; Speirs et al., 2011).

Despite the insight into the past developments and the agreement on the most important future technologies, there is however little insight into the way these three technologies will constitute the market. To show this, the different estimates and assumptions found in literature are summarized in Table 5. The market shares presented are for the year 2050.

Table 5: Estimates and assumptions of the 2050 market share of different solar PV technologies.

Market share technology (%)				
a-Si	CdTe	CIGS	c-Si	Source
0%	20%	20%	60%	Speirs et al., 2011
0.5%	0%	1%	98.5%	Viebahn et al., 2015, continuity roadmap
11%	0%	31%	58%	Viebahn et al., 2015, thin film revolution
-	-	25%	-	Choi et al., 2016
-	-	30%	-	Stamp et al., 2014
5%	50%	5%	40%	Bustamante & Gaustad, 2014 (CdTe dominated)
50%	5%	5%	40%	Bustamante & Gaustad, 2014 (a-Si dominated)
5%	5%	50%	40%	Bustamante & Gaustad, 2014 (CIGS dominated)

5%	5%	5%	85%	Bustamante & Gaustad, 2014 (c-Si dominated)

4.1.2. Material resources

Characterizing materials

Solar cells contain different layers. The layer that characterizes the cell is the absorber layer. Solar PV cells are usually named after this layer which makes it easy to determine the characterizing materials. For CdTe solar PV the characterizing material resources are thus cadmium and tellurium. For CIGS solar PV they are copper, indium, gallium and selenium. c-Si is characterized by silicon. Next to these material resources that form the absorber layers of the cells, there are also material resources embedded in the other layers of the cells. CdTe cells, like many other thin film technologies, have a transparent conductive oxide (TCO) layer. This TCO layer could possibly contain indium. The indium in this layer is however easily substitutable by other materials (Nassar et al., 2016) and is therefore not considered part of the characterizing materials. The amount of indium needed in this layer is not taken into account in this analysis. Furthermore, a window layer made of cadmium sulphide (CdS) is present in both CdTe and CIGS cells. As the name indicates, this layer contains cadmium. The layer is however relatively thin compared to the absorber layer and can be substituted by other materials (Nassar et al., 2016). Cadmium in the window layer is thus also not taken into account in the analysis. c-Si cells use silver as a conductor. Silver can be seen as a critical material and is indicated as characterizing for c-Si by Nassar et al. (2016). Still, most papers on material resource needs for solar PV technologies do not take silver into account. Less information was therefore found for silver. Still, it was included in the analysis to provide a more complete picture, as c-Si cells remain the most important technology. Results are however less certain.

Material intensity

To understand how the MI of solar PV technology can change, it is important to know the underlying factors that determine this MI.

- The first factor is the *conversion efficiency*. Under an expected generation capacity this conversion efficiency determines the amount of cells that is needed.
- A second factor is the *thickness of the absorber layer*. The thinner the absorber layer, the less material is needed.
- A number of factors can be grouped into one factor that in this research will be called '*manufacturing efficiency*'. The manufacturing efficiency indicates the amount of material that actually ends up in the cells that are sold, compared to the amount of material that is used for production. During the production process material is lost in de 'sputtering process'. During this process the absorber layer is created by spraying the absorber material onto a substrate. Some of the material is however sprayed next to the substrate and is thus lost. After production, some finished modules might not meet the quality demands. They are rejected and form another source of losses. Together with recycling efficiencies these losses determine the manufacturing efficiency.
- Finally the MI is determined by the *material ratio* in the absorber layer. The characterizing materials can be used in the absorber layer in different proportions.

The way authors handle these factors differs. In most papers (almost) all of the different factors are mentioned. However, the factors are more used as guidelines, and not explicitly used to determine the future MI. A more elaborate approach is taken by Nassar et al. (2016) that do make projections for the MI based on developments of each of the factors underlying this MI. Developments in these factors are based on the range of values found in a list of papers. However, estimates in these paper are still estimates, which does not necessarily make the results of Nassar et al. (2016) more reliable. To get an idea of how different factors might develop, the projections of Nassar et al. (2016) are included in Table A 1 of the appendix.

Development of material intensity

Currently estimates for the MI of tellurium in CdTe cells range between 60 and 200 kg/MW installed capacity, averaging 120 kg/MW. For indium in CIGS cells current estimates lay between 23 and 55.5 kg/MW installed capacity, averaging 32 kg/MW. There is agreement that this material intensity will decrease. Most authors believe this decrease to be exponential. The magnitude of the decrease is however more uncertain. Estimates from Viebahn et al. (2015) for 2050 are 5 times higher than the lowest estimates found by Nassar et al. (2016). To provide an impression of the range, estimations from different sources of the tellurium and indium content of CdTe and CIGS cells, respectively, are provided in Table 6.

Table 6: Material intensity of tellurium in CdTe and indium in CIGS cells by 2050.

	Material intensity (kg/MW installed capacity)					
Tellurium (CdTe)	35.3	11.1	20	30	18	
Indium (CIGS)	3	4.1	10			9
Source	Viebahn et al. (2015)	Nassar et al. (2016) (Neutral scenario)	Kavlak et al. (2015) in Davidsson & Höök (2017)	Bustamante & Gaustad (2014)	Houari et al. (2014)	Stamp et al. (2014)

Most sources give the current MI, the MI in 2050 and the MI at a year in between (usually 2025). To calculate the MI in the intermediate years an exponential curve is fitted to the three data points. For silver, the range of estimates found in literature is smaller. Nassar et al. (2016) and Davidsson & Höök (2017) expect similar MIs. Taking the average of the two papers gives a MI that decreases exponentially from 27.9 kg/MW in 2018 to 1.5 kg/MW by 2050.

4.1.3 Scenarios

It is thus uncertain how the market and MI will develop. This shows in the wide range of estimates used even within papers. These variations between and within papers indicates the need to take a cautious approach when performing calculations that are (partially) dependent on the future market share and MI of the technologies. To account for this uncertainty this paper used scenarios. In these scenarios three general trends regarding market share are kept in mind.

First, in every scenario c-Si has a significant, and in most cases the largest, share in the solar PV market. c-Si will therefore hold at least 50% of market share in the scenarios created in this paper. The possibility for a second 'silicon crisis' as happened in the 2008-2010 period was considered. Because of past experiences of the c-Si industry a second crisis is however not expected in this research. If a crisis would appear, it is expected to be solved sufficiently fast to not significantly affect the solar PV market. Secondly, a-Si seems to be disappearing from the market. There are scenarios that expect a small share of the market to be fulfilled by a-Si. However, this already commercial technology has been losing market share over the past years. In combination with the problems indicated by Jean et al. (2015) this paper assumes a-Si to not be part of the future solar PV market. Thirdly, the rise of 3rd generation solar PV technologies is taken into account. There is a large amount of research into these technologies and developments in the solar PV market are rapid. It would therefore be unrealistic to leave out 3rd generation solar PV in the future market. To date however these technologies are not yet commercial. It will thus take time before 3rd generation technologies obtain a visible market share. They are assumed to enter the market only after the investigated period.

To account for the range in estimates of the MI, different values are taken into account in the scenarios. The first scenario is a scenario in which CdTe and CIGS technologies fail to overcome their final drawbacks. This results in higher cost for these thin film technologies, making them unsuited for large scale deployment. Though the technologies will be preferred for some specific applications, c-Si dominates the market. c-Si will have a 90% market share. The remaining 10% is equally distributed between CdTe and CIGS cells. This scenario is similar to the *Continuity Roadmap* of Viebahn et al. (2015) and the *c-Si dominated* scenario of Bustamante & Gaustad (2014). Because of the limited development of CdTe and CIGS technologies, the decrease in MI is limited. The highest expected values of the MI for 2050 (Viebahn et al., 2015, for CdTe and Kavlak et al., 2015 for CIGS) are taken. This scenario is termed *'thin film failure'* (TFF).

The second scenario is a scenario in which thin film technology does take off. Though the 'incumbent' c-Si technology will still play an important role, a significant part of the market is taken by thin film solar PV. The question then arises which of the thin film technologies will win the battle for market share. This second scenario assumes that CIGS will outcompete CdTe and thus gain the largest market share. The market share of c-Si will decrease to 50%. 35% of the market is taken by CIGS solar PV and the remaining 15% are cells based on CdTe technology. This CIGS share is similar to the *Continuity Roadmap* of Viebahn et al. (2015) and the *CISG dominated* scenario of Bustamante & Gaustad (2014). Also Stamp et al. (2014) and Choi et al. (2016) expect a large share of the market (30% and 25%, respectively) to be taken by CIGS solar PV. It must be noted however that these two latter researches only look at CIGS solar PV. Regarding the MI, the MI of CIGS is expected to decrease significantly given the successful development of the technology. The lowest estimate for the MI of indium in CIGS technology (from Viebahn et al., 2015) is used. CdTe technology does not develop as well as CIGS technology, but MI still decreases significantly. The average of the values presented in Table 6 is used for the MI of tellurium in CdTe technology.

The third scenario is similar to the second scenario, only CdTe and CIGS switch places. This corresponds most closely to the CdTe dominated scenario of Bustamante & Gaustad (2014). c-Si thus has a market share of 50%, the share of CdTe is 35% and CIGS takes the remaining 15%. The MI of tellurium in CdTe cells is the lowest value, the one expected in the neutral scenario by Nassar et al. (2016). The MI of indium in CIGS cells is the average of the values presented in Table 6.

The scenarios are presented in Table 7 and Table 8. In each scenario, developments of silver in c-Si cells is assumed to be the same, as in each scenario c-Si cells retain a large market share. This provides sufficient opportunity to decrease the MI in every scenario. Applying the three scenarios in the Baseline and Climate Policy case gives a total of 6 scenarios for solar PV.

Table 7: Development of market share in the different scenarios.

Scenario	Technology	Market share (%) in:		
		2030	2040	2050
Thin film failure Thin film fails to overcome drawbacks and remains inferior to c-Si	CdTe	2.5	3.8	5
	CIGS	2.5	3.8	5
	c-Si	95	92.5	90
CIGS Success Thin film overcomes its current drawbacks and CIGS wins from CdTe	CdTe	6.3	10.6	15
	CIGS	13.8	24.4	35
	c-Si	79.9	65	50
CdTe Success Thin film overcomes its current drawbacks and CdTe wins from CIGS	CdTe	13.6	24.4	35
	CIGS	6.3	10.6	15
	c-Si	79.9	65	50

Table 8: Development of MI in the different scenarios.

Scenario	Technology (material)	MI (kg/MW) in:		
		2030	2040	2050
Thin film failure Thin film fails to overcome drawbacks and remains inferior to c-Si	CdTe (Tellurium)	52.4	40.8	35.3
	CIGS (Indium)	10.5	10	10
	c-Si (Silver)	9.2	3.7	1.5
CIGS Success Thin film overcomes its current drawbacks and CIGS wins from CdTe	CdTe (Tellurium)	34.8	26.3	21.8
	CIGS (Indium)	18.5	8	3
	c-Si (Silver)	9.2	3.7	1.5
CdTe Success Thin film overcomes its current drawbacks and CdTe wins from CIGS	CdTe (Tellurium)	30.9	18.5	5.8
	CIGS (Indium)	13.6	8.9	6.4
	c-Si (Silver)	9.2	3.7	1.5

4.2 Wind Turbines

4.2.1. Technologies

Different types of wind turbines are available on the market nowadays. The types of turbines can be distinguished in many different ways. Brumme (2012) identifies classifications according to generator type, size, shape and tower design. For this research, wind turbines are distinguished on the basis of generator type. This is done because the generator is the part of the wind turbine that contains the characterizing materials for wind turbine technologies. The material resources are discussed more elaborate in section 4.2.2. of this report. Within generator types, more distinctions can be made. The first, and for this research most important, one is whether the generator contains a permanent magnet (PM). Then, a distinction can be made between geared (high speed, HS, and middle speed, MS) and direct-drive (DD) systems. A final distinction is between synchronous and asynchronous generators (SG and AG, respectively). On the basis of these classifications, the following generator types can be distinguished:

Asynchronous generator (AG)
Synchronous direct drive generator without permanent magnets (SG-E-DD)
Synchronous middle speed geared generator with permanent magnets (SG-PM-MS)
Synchronous high speed geared generator with permanent magnets (SG-PM-HS)
Synchronous direct drive generator with permanent magnets (SG-PM-DD)

These are the five main types of generators used in the analysis of Viebahn et al. (2015). Similar classifications are used by other authors. Next to these existing types of generators, Viebahn et al. (2015) identify *high temperature superconductor, direct drive (HTS-DD) wind turbines* as an emerging technology. Also Lacal-Arántegui (2015), Pavel et al. (2017) and Hernández et al. (2017) indicate the possible emerge of HTS-DD turbines. An overall distinction can be made regarding the location of the wind turbines: on- and offshore. This distinction is important as not all types of generators are equally suited for on- and offshore application.

Past developments in the wind turbine market

Before discussing the future developments in the wind turbine market it is useful to have an insight into the past developments of the market. Zhang (2013) gives a clear and concise description of the past developments. In the first years of the 20th century the first wind turbines for electricity generation were already installed. From the first wind turbines with a capacity of 35 kW developments have led to wind turbines with a capacity of 6 MW. With the capacity the size of the turbines increases as is clearly shown in Figure 6. Initially wind turbines were all built on land but in the past years the amount of wind turbine projects located offshore has been increasing. Offshore projects started in 1991 with a 5000 kW windfarm. Nowadays GW scale projects are under development for offshore locations. With respect to the type of generator, AG and SG-E-DD generators have dominated the market in de past decades (Viebahn et al, 2015; Nassar et al, 2016). These AG and SG-E-DD generators can thus be considered as the 'traditional' generators. Together they hold a global market share of about 90%. This share however seems to have been decreasing in the past years in favour of SG-PM generators, mainly the DD type (Pavel et al., 2017), that were introduced in 2005 (Zhang, 2013). The newer SG-DD-PM generators have several advantages over the traditional generators. The main advantage mentioned by most authors is a reduced need for operation maintenance (O&M) of the DD concept compared to a geared turbine (Hoenderdaal et al., 2013; Zimmermann et al., 2013; Brumme, 2012). Furthermore, SG-PM-DD generators are lighter and have a more compact design (Brumme, 2012; Pavel et al., 2017).

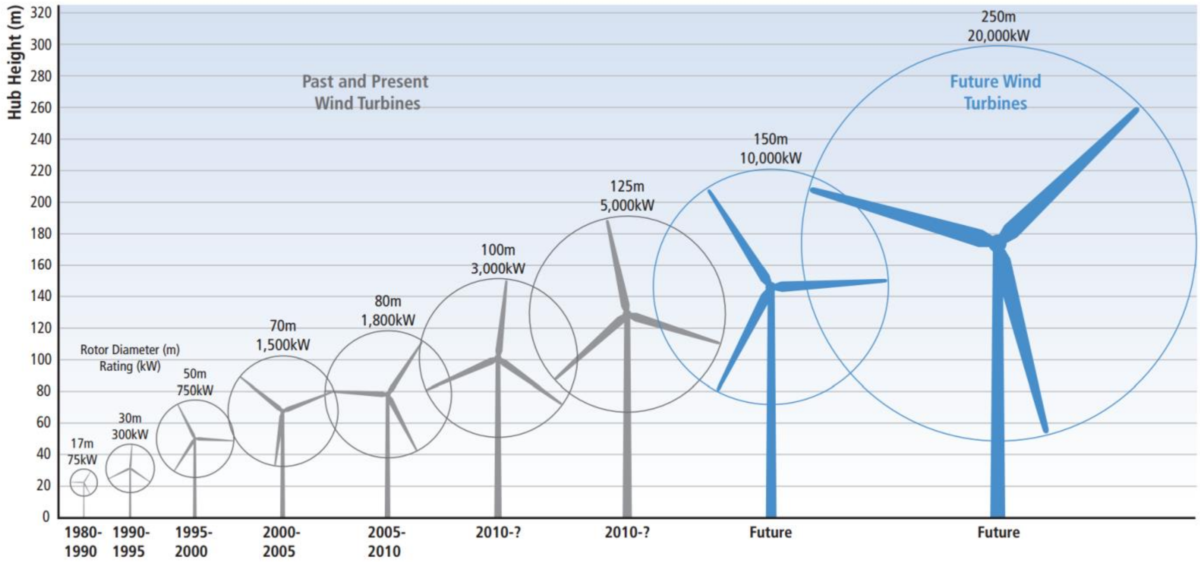

Figure 6: Increasing wind turbine size and capacity (IPCC, n.d.).

Future developments in the wind turbine market

To understand the future developments in the wind turbine market, we first have to look at the developments in on- versus offshore wind. Offshore wind currently has a market share of only 3% (Hernández et al., 2017). Because of several factors the offshore market share is expected to increase. Large turbines face difficulties in transportation over land (Zimmermann et al., 2013). Furthermore, available space on land is scarcer than at sea (Kumar et al., 2016) and public resistance against land based wind turbines in growing. The new offshore capacity is expected to be largely constituted by SG-PM-DD turbines (Zimmerman et al., 2013; Viebahn et al, 2015). They require a larger investment than the traditional turbines. This larger investment, however, is compensated by the advantages of PM-DD turbines, mainly the reduced O&M. Especially for offshore turbines these advantages result in lower O&M cost. The HTS-DD concept is unlikely to have gained significant market share by 2050, to date there are no prototypes available for this technology (Pavel et al., 2017). The only authors that take into account a possible market share for HTS-DD generators are Viebahn et al. (2015). Expectations of different authors for the market share of different wind turbine technologies are given in Table 9 (onshore) and Table 10 (offshore).

Table 9: Onshore market share of different wind turbine technologies by 2050.

Onshore market share of different wind turbine technologies by 2050					Source
Traditional		Permanent Magnet Based			
AG	SG-E-DD	SG-PM-HS	SG-PM-MS	SG-PM-DD	
12%	52%	31%	5%	0%	Viebahn et al. (2015) Continuity Roadmap, Germany
2%	3%	41%	14%	40%	Viebahn et al. (2015) Upscaling Roadmap, Germany
95%		5%			Nassar et al. (2016) Low PM share, no on/offshore distinction, US
50%		50%			Nassar et al. (2016) High PM share, no on/offshore distinction, US
65%				35%	Hoenderdaal et al. (2013) Low PM-DD share
50%				50%	Hoenderdaal et al. (2013) High PM-DD market share

20%	40%			40%	Zimmermann et al. (2013) Germany
90%		10%			Brumme (2012) Low PM share
75%		25%			Brumme (2012) High PM share

Table 10: Offshore market share of different wind turbine technologies by 2050.

Offshore market share of different wind turbine technologies by 2050					Source
Traditional		Permanent Magnet Based			
AG	SG-E-DD	SG-PM-HS	SG-PM-MS	SG-PM-DD	
50%	0%	1%	34%	15%	Viebahn et al. (2015) Continuity Roadmap, Germany
2%	0%	0%	61%	37%	Viebahn et al. (2015) Upscaling Roadmap, Germany
95%		5%			Nassar et al. (2016) Low PM share, no on/offshore distinction, US
50%		50%			Nassar et al. (2016) High PM share, no on/offshore distinction, US
65%				35%	Hoenderdaal et al. (2013) Low PM-DD share, no on/offshore distinction
50%				50%	Hoenderdaal et al. (2013) High PM-DD share, no on/offshore distinction
10%	40%			50%	Zimmermann et al. (2013) Germany
90%		10%			Brumme (2012) Low PM share
25%		75%			Brumme (2012) High PM share

4.2.2. Material Resources

Characterizing materials

The part of the wind turbine that characterizes *the turbine itself* is the generator technology. The generator types that were discussed either do or do not contain a permanent magnet. AG and SG-E-DD generators do not have a permanent magnet and contain bulk materials like copper and steel. For the generators that do contain a permanent magnet (SG-PM-MS/HS/DD generators) the material resources in the permanent magnet are the characterizing materials.

The magnets used in PM turbines are neodymium based (neodymium-iron-boron, NdFeB). Neodymium is thus one of the characterizing materials. Usually about 30 m% (mass percentage) of an NdFeB magnet consists of Nd (Hoenderdaal et al., 2013). However, pure NdFeB magnets have a maximum working temperature of 80 ^{o}C. To increase the maximum working temperature, and reduce the need for cooling, a small amount of dysprosium is often added to the magnets. This increases the working temperature to 120 ^{o}C, and additionally reduces corrosion. Nowadays Dy makes up for about 4.5 m% of NdFeB magnets for wind turbines (Hoenderdaal et al., 2013).

Next to Nd and Dy, NdFeB magnets can contain praseodymium (Pr) and terbium (Tb) (Nassar et al., 2016; Zhang, 2013; Pavel et al., 2017; Hjortsberg, 2016). Pr and Tb are however only briefly addressed in some papers. Too little information on these material is available to further take them into account in this paper. The characterizing materials for wind turbines that are discussed in this paper are thus Nd and Dy. Pavel et al. (2017) looked into possible substitutes for material resources in PM generator. However, no feasible options were found.

Material intensity
The factors that determine the MI of wind turbine generators are less complex than is the case for solar PV. The generator type determines to a large extend the size of the magnet. The size of the magnet in turn determines the amount of Nd and Dy needed, as the magnet is mainly made out of those two material resources. The exact amount of Nd and Dy depends on the m%, but figures for these percentages differ only slightly. The m% is thus not a variable that could change to such values that it would significantly influence the MI. It should be noted here that the MI of SG-PM-MS/HS turbines is significantly lower than of a SG-PM-DD turbine. This is the result of the fact that the geared MS and HS turbines have significantly smaller magnets. Because of the fact that most of the PM turbines are expected to be of the DD type and only little material resources are required for the MS/HS turbines, these MS/HS turbines are not further included in the analysis.

Development of material intensity
Currently, the MI of Nd and Dy in wind turbines is around 200 and 20 kg/MW installed capacity, respectively. For reasons of simplicity, many papers assume the MI to remain constant in the coming decades (Pavel et al., 2017; Hoenderdaal et al., 2013). However, as for solar PV, it can be expected that the MI will decrease in the coming years because of technological development. Nassar et al. (2016), Viebahn et al. (2015) and Brumme (2012) make projections for the MI in wind turbines by 2050. An overview of their results is presented in Table 11.

Table 11: Material intensity of Nd and Dy in SG-PM-DD wind turbines by 2050.

	Material intensity (kg/MW installed capacity)		
Neodymium	130	143	142.6
Dysprosium	11.7	7.5	8.3
Source	Viebahn et al. (2015)	Brumme (2012)	Nassar et al. (2016)

The estimates of the MI display only a small range. It was therefore decided to use the average of these values (139 kg Nd/MW and 9.2 kg Dy/MW) for further calculations related to the material resource demand for wind turbines. Most sources give the current MI and the MI in 2050. To calculate the MI in the intermediate years an exponential curve is fitted to the data points.

4.2.3. Scenarios
As is the case with the solar PV market, there is a range in the estimates of the future market share of different technologies. There does however seem to be a more clear trend than was the case for solar PV. Still, these projections are only expectations. A cautious approach is again necessary when performing calculations on basis of these expectations. To account for the uncertainty of the future developments three scenarios were created. In these scenarios, some general trends are kept in mind.

The first trend is that the traditional technologies lose market share to PM technologies. This is the case for both on- and offshore located turbines. In each scenario, the share of traditional technologies will thus be lower and the share of PM technologies higher compared to current shares. The second trend that can be seen is that the share of PM technologies is higher offshore than onshore. Each scenario will thus have a higher PM share offshore than onshore. Finally, PM-DD turbines are expected to constitute the majority of the PM turbine capacity.

Three different scenarios, Low PM, Medium PM and High PM, were created. For the Low PM scenario, the average of the low PM estimations of Nassar et al. (2016), Hoenderdaal et al. (2013)

and Brumme (2012) is used. For the Medium PM scenario, the average of all total PM share estimations is used. For the High PM scenario, the average of the high PM estimates of Nassar et al. (2016), Hoenderdaal et al. (2013) and Brumme (2012) is used. It must be noted however that Nassar et al. (2016) and Brumme (2012) do not explicitly distinguish between different PM types. Given the fact that PM-DD turbines are expected to gain the largest market share, it is assumed that 90% of their projected PM share can be allocated to the DD type. Given the small range in estimates for the MI, the MI is assumed to be the same in each scenario. This lead to the PM-DD market shares within the wind turbine market and constant MI as presented in Table 12 and Table 13. Applying the three scenarios in the Baseline and Climate Policy case gives a total of six scenarios for wind turbines.

Table 12: Development of SG-PM-DD market share in the wind turbine market in the different scenarios.

Scenario	Technology	Market share[1] (%) in:		
		2030	2040	2050
Low PM PM turbines do not overcome and remain inferior to non-PM turbines	Onshore SG-PM-DD	15.5	15.8	16.2
	Offshore SG-PM-DD	15.5	15.8	16.2
Medium PM PM turbines overcome some drawbacks, slowly gain market share	Onshore SG-PM-DD	22.9	29.4	36.0
	Offshore SG-PM-DD	25.9	34.9	44.0
High PM PM turbines overcome most drawbacks,	Onshore SG-PM-DD	24.1	31.6	39.2
	Offshore SG-PM-DD	29.7	42.0	54.2

[1]Market share within the wind turbine market.

Table 13: Development of MI of Nd and Dy in SG-PM-DD turbines in the different scenarios.

Scenario	Material resource	MI (kg/MW) in:		
		2030	2040	2050
The MI is the same in each scenario and for on- and offshore turbines	Neodymium	180.0	157.2	139
	Dysprosium	11.9	10.4	9.3

4.3. Other uses of material resources

The other uses of the five material resources under investigation have already shortly been addressed in the Introduction. In this chapter these other applications are explored in more detail. Of each material resource it is discussed what the main other uses are.

4.3.1. Tellurium

Tellurium is mainly extracted as a by-product of copper. It is a material that is found in the 'waste' that remains after copper ore is refined to copper. This waste still has to undergo some complex processes before several material resources, such as tellurium, can be extracted (Speirs et al., 2011).

In 2009, CdTe solar PV was responsible for 11% of the demand for tellurium (Shon-Roy, 2009, in Speirs et al., 2011). In the past years however, the production of CdTe cells has grown to such a size that nowadays the largest demand for tellurium comes from the CdTe solar PV industry (Schulz et al., 2018). Furthermore, a large part of tellurium demand comes from the thermo-electric devices industry (e.g. refrigeration, heat-to-energy appliances) (EU Commission, 2017). An overview of the application of tellurium is given in Figure 7.

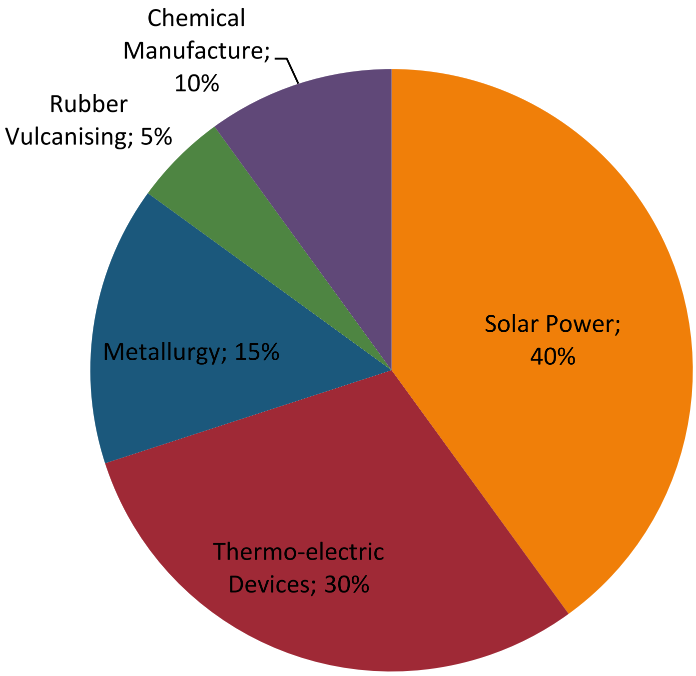

Figure 7: End uses of tellurium (based on EU Commission, 2017).

Variable supply of tellurium and foreseen demand from the solar PV industry already led to great price variations in the past (Speirs et al., 2011). Speirs et al. (2011) attribute these variations in price to the lack of a solid constant market for tellurium.

4.3.2. Indium

Indium is a metal that is mainly extracted as a by-product of zinc. This means that indium recovery is not solely dependent on the indium price but also on the price of zinc. There are other minerals that contain indium as a by-product, but the indium concentration in those minerals is generally significantly lower (Speirs et al., 2011). This makes extraction of indium less attractive.

Indium is mainly used to make indium-tin-oxide (ITO). This ITO finds its main uses in appliances with flat screens like televisions and computer screens (Speirs et al., 2011). It was estimates in 2009 that 65% of indium was used for application in flat screens (Fthenakis, 2009, in Speirs et al., 2011).

Furthermore, indium is used for CIGS solar PV cells and certain solders (EU Commission, 2017). An overview of the worldwide indium end-use in 2013 is given in Figure 8.

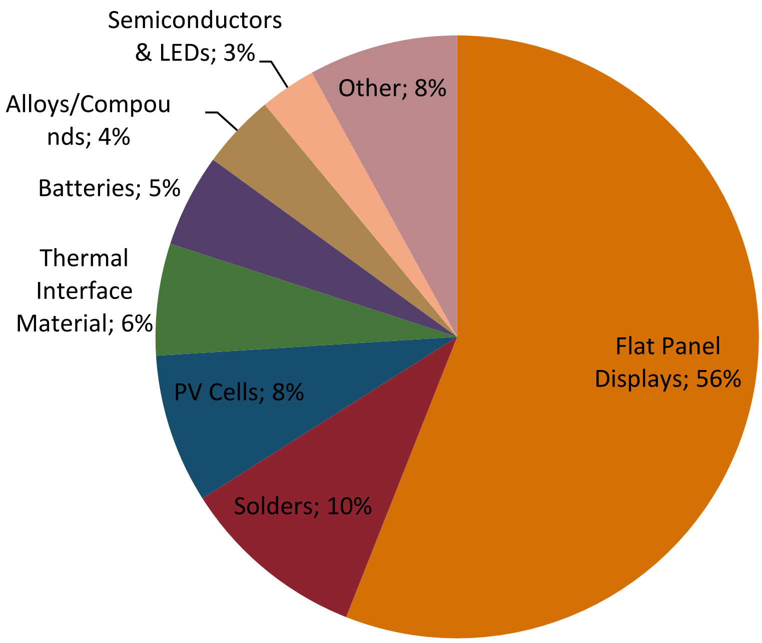

Figure 8: End uses of indium in 2013 (based on Indium Corporation, 2013, in EU Commission, 2017).

4.3.3. Silver

Silver is an element that is extracted as a primary product. Most of the silver is used for different industrial purposes (59%), mainly in electrical and electronic devices (24%). Furthermore jewellery is responsible for a large share of the silver use (20%). An overview of the worldwide silver end-use is given in Figure 9.

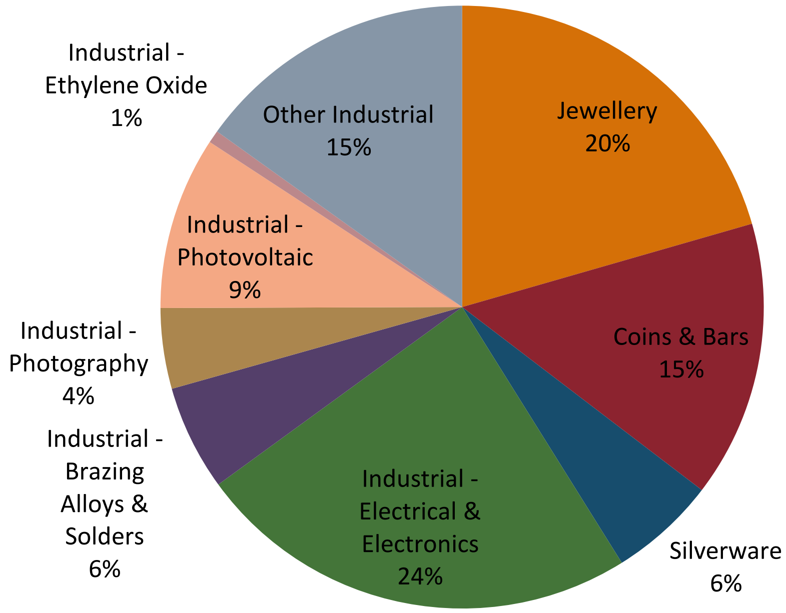

Figure 9: End uses of silver in 2017 (based on Statista, n.d.).

4.3.3. Neodymium

Neodymium is an element that is mainly found in the minerals monazite and bastnäsite. Monazite however contains the radioactive compound thorium, making the mineral difficult to handle safely. Bastnäsite is therefore the main source of neodymium (Zhang, 2013).

Neodymium finds its main use in strong permanent magnets. These magnets are not only used in the upcoming wind turbine market but also applied widely in many consumer items like smartphones and computers. All electronical and electric devices combined are responsible 58% of the tellurium demand. Another upcoming market is also the EV industry, that is already responsible for 19% of the neodymium demand. An overview of the end uses of neodymium is given in Figure 10, based on Peiró et al. (2013) in Zhang (2013).

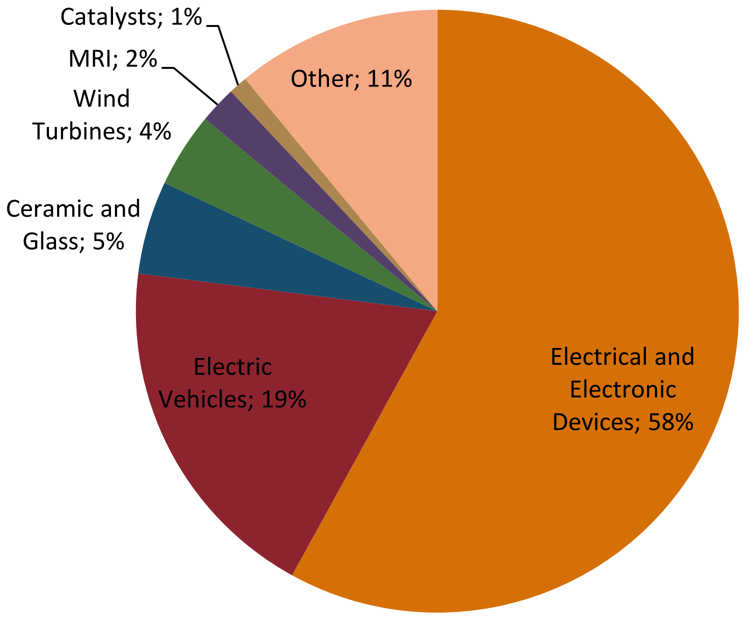

Figure 10: Neodymium application by percentage (based on Zhang, 2013).

4.3.4. Dysprosium

Like neodymium, dysprosium is found in several minerals. Dysprosium is discussed in this paper as part of neodymium based magnets. This is also the most important demand source for dysprosium, accounting for about 90% of demand (Bell, 2018). These magnets are used in wind turbines and EVs. Because of the expected growth of those two applications, the PMs share in dysprosium demand will rise even further in the next years (RCS, n.d.).

4.4. Televisions

From the IMAGE data (Deetman et al., 2018) it becomes clear that TVs are the largest individual category within the electronic appliances group. Furthermore, from the review of the five material resources it becomes clear that today these TVs also constitute the largest source of indium demand. Data from IMAGE can thus again serve as the basis for determining indium demand. Additionally, literature is reviewed to find the market share of TVs that contain indium and to determine the MI of indium in TVs.

4.4.1. Technologies

The amount of televisions has grown rapidly in the past decades (Chen et al., 2018). This growth will continue in the coming decades as nearly each year TV sales are expected to rise (Deetman et al., 2018). The expected amount of newly bought TVs in the years up to 2050 is shown in Figure 11, based on projections by IMAGE.

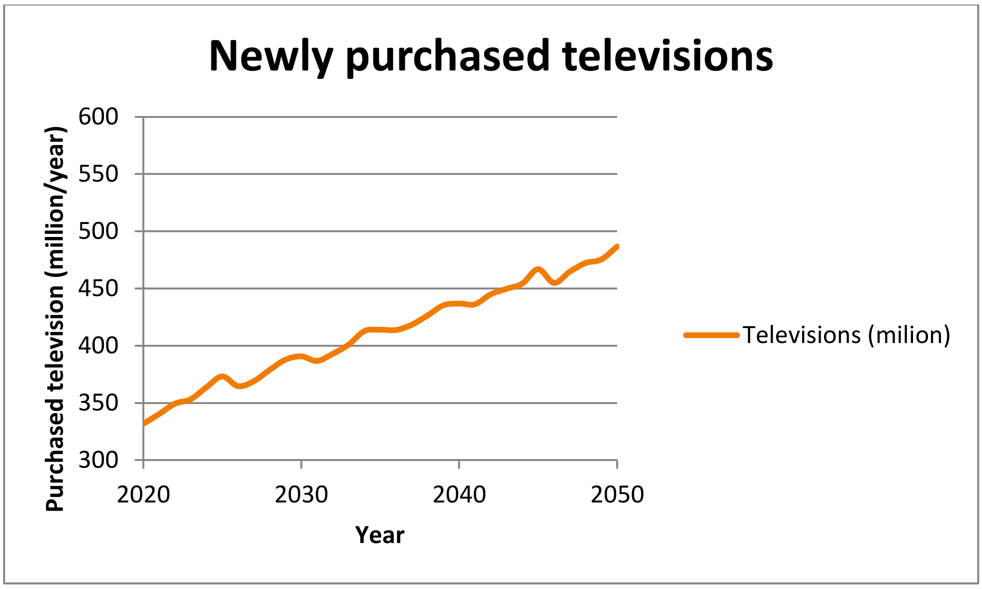

Figure 11: Newly purchased televisions.

With the increase in TV sales, the size of the TVs also increases. This has been the case in recent years and is expected to remain a trend in the coming years. Current TVs are mainly based on 3 different technologies.

- The most 'traditional' one is the liquid crystal display (LCD) TV. This technology has been on the market since the beginning of the century. It uses tiny LEDs that shine light on the liquid crystals in the screen. These crystals in turn light up and create the actual image (Oving, 2018).
- A new technology that uses the LCD principle as basis is quantum dot (QD) technology. The name used by TV brands differs from simply QD TV to QLED and SUHD. The technology uses and LCD screen to which nano-crystals are added. These crystals increase the brightness of the TV and reduce energy use (Chel, 2015).
- In organic LED (OLED) televisions the LCD screen and the LEDs are replaced by OLEDs. These OLEDs are pixels that light up individually and directly create the image on your screen (Oving, 2018).

For a more elaborate explanation of OLED and LCD, see Oving (2018). A distinction can thus be made between TVs that do and do not use an LCD screen. This distinction is important as LCD screen contain one of the material resources that are investigated in the current research: indium. To determine the future indium demand from the TV industry, it is necessary to determine the future market share of LCD TVs and the indium content of those televisions.

Market share

Most of the modern television screen are LCD screens. These types of screens have dominated the market since the beginning of the century (Chen et al., 2018). For many years there was little competition, but in 2012 LG introduced the OLED TVs (LG, n.d.). More new technologies have been introduced since and LCD TVs are starting to lose market share to these new technologies (Chen et al., 2018). Chen et al. (2018) expect OLED TVs to take a total market share of 2.7% by 2021, coming from 0.6% in 2017. In that same period, Chen et al. (2018) expect QD LCD TVs to rise from 2.1% to 6.7% market share. When we make the same assumption as for the development of the market shares of wind turbines and solar PV cells, the share of these technologies increases linearly. This would mean that OLED TVs acquire 18% of market share by 2050, leaving 40% for QD LCD TVs and 42% for traditional LCD TVs.

4.4.2. Material resources

Material intensity

The indium in LCD televisions is located in the LCD glass of the TV. Several researchers look into the recycling of indium from this LCD glass and find indium contents ranging between 200 and 300 g indium/tonne LCD glass (Yang et al., 2013; Lee et al., 2013; Silveira et al, 2015; Ma and Xu, 2013; Kato et al., 2013). The average of the estimations is 247 g indium/tonne LCD glass.

Now, the amount of LCD glass in a television has to be determined. Thomas et al. (2012) look at the global warming potential of LCD flat screens by performing a life cycle analysis. In their analysis, they use a standard 40-in. LCD television that weights 12 kg. This television contains an LCD screen that weight 1.758 kg, giving a m% of LCD glass in an LCD television of 15%. It is a gross assumption that this represents the average television. Still, this distribution in weight is also used in the current research due to lack of better data. A standard 40-in. 12 kg LCD television would then contain 0.43 grams of indium.

Development of material intensity

No information was found on the development of the amount of indium contained in the LCD glass. It could be expected that, as is the case with solar PV, there is some kind of technological learning. This learning would results in a reduce in material resource use, including indium. At the same time however, the size of the TVs increases. This leads to bigger LCD screens and thus an increase in indium demand. Because of a lack of data and the two counteracting trends, it is assumed that the material intensity does not change in the investigated period.

An overview of the development of the TV market until 2050 is given in Table 14.

Table 14: Developments of market share and MI of TV technologies.

		Market Share (%)				MI
Year	Televisions (milion)	OLED TV	QD LCD TV	Traditional LCD TV	Total LCD (QD + Traditional)	gram indium/TV
2030	391	7%	17%	76%	93%	0.43
2040	437	13%	29%	59%	87%	0.43
2050	487	18%	40%	42%	82%	0.43

5. Results

The aim of this research was to find the annual demand for the material resources needed in green energy technologies. Combining all the data that was gathered on the technologies and their development results in this yearly demand for each of the investigated materials. These results are presented in this chapter. The yearly demand is dependent on three factors, namely the market share of the technologies, their material intensity and the yearly installed capacity. The influence each of these factors has on the results is explained. First, results for solar PV are presented, then results for wind turbines are shown. After discussing the developments in solar PV an wind turbines individually, observations that can be made from combining and comparing wind and solar, and the Baseline case and Climate Policy case, are discussed. Then, demand for indium from the TV industry is presented. To put the results into perspective, the results section concludes with a comparison of the material resource demand to current production levels and reserves.

5.1. Solar PV

Table 15 and Table 16 show how the yearly demand for the tellurium, indium and silver develops. They show the development of the material resource demand in different scenarios in the Baseline case and the Climate Policy case, respectively. The results are given in tonne/year in steps of 5 years until the end of the investigated period, 2050. Additionally Table A 2 and Table A 3 were included in the appendix to clearly show the relative increase in demand for each year in every scenario.

Table 15: Development of annual material resource demand for solar PV in different scenarios in the Baseline case.

Scenario	Material	Demand in tonne/year for:						
		2020	2025	2030	2035	2040	2045	2050
TFF	Tellurium	13	28	48	84	88	112	131
	Indium	4	7	10	18	22	31	41
	Silver	360	353	323	316	198	154	112
CIGS SUC	Tellurium	19	47	80	142	162	219	270
	Indium	21	59	94	135	113	112	100
	Silver	350	320	271	244	139	97	62
CdTe SUC	Tellurium	26	85	157	264	261	303	318
	Indium	7	19	31	53	55	69	80
	Silver	350	320	271	244	139	97	62

A number of observations can be made regarding the development of the material resource demand. The amount of newly installed solar PV capacity keeps increasing until 2050. The decrease of MI is not enough to offset the effect of the increase in installed capacity and the increased market share of thin film solar PV. The demand for indium and tellurium thus keeps increasing. One exception to this trend is the demand for indium in the CIGS SUC case. Because of the significant decrease of the MI, the yearly demand for indium constantly decreases from 2043 onwards. The demand for silver decrease significantly in every scenario. This is caused by a combination of a decrease in market share and a decrease in MI.

Taking a closer look at the relative increase in Table A 2 provides insight into the years in which supply for the material resources should scale up fastest. The table shows that for solar PV, the percent increase in demand is strongest in the years till 2026 with again a small peak around 2033. For silver these two periods are the only time there is a percent increase. For all other years the demand for silver decreases compared to the previous year. Of the three factors that determine the yearly demand, only two (yearly installed capacity and MI) affect the development of the relative increase. On the one hand, the exponentially decreasing MI reduces the material resource demand, especially in the first years of the investigated period. At the same time however in those years the installed capacity of solar PV increases fastest (relatively). This fast relative increase in installed capacity causes the material resource demand to increase faster than the MI decreases it. The third factor, market share, changes linearly and thus does not influence the *relative* change in demand.

Table 16: Development of annual material resource demand for solar PV in different scenarios in the Climate Policy case.

Scenario	Material	Demand in tonne/year for:						
		2020	2025	2030	2035	2040	2045	2050
TFF	Tellurium	11	20	42	169	187	205	165
	Indium	3	5	8	37	46	57	52
	Silver	307	250	279	641	419	281	141
CIGS SUC	Tellurium	16	33	69	288	342	400	342
	Indium	18	42	81	272	239	205	127
	Silver	298	227	234	494	294	177	78
CdTe SUC	Tellurium	22	60	136	534	551	554	402
	Indium	6	13	27	107	116	126	101
	Silver	298	227	234	494	294	177	78

In the Climate Policy case developments start later and, in order to meet the climate targets, lead to a higher cumulative installed capacity and material resource demand than in the Baseline case. After the rapid increase in the 2030-'35 period tellurium and indium demand levels off and starts to decrease after 2046. This decrease is the result of a decreasing MI and a slight decrease in newly installed capacity. Indium in the CIGS SUC case is again an exception. With its peak demand in 2037 demand already starts decreasing from 2038 onwards because of the significant decrease in MI.

Table 15 and Table 16 and Table A 2 and Table A 3 give the most detailed information about the development of material resource demand. However, it is hard to visualise the development and compare the different cases on basis of these tables. Figure 12 through Figure 14 allow for easier comparison of both the development path and the total demand for the material resources in the investigated period. These figures show the cumulative demand for material resources for solar PV.

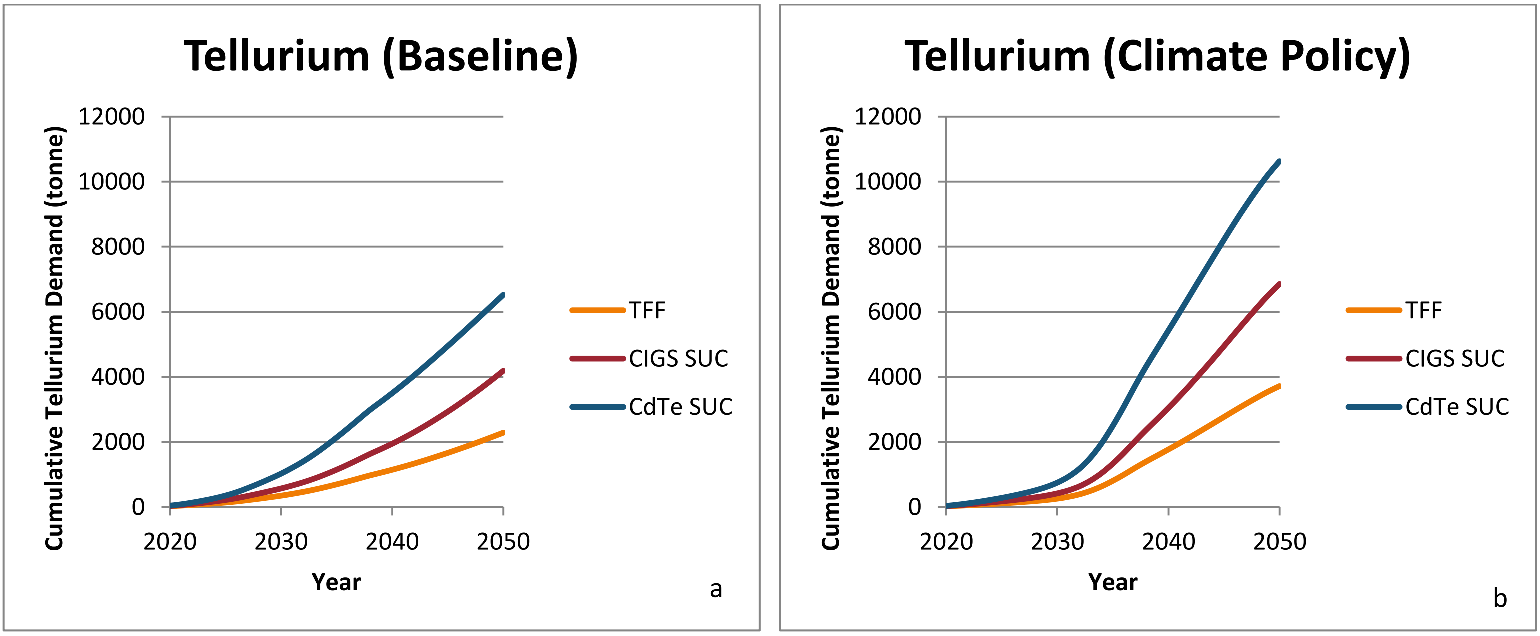

Figure 12: Cumulative demand for tellurium in a) Baseline case and b) Climate Policy case.

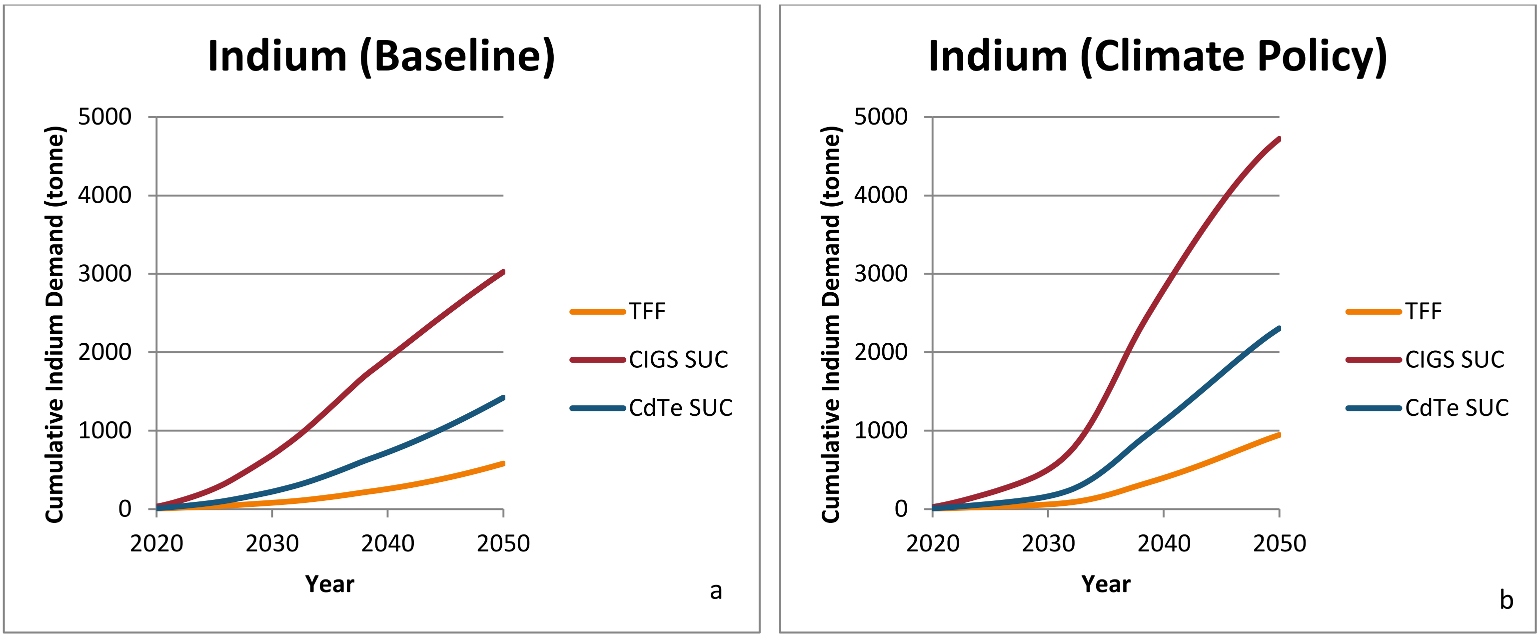

Figure 13: Cumulative demand for indium in a) Baseline case and b) Climate Policy case.

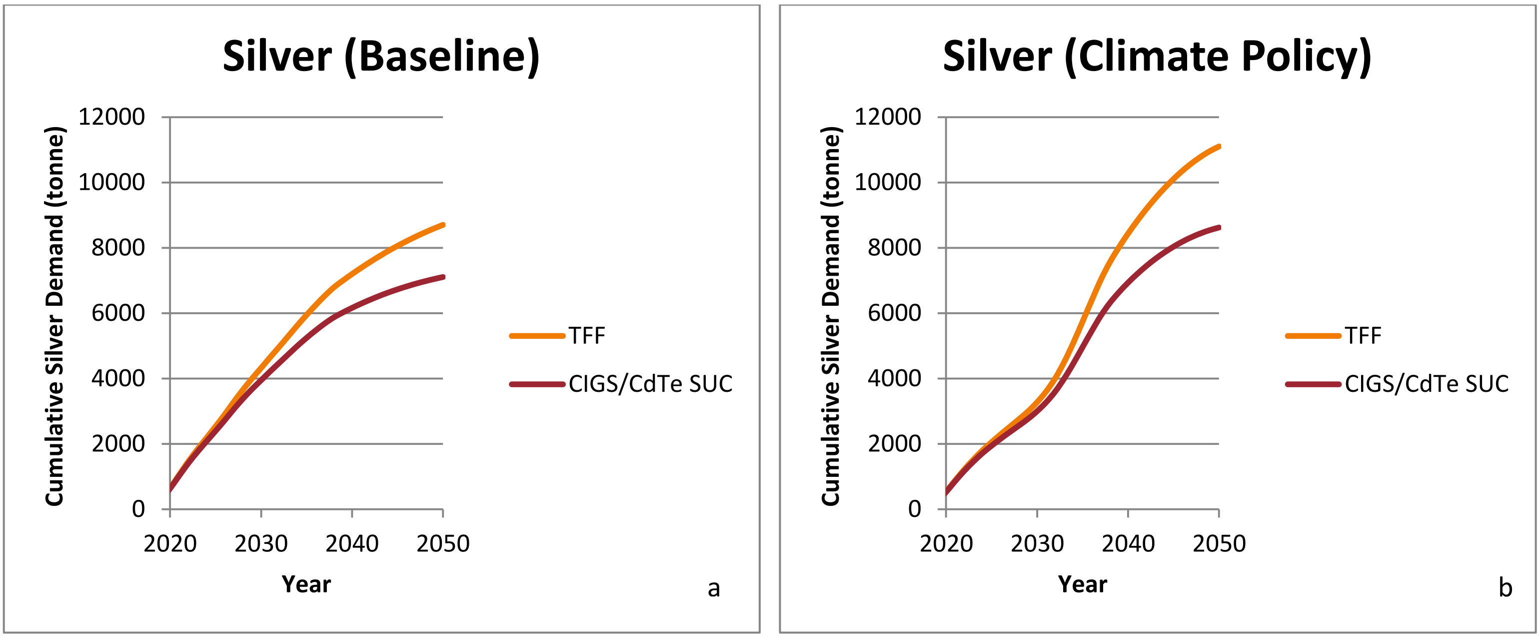

Figure 14: Cumulative demand for silver in a) Baseline case and b) Climate Policy case.

In both the Baseline and the Climate Policy case, it can be observed that the amount of (near-) critical materials needed is more than 50% smaller in the CIGS SUC scenario than in the CdTe SUC scenario. This smaller requirement for materials results from the fact that the indium intensity of CIGS solar PV is smaller than the tellurium intensity of CdTe solar PV. Whether this is positive in the light of material resource constraints should be determined on the basis of data on the availability of both material resources and demand from other applications.

Furthermore, both cases show that with the decreasing share of c-Si cells, the yearly demand for silver also decreases. In the Baseline case this is mainly the result of the decreased MI; the absolute amount of yearly installed capacity still increases in the first half of the investigated period and does not decrease significantly in the second half. In the Climate Policy case the decrease in yearly silver demand stems from a combination of the two factors. From 2037 onwards the yearly installed c-Si capacity decreases significantly.

5.2. Wind turbines

To show how the yearly demand for neodymium and dysprosium develops Table 17 and Table 18 were created. They show the development of the material resource demand in different scenarios the Baseline case and the Climate Policy case, respectively. The results are given in tonne/year in steps of 5 years until the end of the investigated period, 2050. Additionally Table A 2 and Table A 3 were included in the appendix to clearly show the relative increase in demand for each year in every scenario.

Table 17: Development of annual material resource demand for wind turbines in different scenarios under the Baseline case.

Scenario	Material	Demand in tonne/year for:						
		2020	2025	2030	2035	2040	2045	2050
Low PM	Neodymium	556	861	1294	1377	1318	1399	1119
	Dysprosium	37	57	85	91	87	92	74
Medium PM	Neodymium	603	1114	1941	2348	2509	2928	2556
	Dysprosium	40	74	128	155	166	193	169
High PM	Neodymium	611	1161	2063	2538	2742	3224	2838
	Dysprosium	40	77	136	168	181	213	188

In the Baseline case, the amount of yearly installed capacity of onshore and offshore wind turbines increases until 2044, after which a slight decrease can be observed. The share of PM turbines keeps increasing during the final years but the combination of a decrease in total installed capacity and a decreasing MI causes an overall decrease in neodymium and dysprosium demand.

Taking a closer look at the relative increase in Table A 2 shows similar development for wind turbines as for solar PV. The highest relative increase occurs in the years till 2026 with again a small peak around 2033. Relative increases are however less strong than for solar PV.

Table 18: Development of annual material resource demand for wind turbines in different scenarios under the Climate Policy case.

Scenario	Material	Demand in tonne/year for:						
		2020	2025	2030	2035	2040	2045	2050
Low PM	Neodymium	582	345	487	1727	2068	2553	2913
	Dysprosium	39	23	32	114	137	169	192
Medium PM	Neodymium	631	449	734	2941	3913	5295	6577
	Dysprosium	42	30	48	194	258	350	435
High PM	Neodymium	639	470	783	3174	4259	5795	7245
	Dysprosium	42	31	52	210	281	383	479

Developments for wind turbines are similar those of solar PV in the first half of the investigated period. Developments start later, but lead to a higher cumulative installed capacity, and the relative increase in demand is strongest in the 2030-’35 period. This can be seen more clearly in Table A 3 of the appendix. For solar PV however, material resource demand started to drop after 2046. For neodymium and dysprosium, demand just keeps increasing until the end of the investigated period. This can again be seen more clearly in Table A 3 of the appendix.

Table 17 and Table 18 and Table A 2 and Table A 3 give the most detailed information about the development of material resource demand. However, it is hard to visualise the development and compare the different cases from these tables. Figure 15 and Figure 16 allow for easier comparison of both the development path and the total demand for the material resources in the investigated period. These figures show the cumulative demand for material resources for wind turbines.

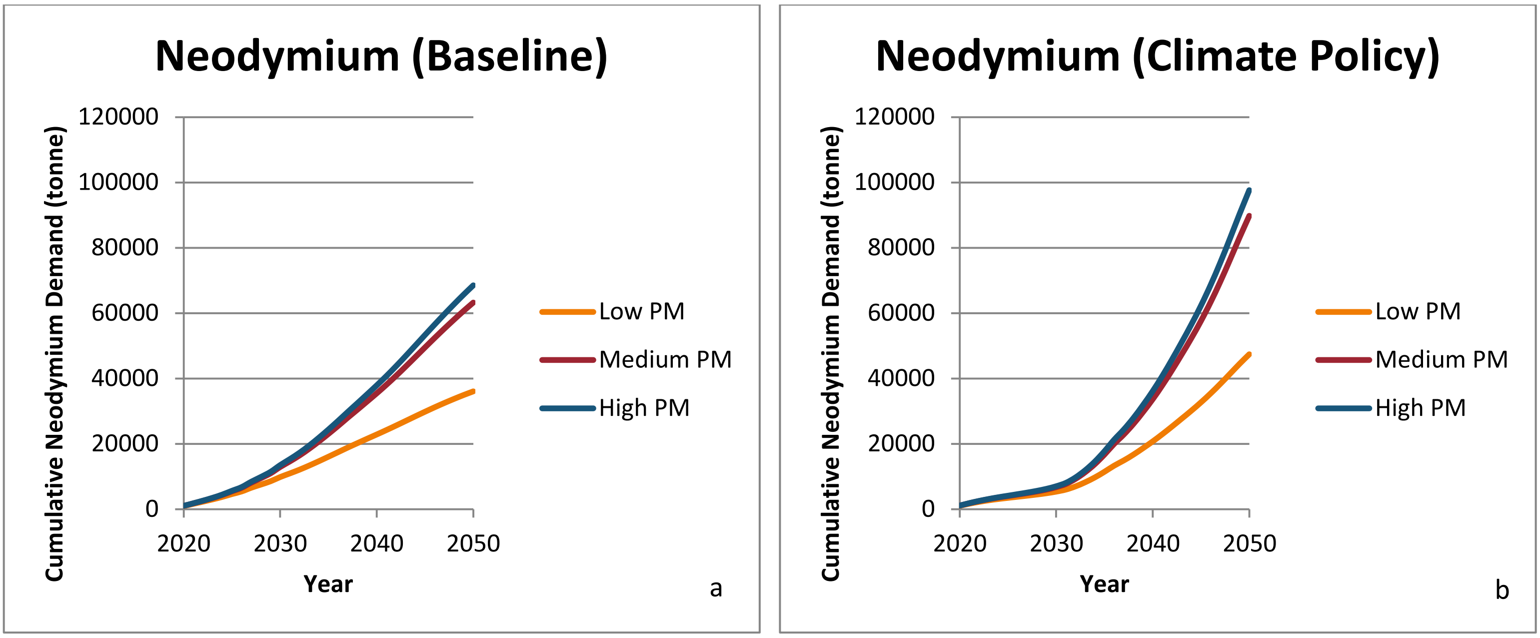

Figure 15: Cumulative demand for neodymium in a) Baseline case and b) Climate Policy case.

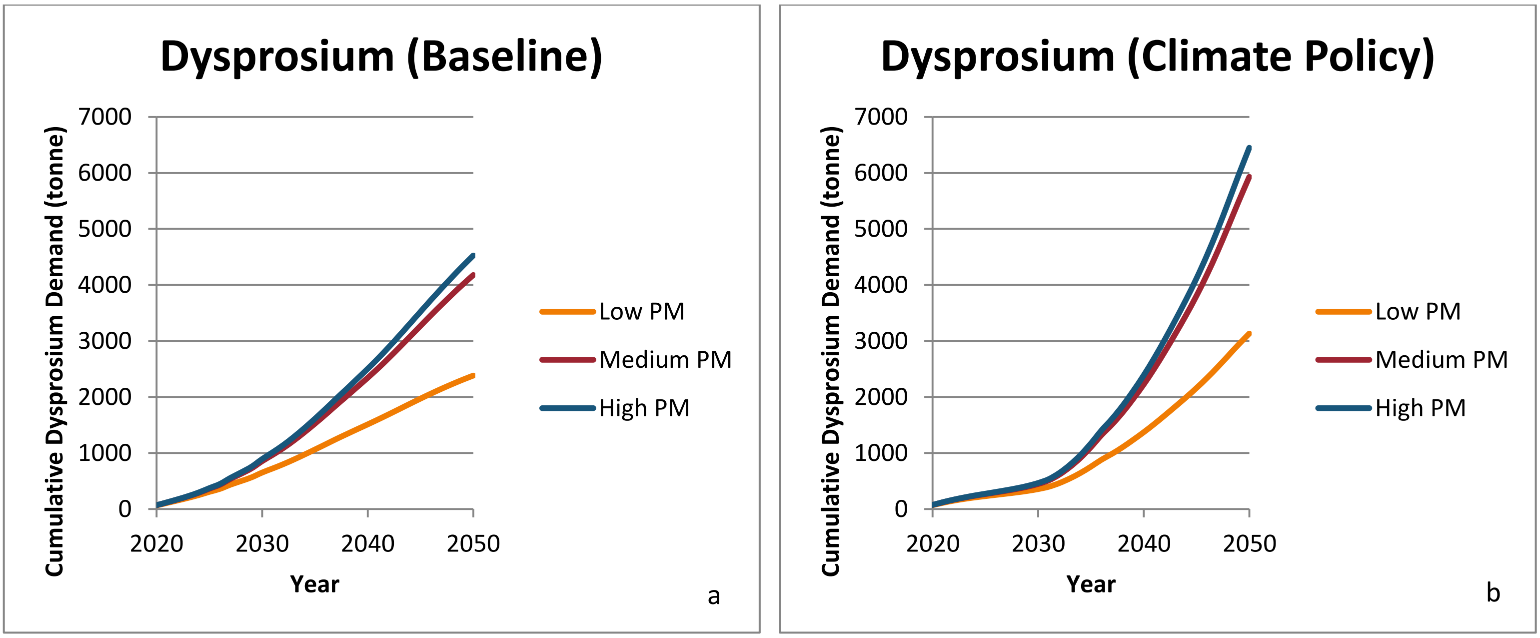

Figure 16: Cumulative demand for dysprosium in a) Baseline case and b) Climate Policy case.

In both cases, it can be observed that there is only a small difference between the Medium PM and High PM scenario. The MI is the same in both scenarios and the difference thus stems from the market share. Most researchers that look into the developments of wind turbines expect PM turbines to gain a significant market share. The average of *all* estimations, that was used for the Medium PM scenario, therefore does not differ that much from the average of the *high* estimations, resulting in similar material resource demand.

Furthermore, neodymium and dysprosium demand display a very similar development path. This results from the fact that the MI of dysprosium is a constant share of the MI of neodymium. Moreover, the relative in decrease of neodymium and dysprosium intensity is almost similar.

5.3. Combining the scenarios and cases

Some differences can be observed between the development of solar PV and wind turbines and between the Baseline case and the Climate Policy case. First the differences between solar PV and wind turbines are discussed, then the differences between the Baseline case and the Climate Policy case are addressed.

5.3.1. Solar PV versus wind turbines

In the Baseline case a difference can be observed in the development of the material resource demand for wind and solar in the final years of the investigated period. Whereas the demand for tellurium and indium keep rising until 2050, the demand for neodymium and dysprosium decreases from 2044 onwards. This can be seen clearer in Table A 2 of the appendix. In the Climate Policy case, the opposite development is found. While the demand for neodymium and dysprosium still increases in the final years, the demand for tellurium and indium decreases. This can be seen clearer in Table A 3 of the appendix.

The relative decrease in MI of solar PV cells is larger than the relative decrease in MI of wind turbines. Whereas the MI of material resources for solar PV decreases at least 55%, neodymium and dysprosium intensity decreases only 35%. The strength and thermal performance of a permanent magnet are directly related to the neodymium and dysprosium content. The decrease in MI is thus mainly the result of improvements in efficiency in other parts of the turbine. The performance of solar PV cells does not have such a direct relationship with the amount of tellurium, indium or silver used. A decreasing MI can thus be the result of an improvement in efficiency in other parts of the cell as well as a decrease of layer thickness, and therewith tellurium, indium or silver content. Furthermore, decreasing intensity can also be the result of a more efficient production process, resulting in fewer losses during production.

From both the Baseline and the Climate Policy case it becomes clear that the range in estimates for tellurium and indium demand is larger than for neodymium and dysprosium. This results from the fact that a smaller range of estimates for the development of market share and MI was found in literature. This shows that there is a greater uncertainty in the development of solar PV than in the development of wind turbines. This difference is mainly caused by the fact that for solar PV there is more uncertainty about what technology will be the most successful. Furthermore, estimates in literature for the future MI display a larger range for solar PV than those for wind turbines. Another observation that can be made in both the Baseline and the Climate Policy case is that the material resource demand in the medium and high PM scenario differs only slightly. Since the newly installed capacity and the MI are fixed, this small difference is caused by a similar PM share in both scenarios. This again indicates that the developments of wind turbines are more certain.

5.3.2. Baseline versus Climate Policy case

A noteworthy difference between the Baseline and Climate Policy case is that the moment at which the cumulative demand really starts to increase differs. Whereas the Baseline case shows a gradual increase from the first years on, significant developments start from 2030 onward in the Climate Policy case. Given the fact that the market shares and the MIs are the same in both cases, this difference must stem from a difference in the developments in newly installed capacity. As mentioned before, the IMAGE model that generated the data for newly installed capacity discounts future costs. Money in the future is thus cheaper than money today. Therefore the model waits as long as possible with installing the capacity that is required to reach the climate target. The Baseline case does not display a similar development because in the Baseline case no additional efforts are taken to reduce GHG emissions. The newly installed capacity in the Baseline case is thus the capacity that will be installed anyway without extra policy/motivation.

5.4. Televisions

Table 19 shows how the yearly demand for indium in TVs develops. The results are given in tonne/year in steps of 5 years until the end of the investigated period, 2050. Additionally Table A 4 was included in the appendix to clearly show the relative increase in demand for each year in every scenario.

Table 19: Development of indium demand for televisions.

	Demand on tonne/year for:					
	2025	2030	2035	2040	2045	2050
Indium demand (tonne/year)	153	156	160	164	170	172

Table 19 and Table A 4 give the most detailed information about the development of annual material resource demand. However, it is hard to visualise the development on basis of this table. For better visualization and to allow comparison with indium demand from CIGS cells the developments are shown in a graph in Figure 17.

From Table 19 and Figure 17 it becomes clear that the demand for indium remains very constant over the years. Over the investigated period the average yearly demand growth is only 0.7%. Despite the increase in TV purchases, the shift towards OLED TVs limits the growth of LCD TVs and thus limits the increase in indium demand.

Comparing the results of demand for indium in the TV industry with the results of demand for indium in the Solar PV industry shows that demand from the TV industry is similar in terms of cumulative indium demand. Whereas the TV industry demands a total of about 5,300 tonne, the solar PV industry demands about 4,700 tonne in the most indium intensive scenario (CIGS SUC). Adding the demand from both industries gives a more consistent demand for indium with smaller increases in demand (relatively). This more constant demand for indium might make it easier for suppliers to adjust to the now relatively smaller changes in demand caused by the development of the solar PV industry. Figure 17 shows the more constant demand for indium.

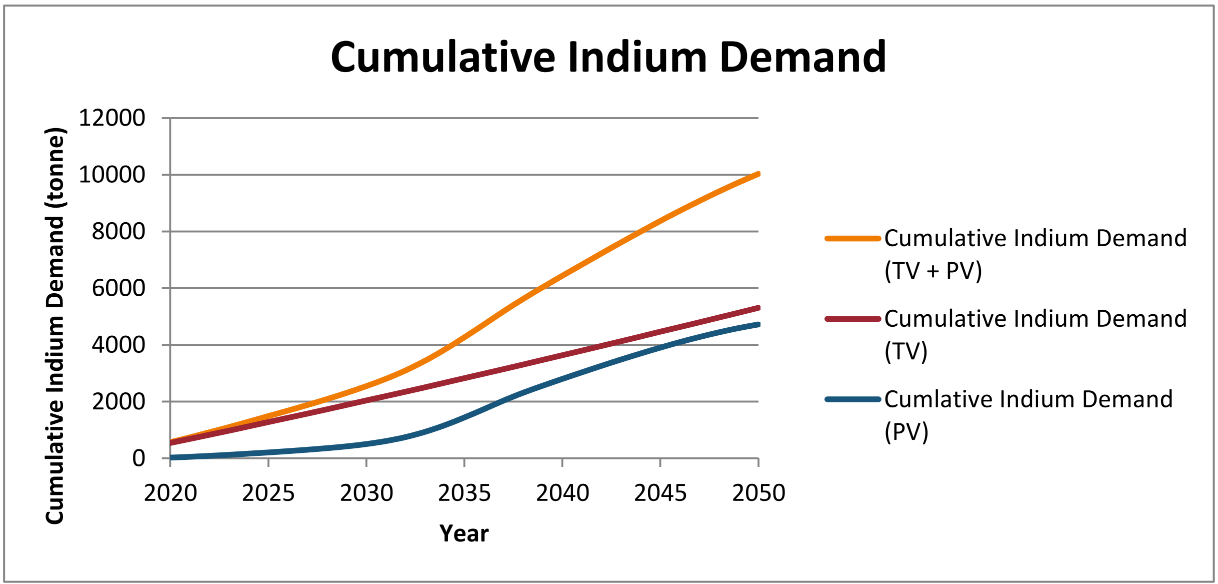

Figure 17: Combined cumulative indium demand from TV and solar PV in the CIGS SUC scenario.

5.5. Total use of the material resources under investigation.

Developments at the supply side of the material resources are outside the scope of the current research. It is however useful to have some perspective on the amount of tellurium, indium, silver, neodymium and dysprosium that is demanded from solar PV and wind turbines. Therefore the future demand for these material resources from solar PV and wind turbines is compared to current production levels. This comparison is discussed in more detail in the next paragraphs. An overview is presented in Table 20. For all material resources counts: conclusions about whether supply can keep up with demand can not yet be drawn. To draw such conclusions, first the demand from all other sector has to be mapped. Then it should also be taken into account that four of the material resources are by-product elements. Their production is therefore dependent on the development of demand for other material resources.

5.5.1. Tellurium

The highest yearly tellurium demand reaches from 130 tonne/year in the TFF scenario of the Baseline case to 633 tonne/year in the CdTe SUC scenario of the Climate Policy case. Current estimates for the yearly production of tellurium lay between 400 and 700 tonne/year (Davidsson & Höök, 2017), of which about 40% is already used for the production of CdTe cells (EU Commission, 2017). Cumulative demand for tellurium reaches between 2281 tonne in the TFF scenario of the Baseline case to 10,626 tonne in the CdTe SUC scenario of the Climate Policy case. Davidsson & Höök (2017) find that tellurium reserves are about 24,000 tonne. Tellurium demand from CdTe cells could thus make up for a significant part of tellurium demand.

5.5.2. Indium

The highest yearly indium demand reaches from 41 tonne/year in the TFF scenario of the Baseline case to 302 tonne/year in the CIGS SUC scenario of the Climate Policy case. 2014 indium production was estimated to be 820 tonne, of which only a small share (~6%) is already used for the production of CIGS cells (Davidsson & Höök, 2017). Hjortsberg (2016) finds a similar yearly production of indium (755 tonne) in 2015.Cumulative demand for indium reaches between 580 tonne in the TFF scenario of the Baseline case to 4,721 tonne in the CIGS SUC scenario of the Climate Policy case. Davidsson & Höök (2017) find that there is a range of estimates for indium reserves of 11,000 to 50,000 tonne.

On basis of the figures above it might seem like more than enough tellurium is available for CdTe cells. Other industries however also have a demand for indium. The TV industry that was studied in the current research is currently responsible for about 50% of the total indium demand. Though its relative share might decrease because of the rise of the application of indium in solar PV, cumulative demand for indium from the TV industry will still exceed cumulative demand from the PV industry in the investigated period. Indium demand from the TV industry is projected to reach 172 tonne/year by 2050 with a cumulative demand of 5,307 tonne. In the CIGS SUC scenario of the Climate Policy case the combined cumulative indium demand would exceed 10,000 tonne and come close to the lowest reserve estimations. This indicates the importance of taking other demand groups into account before drawing conclusion about the availability of a material resource for green energy technologies.

5.5.3. Silver

The highest yearly silver demand reaches from 392 tonne/year in the CdTe/CIGS scenario of the Baseline case to 647 tonne/year in the TFF scenario of the Climate Policy case. Current silver production is estimated to be 26,100 tonne/year, of which only a small share (~6%) is already used for the production of c-Si cells (Davidsson & Höök, 2017). Cumulative demand for silver reaches between 7,105 tonne in the CdTe/CIGS SUC scenario of the Baseline case to 11,100 tonne in the TFF scenario of the Climate Policy case. Davidsson & Höök (2017) find estimated silver reserves are 530,000 tonne.

5.5.4. Neodymium

The highest yearly neodymium demand reaches from 1,419 tonne/year in the Low PM scenario of the Baseline case to 7,552 tonne/year in the High PM scenario of the Climate Policy case. For neodymium, no recent estimates were found. Estimates from Hjortsberg (2016) are based on 2008 values. In 2008, the total use of neodymium was 23,868 tonne (Hjortsberg, 2016). 4% of current neodymium demand comes from the wind turbine industry (Zhang, 2013). Cumulative demand for neodymium reaches between 36,068 tonne in the Low PM scenario of the Baseline case to 97,643 tonne in the High PM scenario of the Climate Policy case. Habib & Wenzel (2014) estimate neodymium reserves of 400,000 tonne (in 2011).

5.5.5. Dysprosium

The highest yearly dysprosium demand reaches from 94 tonne/year in the Low PM scenario of the Baseline case to 499 tonne/year in the High PM scenario of the Climate Policy case. For dysprosium, no recent estimates were found. Estimates from Hjortsberg (2016) are based on 2008 values. In 2008, the total use of dysprosium was 1,310 tonne (Hjortsberg, 2016). Cumulative demand for dysprosium reaches between 2,383 tonne in the Low PM scenario of the Baseline case to 6,448 tonne in the High PM scenario of the Climate Policy case. Habib & Wenzel (2014) estimate dysprosium reserves of 54,000 tonne (in 2011).

Table 20: Current production and reserves compared to future (cumulative) demand.

	Current share of current production	Current annual production (tonne/year)	Highest annual future demand (tonne/year)	Estimated reserves (tonne)	Cumulative demand (tonne)
Tellurium	40%[a]	400 – 700[b]	130 – 633	24,000[b]	2,281 – 10,626
Indium (PV)	6%[b]	755[d] – 820[b]	41 – 302	11,000 – 50,000[b]	580 – 4,721
Indium (PV + TV)	56%[b]		213 – 474		5,887 – 10,028
Silver	6%[b]	26,100[b]	392 – 647	530,000[b]	7,105 – 11,100
Neodymium	4%[c]	23,868[d]	1,419 – 7,552	400,000[e]	39,068 – 97,643
Dysprosium	n/a	1,310[d]	94 – 499	54,000[e]	2,383 – 6,448

[a] EU Comission (2017)
[b] Davidsson & Höök (2017)
[c] Zhang (2013)
[d] Hjortsberg (2016)
[e] Habib & Wenzel (2014)

Though the current share in demand is still small for indium and silver from PV and neodymium from wind turbines, their future share might become significant. Additionally, when other application of the material resources also increases, future demand might rise well above current supply. Future demand for tellurium could rise well above current annual production levels if CdTe cells become the most successful solar PV technology. Furthermore, cumulative demand for indium from only solar PV and TVs might already require almost all current reserves by 2050.

6. Sensitivity Analysis

6.1. Different scenario for yearly installed capacity

Data from the IMAGE model was used to determine the future installed capacity. This model is however purely based on cost. From a purely economic perspective, installing new capacity as late as possible might be the best option in the Climate Policy case. This however implies a huge strain on production and installation capacity and might thus not be the best option from a practical point of view. To determine the effect of a different installation path, a linear increase of installed capacity was assumed. For this the cumulative newly installed capacity projected by IMAGE for the Climate Policy case was divided evenly over the investigated period. The resulting change in cumulative demand by 2050 is shown in Table 21. For each of the material resources the cumulative 2050 demands are compared for the scenario with the highest cumulative demand in the Climate Policy case by 2050. For tellurium, indium and silver these are thus the CdTe SUC, CIGS SUC and TFF scenario, respectively. For neodymium and dysprosium this is the High PM scenario.

Table 21: Change in cumulative demand from applying a different installation path.

Material	Development	Cumulative demand 2050 (tonne)	% change
Tellurium	IMAGE	10,626	
	Linear	9,364	-13%
Indium	IMAGE	4,721	
	Linear	4,801	2%
Silver	IMAGE	11,100	
	Linear	19,879	44%
Neodymium	IMAGE	97,643	
	Linear	86,986	-12%
Dysprosium	IMAGE	6,448	
	Linear	5,746	-12%

For tellurium, neodymium and dysprosium the demand would decrease more than 10% in the new situation. The reason for this development can be found in the market share of the technologies. The market share of these technologies is high towards the end of the investigated period. In the IMAGE model, most of the new capacity is installed towards this end of the investigated period. Most installations of PM wind turbines and CdTe cells thus happen at a moment at which the market share of these technologies is at its highest. In contrary, in the linear model new capacity is installed equally at each moment of the investigated period. Compared to the IMAGE model, more capacity is thus installed in the beginning of the investigated period. At the beginning of this period, the market share of PM turbines and CdTe cells is still low. This leads to a cumulative installed capacity and subsequently a lower cumulative material resource demand that is lower in the linear model than in the IMAGE model. For indium, only a small increase in demand of 2% occurs. A decrease similar to the decrease of tellurium could be expected for indium. There is however a relatively large decrease in MI of indium in CIGS cells, which is strongest towards the end of the investigated period. Installing CIGS cells earlier, at a moment of higher MI, which happens in the linear model, therefore leads to somewhat higher indium demand in those years. This higher demand in turn lead to a higher cumulative demand in the linear model than in the IMAGE model, even though cumulative installed capacity decreases in the linear model.

For silver in c-Si cells the demand increases significantly with 44%. The reason for this increase can be found again in the market share. In the linear model, more c-Si capacity is installed in the first years of the investigated period. During those years, the c-Si is higher than in the final years, the period in which the IMAGE model projects most installations. Additionally, the MI of silver in c-Si cells is higher during the first years of the investigated period. This combination leads to a higher cumulative silver demand in the linear model than in the IMAGE model.

The sensitivity analysis of the installation path shows that the moment of installation can have a significant impact on material resource demand. In order to adequately anticipate future demand it is thus important to plan in advance when new capacity will be installed. Furthermore, it also shows that the market share of technologies has a big influence on the material resource demand.

6.2. On- vs. offshore market share

In Deetman et al. (2018) offshore wind gained a market share of 8.8% in the Climate Policy case. Other studies however suggested a market share of up to 50% (Elshkaki & Graedel, 2014). A sensitivity analysis was therefore performed to determine the effect of a different division of market share between onshore and offshore wind turbines. To show how demand for neodymium and dysprosium changes as a result of the changed market shares, Figure 18 and Figure 19 present the cumulative demands in the Climate Policy situation (Medium PM) with original offshore market share (3%) and with a linear increase to 50% market share.

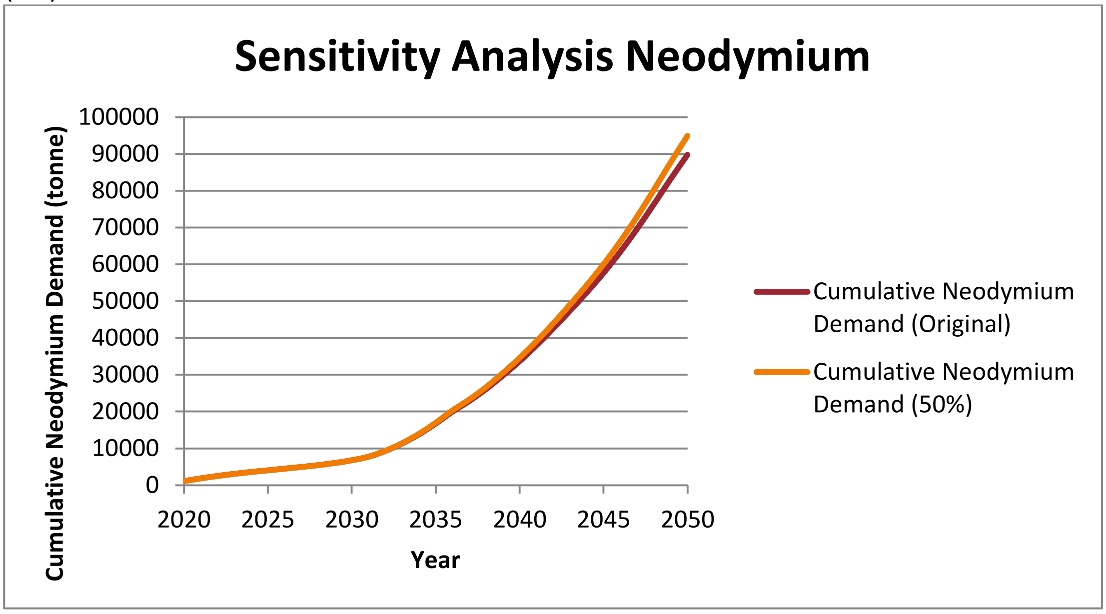

Figure 18: Change in cumulative neodymium demand from changed market share in Medium PM scenario.

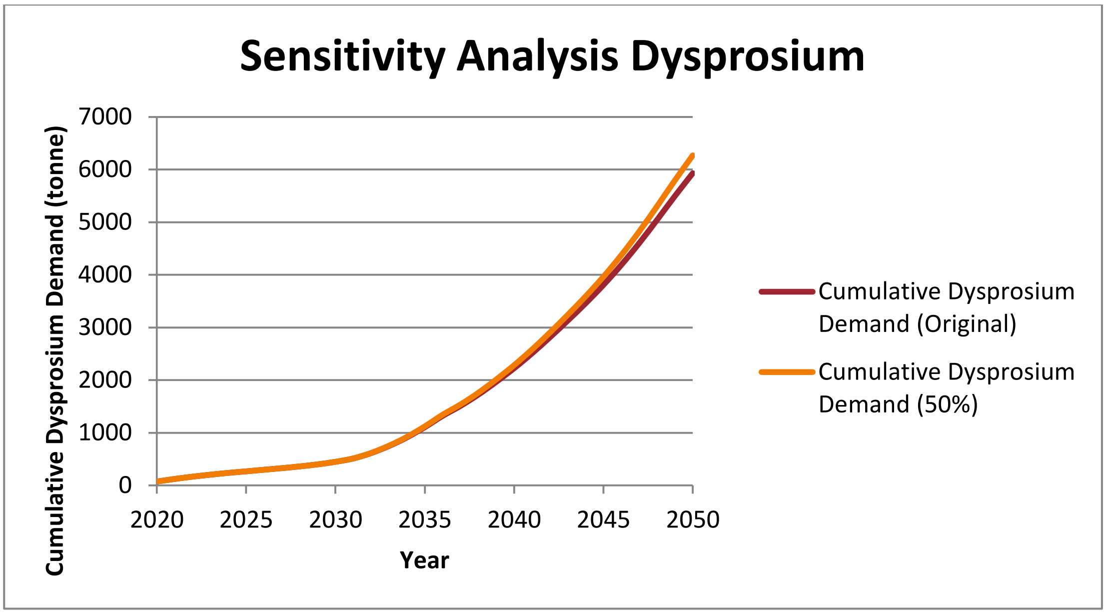

Figure 19: Change in cumulative dysprosium demand from changed market share in Medium PM scenario.

When the share of offshore wind capacity increases, the amount of neodymium and dysprosium needed also increases. This makes sense because the share of PM turbines is expected to be greater in the offshore market than in the onshore market. This does indicate that in terms of material use, it might be preferable to install greater amounts of wind turbine capacity onshore. The increase in demand for neodymium and dysprosium is however small. This indicates that the division between onshore and offshore turbines does not have a great influence on the material resource demand. A difference between the two market share situations only becomes visible in the final decade of the investigated period. The reason for this is that in the final years the offshore market share is largest and newly installed capacity greatest.

For the High PM scenario the same trend can be observed as for the Medium PM scenario. Figures for the High PM scenario are included in the appendix, Figure A 1 and Figure A 2. For the Low PM scenario, no change in material resource demand occurs. In that scenario, the onshore and offshore PM shares are equal and the division between on- and offshore thus does not matter for the neodymium and dysprosium requirements.

6.3. Different estimates for neodymium and dysprosium content

An average of the values found for the MI of neodymium and dysprosium was used to perform all calculations for these two material resources. Instead of this average, a range of the actual values of different estimations could have been used. A sensitivity analysis was performed to find the effect of this change. In this sensitivity analysis the highest and lowest estimates (see Table 11) found in literature were used to calculate material resource demand. Results for the change in cumulative demand in the High PM scenario of the Climate Policy case are presented in Table 22.

Table 22: Change in cumulative demand from different MI estimates in the High PM scenario of the Climate Policy case.

Cumulative demand	Neodymium (tonne) (% change)	Dysprosium (tonne) (% change)
Average MI	97643	6448
Highest MI	101607 (+ 4%)	7774 (+ 20%)
Lowest MI	94866 (- 3%)	5736 (- 11%)

From this analysis it becomes clear that neodymium demand changes only a few percent. The dysprosium demand however increases or decreases 20% or 11% with the highest and lowest estimates. Though the absolute range in estimates is smaller for dysprosium, the relative difference between these estimates is larger for dysprosium than for neodymium. This indicates that using an average is justified for neodymium, but for dysprosium it might be better to use a range. Though more estimates might be available for the MI of neodymium that could lead to a somewhat larger range, the estimations used in the current research are expected to give a solid representation of the possible MIs.

7. Discussion

In this section of the report, first the findings of this research are put into perspective by comparing them with similar research. Reasons for and lessons that can be learned from the differences between the current research and other research are presented. On the basis of these differences, the importance of taking technological detail into account is emphasised. Then the assumptions made in the current research and how they might impact the results are discussed. Finally, the policy implications and suggestions for further research are presented.

7.1. Comparison with other research

One of the material resources in the current research, neodymium, is also taken into account by Deetman et al. (2018). Figure 3 in Deetman et al. (2018) shows the neodymium demand for different applications with low estimations for neodymium content. The current research finds a cumulative demand for neodymium in wind turbines of almost 50 ktonne in the Low PM scenario of the Climate Policy case. Deetman et al. (2018) find a total cumulative neodymium demand of about 84 ktonne in the Climate Policy case, of which only a minor fraction comes from renewable energy technologies. There is thus a big difference between these findings. The low estimations of Deetman et al. (2018) however do not take into account the different wind turbines technologies or development of market shares. The low content estimations are based on wind turbines in general. Since the 'traditional' wind turbines do not contain neodymium, the lowest estimations are thus based on wind turbines that do not contain neodymium.

Figure 5 of Deetman et al. (2018) presents the annual neodymium demand under medium metal content assumptions. An average annual neodymium demand of about 4.0 ktonne/year is found in the period 2045-2050 for the Climate Policy case. This is still significantly lower than 6.4 ktonne/year average found in the *Medium PM scenario* in the current research. This indicates that taking market shares of specific technologies into account is important in determining the future material resource demand.

Brumme (2012) finds an annual demand for neodymium of about 3.2 ktonne by 2050 and a dysprosium demand of about 0.2 ktonne by 2050. This corresponds closely to the annual 2050 demand found in the current research, 2.9 ktonne neodymium and 0.2 ktonne dysprosium, in the Low PM scenario. The Medium PM and High PM scenario of the current research however show an annual neodymium and dysprosium demand that is more than double the demand found by Brumme (2012). So what causes this difference? Whereas the cumulative installed capacity in the current research is almost similar to the cumulative capacity in Brumme (2012), there is a difference in the assumed onshore PM share. About 1.5 ktonne of the difference can be explained by these different assumptions for onshore PM share. The current research assumes onshore PM shares of 36% and 39.2% by 2050 in the Medium and High PM share scenario, respectively. Brumme (2012) assumes a maximum onshore PM share of 25%. The remaining difference can be explained by a slight difference in MI and differences in the division between on- and offshore market share. This indicates that the share of PM turbines in onshore capacity is an important factor for the neodymium demand. This in turn shows that taking the different variations of a technology into account is important in determining the future material resource demand.

For neodymium and dysprosium research was available for comparison. For tellurium, indium and silver comparable research was however hard to find because of big differences in multiple assumptions. Still, to provide some perspective, the work of Speirs et al. (2011) and Davidsson & Höök (2017) is discussed. Additionally, the difficulties with comparison illustrate the need to assess future material resources demand in a comprehensive and consistent way, as emphasized in the introduction.

Speirs et al. (2011) review the literature for estimates on the development of CdTe and CIGS solar PV cells. The 2030 material resource demand is determined on basis of ranges in estimates for the development of the different factors relevant for the future material resource demand. They find a range for tellurium and indium demand of 480 – 1800 tonne/year and 70 – 970 tonne/year for tellurium and indium, respectively, by 2030. In the current research, the highest yearly demand in different scenarios ranges from 130 – 633 tonne/year and 41 – 302 tonne per year for tellurium and indium, respectively. These estimates are thus in the lower range of the estimates provided by Speirs et al. (2011). Speirs et al. (2017) however assume a market of 20 GW/year for both thin film technologies and a decrease in MI is not taken into account, whereas in the current research only 4.4 GW of one of the individual technologies is installed by 2030 in the Climate Policy case with a large decrease in MI. This makes it hard to do a solid comparison.

Studies that estimate the future silver demand from the solar PV industry are scarce. Davidsson & Höök (2017) estimate the future silver demand to be between 62 and 348 ktonne in case c-Si cells dominate the future market. The Climate Policy case TFF case of the current research gives a significantly lower cumulative silver demand of 11 ktonne by 2050. Davidsson & Höök (2017) however work from a scenario with a cumulative installed capacity of 9.3 TW solar PV, instead of 2.5 TW that is used in the current research. This makes comparison harder. Still, with the lowest demand estimated by Davidsson & Höök (2017), 6.7 ktonne silver would be required per TW installed capacity, which is already significantly higher than the 4.4 ktonne silver/TW installed capacity in the current research.

7.2. Assumptions

In most researches, at least a few assumptions have to be made regarding unknown or unknowable information. The current research is no exception. Because the current research focussed at possible developments in the future, it was unavoidable to make assumptions. Though these assumptions were based on expectations and projections published in scientific journals, uncertainty still remains. This uncertainty was tried to be dealt with by using scenarios to show the range of possible future developments. Still it should be kept in mind that factors like market share and MI might very well develop in other ways than anyone could predict with current knowledge. Also the two factors of the SSP, ‘social and economic equality’ and ‘environmental sustainability’ might develop in another way than in the current research. SSP2 was now taken as terminus a quo, but developments under another SSP might lead to very different results. Further research should take the effect of a different SSP into account.

7.2.1. IMAGE

Moment of installation

The development of material resource demand is to a large extent dependent on the yearly installed capacity, as determined by IMAGE. IMAGE makes its projections based on cost from today’s perspective. This means that investments in expensive technologies are made as late as possible. The reason for this is that, because of taking a discount rate into account, future money is less expensive from today’s perspective. This might however not be the best option from a material resource point of view. Though postponing the investments may provide us with more time to anticipate the demand, it also leads to a steeper rise in demand than would have been the case if investments had been spread more evenly over the investigated period. At the same time, the MI will probably be higher in earlier years. Shifting installations to earlier years to spread them more evenly might thus lead to a higher cumulative demand. This is important to keep in mind when planning installations. Performing the calculations for yearly demand with different input data for the yearly installed capacity would be useful to examine the impact of a different installation path. This was done in the sensitivity analysis using a simple linear increase in material resource demand. From the sensitivity analysis it became clear that a change in the moment of installation can significantly impact the material resource requirements.

On- vs. offshore wind turbines

Because of the cost aspect mentioned in the previous paragraph, the IMAGE model projects only a minor share of the newly installed wind turbine capacity to occur offshore. Research on the future division between onshore and offshore wind turbines however suggests a significant offshore capacity. To see how a different division between on- and offshore market share would affect the neodymium and dysprosium demand a sensitivity analysis was performed. This analysis showed that a large change in the share division does not have a significant impact on the material resource demand. Only a small increase in neodymium was observed in a situation with larger offshore market shares.

7.3 Policy implications

When one has insight into potential future developments, one can prepare for these developments. IMAGE shows that it would be cheapest to start installation as late as possible. On the one hand, in terms of the material resource demand, this is also the best time to install because then there is enough time for research to decrease the MI of the technologies. This does cause a big sudden increase in material resource demand around 2030, when suddenly significant amounts of wind turbines and solar PV are installed. This increase can however be prepared for when it is known in advance. On the other hand, technological improvements are usually the result of technological learning. When less capacity is installed, learning effects might decrease and the decrease in MI might be slower. Funding could however possibly be a solution to stimulate research into decreasing the MI despite of the smaller impact from technological learning.

7.4. Further research

7.4.1. Supply side

Production capacity

As indicated in the current research, it is important to know the relative increase of the material resource demand. This is the case because suppliers should be able to meet the increase in demand. The relative increase was determined in the current research. The ability of suppliers to keep up with this increase was however not discussed and should thus be addressed in future research.

By-product elements

To determine the possibilities to scale up, it is important to take into consideration that some material resources are mainly extracted as by-product of another material resource. For example, as indicated in section 4.3. tellurium and indium are extracted as a by-product of copper and zinc, respectively. Their availability is thus almost entirely dependent on the extraction of other material resources.

7.4.2. Source of material resources

The source of the material resources was not taken into account in the current research. The amount of material resources presented is thus not necessarily the amount of material that has to be extracted. Further research should focus on how material resources can be supplied, e.g. through recycling. Recycling could play an important role in decreasing the strain on natural resources and limiting supply issues. Davidsson & Höök (2017) indicate that for solar PV end of life recycling could supply a significant share of the material resource demand from replacing degraded capacity. Stamp et al. (2014) find that end of life recycling could reduce cumulative indium demand from solar PV by 2% to 4%. Hjortsberg (2016) however finds that technologies are available to recycle material resources from wind turbines and solar PV, but that these technologies are often too expensive.

8. Conclusion

In order to reach the climate targets that were set in the Paris Agreement, large amounts of renewable energy generation capacity have to be installed. Technologies for renewable energy generation however contain material resources that are not infinitely available. To identify where problems might occur in the supply of material resources needed for renewable energy generation technologies, it is important to map future material resource demand for these technologies. Though research exists that looks into this future demand, most research lacks consistency and technological detail. Furthermore, research tends to only focus on the specific technology under investigation, and does not take demand from other sectors into account. It is however important to also take this demand from outside the green energy technology industry into account. Material resource demand from these other sectors influences the availability of the material resources for the green energy technology industry.

The current research was conducted to provide a comprehensive and consistent analysis for the future demand for the most characterizing material resources used in renewable energy generation technologies. More specifically**, the aim of this research was to determine the demand for material resources from the wind turbine and solar PV industry until 2050, while taking into account the different possible technologies within those industries.** According to projections of the IMAGE model, solar PV and wind turbines are expected to be the most important renewable energy generation technologies. According to most existing research, cadmium-tellurium (CdTe) cells, copper-indium-gallium-diselenide (CIGS) cells and crystalline silicon (c-Si) cells will be the most important solar PV technologies. Their most characterizing material resources are tellurium for CdTe cells, indium for CIGS cells and silver for c-Si cells. For wind turbines, traditional turbines are expected to battle for market share with permanent magnet (PM) turbines. Though traditional turbines do not contain a characterizing material resource, PM turbines contain neodymium and dysprosium. For wind turbines the focus was therefore on material resource demand from PM turbines. Additionally, indium demand from the TV industry was taken into account. This was done to provide an example of the importance of taking demand from other sectors into account.

To determine the future demand for the characterizing material resources scenarios were created. These scenarios include the yearly installed capacity of the technologies, the development of material intensity (MI) of the material resources in the technologies and the expected market shares of the technologies. Furthermore, a Baseline case and a Climate Policy case were introduced to allow for comparison between the business as usual developments and developments under policy aimed at reaching the climate targets. Combining all information from the scenarios gave the yearly demand for each material resource. While determining this yearly demand, three point of improvement to existing research were taken into account. By looking at different materials than Deetman et al. (2018) did, but with the same basic assumptions for development, *additional material resources* were analysed in a consistent way with the same basic assumptions for development. By taking indium demand from the TV industry into account the relevance of *considering demand from outside the energy generation industry* was shown. Finally, the importance of *taking different variations of a technology (technological detail) into account* was shown by comparing the results of the current research to previous research. The results of the analysis and observations from these results are discussed.

The main results of the current study are the yearly and cumulative demand for the material resources under investigation. These results contribute to creating the complete picture of future material resource demand, which is necessary to determine adequately the problems that might occur in supply of material resources. The Baseline case shows a gradual development towards 2050 with relatively small yearly and cumulative material resource demand. The Climate Policy case shows significantly higher yearly and cumulative demands and a more discontinuous development, which is the result of a large sudden increase in installed capacity halfway the investigated period. In Table 23 results are given for yearly and cumulative demand in the Climate Policy case with successful development of CdTe cells, with successful development of CIGS cells, with a sustained success of c-Si cells and with a medium share of PM turbines. The lower estimates for current yearly production and reserves are also included.

Table 23: Overview of yearly and cumulative demand, compared to current production levels and reserves.

Scenario (material resource)	Current production levels (tonne/year)	Demand in 2025 (tonne/year)	Demand in 2035 (tonne/year)	Demand in 2050 (tonne/year)	Cumulative demand by 2050 (tonne)	Current reserves (tonne)
CdTe SUC (tellurium)	400	60	534	402	10,626	24,000
CIGS SUC (indium)	820	42	272	127	4,721	11,000
TFF (silver)	26,100	250	641	141	11,100	530,000
Medium PM (neodymium)	23,868	449	2941	6577	97,643	400,000
Medium PM (dysprosium)	1,310	30	194	435	6,448	54,000

The yearly demand for each material resource from wind turbines and solar PV is well within the current production levels. Additionally, the cumulative demand is well within estimated reserves. It is however important to take demand from other sectors into account before drawing conclusions on the future availability of the material resources. Including TVs in the analysis clearly showed the importance of including material resource demand from other industries. Indium demand from the TV industry was higher than the demand from the CIGS industry in the most indium intensive scenario. The combined indium demand from just the TV industry and the CIGS industry already came close to the lowest estimated reserves, whereas their current combined share in total indium demand is about 56%.

Comparison with other research clearly showed the importance of taking the variations of wind turbine and solar PV technologies into account. Research that did not account for the different wind turbine technologies found a significantly lower demand for neodymium than the current research. Research that did take the variations into account, but assumed lower shares of PM turbines in onshore application also found a significantly lower neodymium and dysprosium demand. This comparison stresses the importance of taking variations of technologies into account and carefully determining their market shares.

A sensitivity analysis on the development path showed that the moment of installation is important for the material resource demand. In the IMAGE model, most capacity is added in the second half of the investigated period. Changing the development path of IMAGE to a linear development with equal capacity additions in each year resulted in 13% lower till 44% higher demand for different material resources. This does not only show the importance of the model used for projections, but also stresses the need to carefully plan when installation of new capacity takes place.

References

Andersson, B. A., & Råde, I. (2001). Material constraints on technology evolution: the case of scarce metals and emerging energy technologies. Department of Physical Resource Theory, Chalmers University of Technology.

Bell, T. (2018). Applications of the metal dysprosium. Retrieved February 20, 2019, from https://www.thebalance.com/dysprosium-applications-3959893

Brumme, A. (2012). Critical materials for wind power: the relevance of rare earth elements for wind turbines (Doctoral dissertation).

Bustamante, M. L., & Gaustad, G. (2014). Challenges in assessment of clean energy supply-chains based on byproduct minerals: A case study of tellurium use in thin film photovoltaics. Applied Energy, 123, 397-414.

Chel, M. (2015). Wat is een quantum dot (SUHD) tv? Retrieved Februari 10, 2019, from https://www.homecinemamagazine.nl/2015/01/wai-een-quantum-dot-suhd-tv/

Chen, D., Huang, J., Lee, C. Y., Lee, Y. J., Wu, Y. C., Zhang, X., ... & Kim, S. (2018). 29.1: On the Display Technology Trends Resulting from Rapid Industrial Development. In SID Symposium Digest of Technical Papers (Vol. 49, pp. 316-321).

Choi, C. H., Cao, J., & Zhao, F. (2016). System dynamics modeling of indium material flows under wide deployment of clean energy technologies. Resources, Conservation and Recycling, 114, 59-71.

Davidsson, S., & Höök, M. (2017). Material requirements and availability for multi-terawatt deployment of photovoltaics. Energy Policy, *108*, 574-582.

Deetman, S., Pauliuk, S., van Vuuren, D. P., Van Der Voet, E., & Tukker, A. (2018). Scenarios for Demand Growth of Metals in Electricity Generation Technologies, Cars, and Electronic Appliances. Environmental science & technology, 52(8), 4950-4959.

Elshkaki, A.; Graedel, T. E. Dynamic analysis of the global metals flows and stocks in electricity generation technologies. J. Cleaner Prod. 2013, 59, 260−273.

EU Commission. (2017). Study on the review of the list of critical raw materials. European Commission, Brussels.

European Commission. (n.d.). Raw Materials. Retrieved November 11, 2018, from: https://ec.europa.eu/eurostat/web/environmental-data-centre-on-natural-resources/natural-resources/raw-materials

Fthenakis, V. (2009). Sustainability of photovoltaics: The case for thin-film solar cells. Renewable and Sustainable Energy Reviews 13(9): 2746-2750.

Greenpeace International. (2015). Energy [R]evolution: A sustainable world energy outlook 2015.

Habib, K., & Wenzel, H. (2014). Exploring rare earths supply constraints for the emerging clean energy technologies and the role of recycling. Journal of Cleaner Production, 84, 348-359.

Henckens, M. L. C. M., Driessen, P. P. J., & Worrell, E. (2014). Metal scarcity and sustainability, analyzing the necessity to reduce the extraction of scarce metals. Resources, Conservation and recycling, 93, 1-8.

Henckens, M. L. C. M., Driessen, P. P. J., Ryngaert, C., & Worrell, E. (2016). The set-up of an international agreement on the conservation and sustainable use of geologically scarce mineral resources. Resources Policy, 49, 92-101.

Hernández, C. V., Telsnig, T., & Pradas, A. V. (2017). JRC Wind Energy Status Report 2016 Edition. Market, Technology and Regulatory Aspects of Wind Energy.

Hjortsberg, S. (2016). Critical metals in high-growth technologies: A scenario study of equitable technology distribution in 2050.

Hoenderdaal, S., Espinoza, L. T., Marscheider-Weidemann, F., & Graus, W. (2013). Can a dysprosium shortage threaten green energy technologies?. Energy, 49, 344-355.

Houari, Y., Speirs, J., Candelise, C., & Gross, R. (2014). A system dynamics model of tellurium availability for CdTe PV. Progress in Photovoltaics: Research and Applications, 22(1), 129-146.

Indium Corporation (2013). The Indium Market [online] Available at: http://www.etf.com/sections/features-and-news/4864-indium-at-your-fingertips-the-go-to-minor-metal-for-flat-panel-displays?nopaging=1

IPCC. (n.d.). What are the key technology advances impacting wind energy production? Retrieved January 20, 2018, from: https://www.ourworldofenergy.com/vignettes.php?type=wind-power&id=6

Jacobson, M. Z., & Delucchi, M. A. (2011). Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials. Energy policy, 39(3), 1154-1169.

Jean, J., Brown, P. R., Jaffe, R. L., Buonassisi, T., & Bulović, V. (2015). Pathways for solar photovoltaics. Energy & Environmental Science, 8(4), 1200-1219.

Kato, T., Igarashi, S., Ishiwatari, Y., Furukawa, M., & Yamaguchi, H. (2013). Separation and concentration of indium from a liquid crystal display via homogeneous liquid–liquid extraction. Hydrometallurgy, 137, 148-155.

Kavlak, G., McNerney, J., Jaffe, R. L., & Trancik, J. E. (2015). Metal production requirements for rapid photovoltaics deployment. Energy & Environmental Science, *8*(6), 1651-1659.

Kleijn, R., & Van der Voet, E. (2010). Resource constraints in a hydrogen economy based on renewable energy sources: An exploration. Renewable and Sustainable Energy Reviews, 14(9), 2784-2795.

Kumar, Y., Ringenberg, J., Depuru, S. S., Devabhaktuni, V. K., Lee, J. W., Nikolaidis, E., Andersen, B. & Afjeh, A. (2016). Wind energy: Trends and enabling technologies. Renewable and Sustainable Energy Reviews, 53, 209-224.

Kuypers, A., Veenstra, S., & Schermer, J. (2018). Thin film PV roadmap.

Lacal-Arántegui, R. (2015). Materials use in electricity generators in wind turbines–state-of-the-art and future specifications. Journal of Cleaner Production, 87, 275-283.

Lee, C. H., Jeong, M. K., Kilicaslan, M. F., Lee, J. H., Hong, H. S., & Hong, S. J. (2013). Recovery of indium from used LCD panel by a time efficient and environmentally sound method assisted HEBM. Waste management, 33(3), 730-734.

LG. (n.d.) OLED. Retrieved February 19, 2019, from https://www.lg.com/global/business/information-display/technology-solution/oled

Ma, E., & Xu, Z. (2013). Technological process and optimum design of organic materials vacuum pyrolysis and indium chlorinated separation from waste liquid crystal display panels. Journal of hazardous materials, 263, 610-617.

Nassar, N. T., Wilburn, D. R., & Goonan, T. G. (2016). Byproduct metal requirements for US wind and solar photovoltaic electricity generation up to the year 2040 under various Clean Power Plan scenarios. Applied energy, 183, 1209-1226.

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., & Levy, M. (2017). The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environmental Change, 42, 169-180.

Oving, A. (2018). LDC-TV en OLED. Retrieved February 19, 2019, from https://www.consumentenbond.nl/tv/lcd-tv-en-oled

Pavel, C. C., Lacal-Arantegui, R., Marmier, A., Schueler, D., Tzimas, E., Buchert, M., Jenseit, W. & Blagoeva, D. (2017). Substitution strategies for reducing the use of rare earths in wind turbines. Resources Policy, 52, 349-357.

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., & Lutz, W. (2017). The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Global Environmental Change, 42, 153-168.

RSC. (n.d.). Dysprosium. Retrieved February 20, 2019, from http://www.rsc.org/periodic-table/element/66/dysprosium

Schulz, K. J., DeYoung, J. H., Seal, R. R., & Bradley, D. C. (Eds.). (2018). Critical Mineral Resources of the United States: Economic and Environmental Geology and Prospects for Future Supply. Geological Survey.

Shahbazi, S., Wiktorsson, M., Kurdve, M., Jönsson, C., & Bjelkemyr, M. (2016). Material efficiency in manufacturing: Swedish evidence on potential, barriers and strategies. Journal of Cleaner Production, 127, 438-450.

Shon-Roy, L. (2009). "Are Your PV Materials Costs Out of Control?" Retrieved 8th November 2010, from http://www.renewableenergyworld.com/rea/news/article/2009/12/are-your-pvmaterials-costs-out-of-control.

Silveira, A. V. M., Fuchs, M. S., Pinheiro, D. K., Tanabe, E. H., & Bertuol, D. A. (2015). Recovery of indium from LCD screens of discarded cell phones. Waste management, 45, 334-342.

Speirs, J., Gross, R., Candelise, C., & Gross, B. (2011). Materials availability: potential constraints to the future low-carbon economy. Centre for Energy Policy and Technology (ICEPT), Imperial College.

Stamp, A., Wäger, P. A., & Hellweg, S. (2014). Linking energy scenarios with metal demand modeling–The case of indium in CIGS solar cells. Resources, Conservation and Recycling, 93, 156-167.

Statista. (n.d.). Global Silver Demand by Purpose. Retrieved March 13, from https://www.statista.com/statistics/253345/global-silver-demand-by-purpose/

Tanaka, N. (2008). Energy Technology Perspectives 2008–scenarios and strategies to 2050. International Energy Agency (IEA), Paris.

Thomas, N. J., Chang, N. B., & Qi, C. (2012). Preliminary assessment for global warming potential of leading contributory gases from a 40-in. LCD flat-screen television. The International Journal of Life Cycle Assessment, 17(1), 96-104.

United Nations. (2015). Paris Agreement.

U.S. Department of Energy. (2011). Critical Minerals Strategy

USGS. (n.d.). Cadmium; Statistics and Information. Retrieved November 6, 2018, from https://minerals.usgs.gov/minerals/pubs/commodity/cadmium/

Valero, A., Valero, A., Calvo, G., & Ortego, A. (2018). Material bottlenecks in the future development of green technologies. Renewable and Sustainable Energy Reviews, 93, 178-200.

Van Vuuren, D. P., Stehfest, E., Gernaat, D. E., Doelman, J. C., Van den Berg, M., Harmsen, M., ... & Girod, B. (2017). Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. Global Environmental Change, 42, 237-250.

Viebahn, P., Soukup, O., Samadi, S., Teubler, J., Wiesen, K., & Ritthoff, M. (2015). Assessing the need for critical minerals to shift the German energy system towards a high proportion of renewables. Renewable and Sustainable Energy Review*s*, *49*, 655-671.

Worrell, E., Allwood, J., & Gutowski, T. (2016). The role of material efficiency in environmental stewardship. Annual Review of Environment and Resources, 41, 575-598.

Yang, J., Retegan, T., & Ekberg, C. (2013). Indium recovery from discarded LCD panel glass by solvent extraction. Hydrometallurgy, 137, 68-77.

Zhang, Y. (2013). Peak Neodymium: Material Constraints for Future Wind Power Development.

Zimmermann, T., Rehberger, M., & Gößling-Reisemann, S. (2013). Material flows resulting from large scale deployment of wind energy in Germany. Resources, 2(3), 303-334.

Appendix

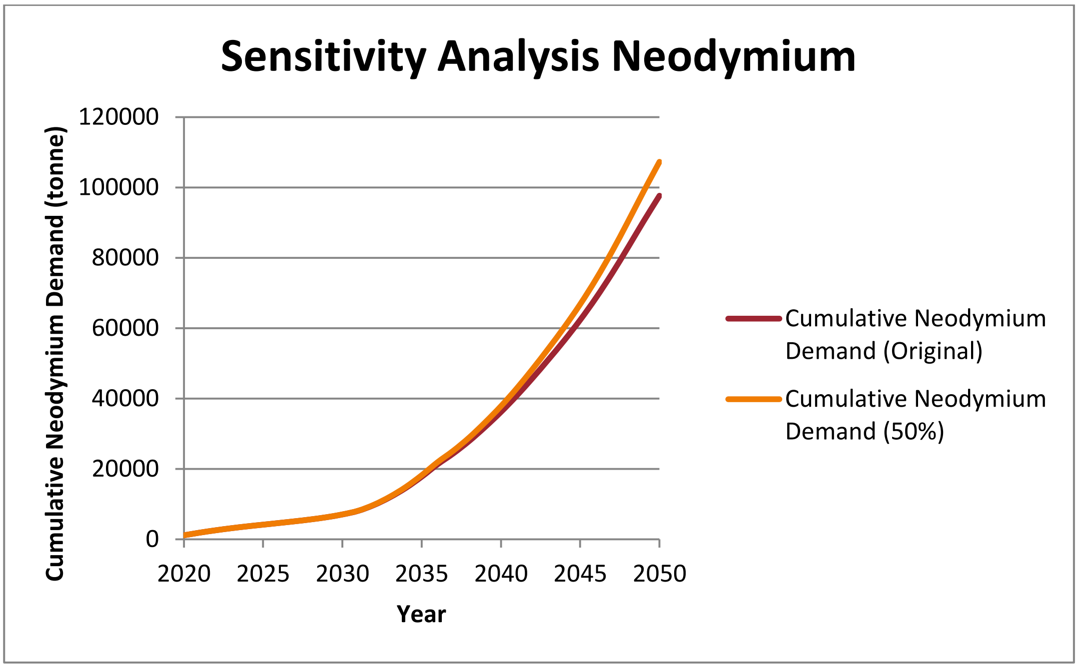

Figure A 1: Change in cumulative neodymium demand from changed market share in High PM scenario.

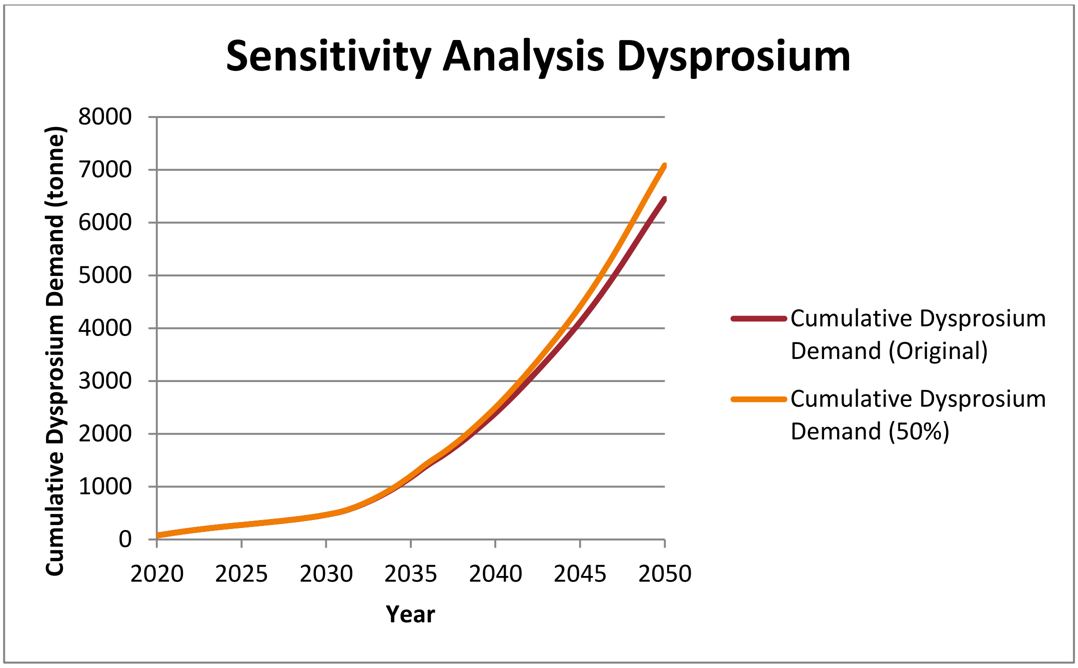

Figure A 2: Change in cumulative dysprosium demand from changed market share in High PM scenario.

	Conservative			Neutral			Optimistic		
	2010	2020	2040	2010	2020	2040	2010	2020	2040
Conversion efficiency (η) [%]									
CdTe	11.7	13.0	15.0	11.7	13.2	16.5	11.7	14.0	18.0
CIGS	11.5	14.0	16.0	11.5	15.9	19.4	11.5	16.3	20.3
α-SiGe	6.8	9.0	13.4	6.8	9.7	15.5	6.8	10.0	16.4
Thickness of the absorber layer (L) [μm]									
CdTe	3.0	2.5	2.0	3.0	1.5	1.0	3.0	1.0	0.8
CIGS	1.6	1.2	1.0	1.6	1.0	0.8	1.6	0.8	0.8
α-SiGe	1.2	1.2	1.1	1.2	1.1	1.0	1.2	1.0	0.8
Deposition efficiency (DE) [%]									
CdTe	55	60	70	65	72	85	75	83	99
CIGS (In, Ga)	40	45	55	50	57	70	70	78	95
CIGS (Se)	30	37	50	40	47	60	60	68	85
Production scrap recovery (PR) [%]									
CdTe/CIGS	50	58	75	70	75	85	75	83	99
Manufacturing yield (γ) [%]									
CdTe/CIGS	85	87	90	90	92	95	95	96	98
Collection rate of rejected modules (CR) [%]									
CdTe/CIGS	80	83	90	90	93	100	100	100	100
Rejected module material recovery rate (MR) [%]									
CdTe/CIGS	90	92	95	95	96	97	97	98	99
Material refining efficiency (RE) [%]									
CdTe/CIGS	80	82	85	85	87	90	90	92	95

Table A 1: Projected evolutions of parameters that impact the net material intensity of byproduct metals used in thin-film solar PVs (Nassar et al., 2016).

Table A 2: Relative increase in material resource demand in Baseline case.

	Material Resource														
	Tellurium			Indium			Silver			Neodymium			Dysprosium		
	Scenario			Scenario			Scenario			Scenario			Scenario		
Year	TFF	CIGS SUC	CdTe SUC	TFF	CIGS SUC	CdTe SUC	TFF	CIGS SUC	CdTe SUC	Low PM	Medium PM	High PM	Low PM	Medium PM	High PM
2019	1,48	1,66	1,96	1,42	1,90	1,67	1,24	1,22	1,22	1,30	1,36	1,37	1,30	1,36	1,36
2020	1,34	1,44	1,59	1,29	1,54	1,45	1,13	1,12	1,12	1,20	1,25	1,26	1,20	1,25	1,26
2021	1,15	1,21	1,29	1,11	1,25	1,21	0,99	0,97	0,97	1,01	1,05	1,05	1,01	1,05	1,05
2022	1,07	1,10	1,15	1,03	1,12	1,10	0,92	0,91	0,91	1,03	1,07	1,08	1,03	1,07	1,08
2023	1,10	1,12	1,16	1,06	1,13	1,12	0,95	0,94	0,94	1,09	1,13	1,13	1,09	1,13	1,13
2024	1,15	1,16	1,19	1,11	1,16	1,16	1,00	0,99	0,99	1,14	1,17	1,18	1,13	1,17	1,18
2025	1,18	1,19	1,22	1,14	1,18	1,19	1,03	1,02	1,02	0,93	0,96	0,97	0,93	0,96	0,97
2026	1,21	1,21	1,23	1,16	1,19	1,21	1,06	1,04	1,04	1,42	1,46	1,47	1,42	1,46	1,46
2027	1,08	1,07	1,09	1,04	1,06	1,07	0,95	0,93	0,93	0,86	0,88	0,89	0,86	0,88	0,89
2028	1,07	1,06	1,07	1,03	1,04	1,06	0,94	0,93	0,93	1,04	1,07	1,07	1,04	1,07	1,07
2029	1,06	1,05	1,06	1,02	1,03	1,04	0,94	0,92	0,92	1,28	1,31	1,31	1,28	1,31	1,31
2030	1,15	1,13	1,15	1,12	1,11	1,14	1,02	1,00	1,00	0,86	0,88	0,89	0,86	0,88	0,89
2031	1,09	1,10	1,09	1,12	1,05	1,09	0,97	0,96	0,96	1,03	1,06	1,06	1,03	1,06	1,06
2032	1,14	1,15	1,14	1,17	1,10	1,14	1,02	1,00	1,00	1,10	1,13	1,13	1,10	1,13	1,13
2033	1,12	1,14	1,11	1,15	1,08	1,12	1,01	0,99	0,99	1,06	1,08	1,09	1,06	1,08	1,09
2034	1,07	1,09	1,06	1,10	1,03	1,07	0,96	0,94	0,94	1,03	1,06	1,06	1,03	1,06	1,06
2035	1,06	1,07	1,05	1,08	1,01	1,05	0,95	0,93	0,93	1,01	1,04	1,04	1,01	1,04	1,04
2036	1,06	1,07	1,04	1,08	1,01	1,05	0,95	0,93	0,93	1,01	1,03	1,04	1,01	1,03	1,04
2037	1,00	1,02	0,99	1,03	0,96	1,00	0,90	0,89	0,89	0,95	0,98	0,98	0,95	0,98	0,98
2038	0,91	0,92	0,89	0,93	0,87	0,90	0,82	0,80	0,80	0,99	1,01	1,02	0,99	1,01	1,02
2039	1,04	1,06	1,03	1,07	0,99	1,04	0,94	0,92	0,92	0,99	1,01	1,01	0,99	1,01	1,01
2040	1,06	1,07	1,04	1,09	1,01	1,05	0,96	0,94	0,94	1,02	1,04	1,04	1,02	1,04	1,04
2041	1,05	1,07	1,04	1,08	1,00	1,05	0,95	0,93	0,93	1,03	1,05	1,05	1,03	1,05	1,05
2042	1,06	1,07	1,04	1,08	1,01	1,05	0,96	0,94	0,94	1,02	1,04	1,04	1,02	1,04	1,04
2043	1,04	1,06	1,02	1,07	0,99	1,04	0,95	0,92	0,92	1,00	1,02	1,02	1,00	1,02	1,02
2044	1,03	1,04	1,01	1,06	0,98	1,03	0,94	0,92	0,92	0,99	1,00	1,01	0,99	1,00	1,01
2045	1,04	1,05	1,02	1,07	0,99	1,04	0,94	0,92	0,92	0,97	0,99	0,99	0,97	0,99	0,99
2046	1,04	1,05	1,02	1,06	0,98	1,04	0,94	0,92	0,92	0,96	0,98	0,98	0,96	0,98	0,98
2047	1,03	1,04	1,01	1,06	0,98	1,03	0,94	0,92	0,92	0,96	0,97	0,97	0,96	0,97	0,97
2048	1,03	1,04	1,01	1,05	0,98	1,03	0,94	0,91	0,91	0,95	0,97	0,97	0,95	0,97	0,97
2049	1,02	1,03	1,00	1,04	0,97	1,02	0,93	0,90	0,90	0,94	0,96	0,96	0,94	0,96	0,96

Table A 3: Relative increase in material resource demand in Climate Policy case.

	Material Resource														
	Tellurium			Indium			Silver			Neodymium			Dysprosium		
	Scenario			Scenario			Scenario			Scenario			Scenario		
Year	TFF	CIGS SUC	CdTe SUC	TFF	CIGS SUC	CdTe SUC	TFF	CIGS SUC	CdTe SUC	Low PM	Medium PM	High PM	Low PM	Medium PM	High PM
2019	1,57	1,76	2,08	1,51	2,01	1,77	1,31	1,30	1,30	1,26	1,31	1,32	1,26	1,31	1,32
2020	1,33	1,43	1,58	1,28	1,53	1,44	1,13	1,11	1,11	1,12	1,16	1,17	1,12	1,16	1,17
2021	1,12	1,17	1,26	1,08	1,22	1,18	0,96	0,95	0,95	0,85	0,89	0,89	0,85	0,89	0,89
2022	1,06	1,09	1,15	1,02	1,11	1,10	0,91	0,90	0,90	0,85	0,88	0,89	0,85	0,88	0,89
2023	1,07	1,08	1,13	1,03	1,09	1,09	0,92	0,91	0,91	0,86	0,89	0,90	0,86	0,89	0,90
2024	1,02	1,03	1,07	0,99	1,03	1,03	0,89	0,88	0,88	0,85	0,88	0,88	0,85	0,88	0,88
2025	1,10	1,10	1,13	1,06	1,09	1,10	0,96	0,95	0,95	0,98	1,02	1,02	0,98	1,01	1,02
2026	1,10	1,09	1,12	1,05	1,08	1,09	0,96	0,95	0,95	0,97	1,01	1,01	0,97	1,01	1,01
2027	1,12	1,12	1,14	1,08	1,10	1,12	0,99	0,98	0,98	1,06	1,09	1,10	1,06	1,09	1,10
2028	1,20	1,19	1,20	1,15	1,17	1,18	1,06	1,04	1,04	1,13	1,16	1,17	1,13	1,16	1,17
2029	1,30	1,30	1,31	1,26	1,27	1,29	1,16	1,14	1,14	1,23	1,26	1,26	1,23	1,26	1,26
2030	1,34	1,31	1,34	1,31	1,29	1,32	1,19	1,17	1,17	1,28	1,31	1,32	1,28	1,31	1,32
2031	1,38	1,39	1,37	1,41	1,33	1,38	1,23	1,21	1,21	1,58	1,61	1,62	1,58	1,61	1,61
2032	1,39	1,39	1,38	1,42	1,33	1,38	1,24	1,22	1,22	1,28	1,31	1,31	1,28	1,31	1,31
2033	1,30	1,32	1,29	1,33	1,25	1,29	1,16	1,14	1,14	1,18	1,21	1,21	1,18	1,21	1,21
2034	1,22	1,24	1,21	1,25	1,17	1,22	1,09	1,07	1,07	1,17	1,19	1,20	1,17	1,19	1,20
2035	1,12	1,14	1,11	1,15	1,08	1,12	1,01	0,99	0,99	1,08	1,11	1,11	1,08	1,11	1,11
2036	1,08	1,10	1,07	1,11	1,03	1,07	0,97	0,95	0,95	0,86	0,88	0,89	0,86	0,88	0,89
2037	0,96	0,97	0,94	0,98	0,91	0,95	0,86	0,84	0,84	1,11	1,13	1,13	1,11	1,13	1,13
2038	0,94	0,95	0,92	0,96	0,90	0,93	0,85	0,83	0,83	1,11	1,13	1,13	1,11	1,13	1,13
2039	1,01	1,03	1,00	1,04	0,97	1,01	0,92	0,90	0,90	1,05	1,07	1,07	1,05	1,07	1,07
2040	1,02	1,03	1,00	1,04	0,97	1,02	0,92	0,90	0,90	1,07	1,09	1,09	1,07	1,09	1,09
2041	1,04	1,05	1,02	1,06	0,99	1,03	0,94	0,92	0,92	1,06	1,08	1,08	1,06	1,08	1,08
2042	1,02	1,03	1,00	1,05	0,97	1,02	0,92	0,90	0,90	1,03	1,05	1,05	1,03	1,05	1,05
2043	1,01	1,02	0,99	1,04	0,96	1,01	0,92	0,90	0,90	1,01	1,03	1,03	1,01	1,03	1,03
2044	1,01	1,02	0,99	1,03	0,96	1,01	0,92	0,90	0,90	1,05	1,06	1,06	1,05	1,06	1,06
2045	1,00	1,01	0,98	1,03	0,95	1,00	0,91	0,89	0,89	1,07	1,09	1,09	1,07	1,09	1,09
2046	0,97	0,98	0,95	1,00	0,92	0,97	0,88	0,86	0,86	1,07	1,08	1,09	1,07	1,09	1,09
2047	0,97	0,98	0,95	0,99	0,92	0,97	0,88	0,86	0,86	1,05	1,07	1,07	1,05	1,07	1,07
2048	0,95	0,96	0,93	0,97	0,90	0,95	0,86	0,84	0,84	1,01	1,03	1,03	1,01	1,03	1,03
2049	0,90	0,91	0,88	0,92	0,85	0,90	0,82	0,80	0,80	0,94	0,96	0,96	0,94	0,96	0,96

Table A 4: Relative increase in indium demand from the TV industry.

Year	Relative increase
2019	1,02
2020	1,02
2021	1,02
2022	1,02
2023	1,01
2024	1,02
2025	1,02
2026	0,97
2027	1,01
2028	1,02
2029	1,02
2030	1,00
2031	0,98
2032	1,01
2033	1,01
2034	1,02
2035	1,00
2036	0,99
2037	1,01
2038	1,01
2039	1,01
2040	1,00
2041	0,99
2042	1,01
2043	1,00
2044	1,00
2045	1,02
2046	0,97
2047	1,02
2048	1,01
2049	1,00
2050	1,02