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Financing Low-Carbon Materials Through Green Bonds

Proposing Criteria and Benchmarks for Green Bonds in the Aluminium Sector

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"Was ist das – was – ist das ….?

"Je, den Düvel ook, c'est la question, ma très chère demoiselle Tony"

"And – and – what comes next …?"

"Oh, yes, yes, what the dickens does come next? C'est la question, ma très chère demoiselle Tony"

The Buddenbrooks, 1901
Thomas Mann

Abstract

Reducing emissions in the basic materials sector, which account for 25% of the global greenhouse gas emissions is a pressing climate mitigation task. Investments into decarbonising this sector are critical and therefore raising capital though climate finance is gaining attention. Green bonds are a new asset class that incorporate sustainability criteria into bonds. Despite the increasing use of green bonds, there are no criteria for this instrument for the materials sector. The lack of criteria inhibits much needed investments, risks environmental integrity, and facilitates greenwashing. This thesis aims to propose effective and transparent criteria for green bonds in the materials sector. The research question and methodology have been developed with a research group at the DIW Berlin. To investigate the question, the aluminium sector has been chosen as a case study. This research draws on elements of the green bond taxonomy by the Climate Bond Initiative and CICERO. As a result, this thesis proposes two complementary sets of green bond criteria for the aluminium sector: one focuses on management strategies and disclosures, and a second set focuses on technological mitigation options. This paper further finds that academic literature on developing criteria for green bonds is largely lacking and urgently requires more attention, so that the potential of this new asset class can further explored.

Keywords:

Climate finance - Green bonds – Low-Carbon Materials – Green Bond Criteria – Aluminium Production

Executive Summary

With 25% of global emissions, basic materials like cement, steel, copper, and aluminium are an important target for mitigation efforts. How can the decarbonisation of the most emission-intensive sectors be accelerated? Climate finance approaches like green bonds to raise capital for this goal are a promising tool. Just over a decade old, green bonds are quickly emerging as an asset class that connects sustainability with the world of finance and business (Schoenmaker, 2019). As the materials sector is very capital-intensive and operates on long time frames, today's investments are critical for the future (Neuhoff et al., 2018). Therefore, green bonds offer new possibilities of addressing investment challenges and improving management towards a low-carbon future.

Despite their potential, criteria defining what "green" means for bonds in the materials sector are largely missing. For other sectors, such as the energy sector, criteria have been developed by international organisations like the Climate Bonds Initiative. Establishing transparent criteria defining what makes a bond "green" or "climate-friendly" is extremely important in order to direct financial flows effectively and avoid greenwashing (Shishlov, Morel, & Chochran, 2016). This paper addresses this research gap and proposes criteria for green bonds in the materials sector.

As the field of green bonds is still nascent, literature on how to develop green bond criteria is largely missing. Together with the German Institute for Economic Research (Deutsches Institut für Wirtschaftsforschung), this thesis has laid out a method to develop sets of strategy- and technology-based criteria for green bonds in the materials sector. For this, elements from the green bond certification schemes developed by the Climate Bonds Initiative and CICERO have been adopted. The analysis furthermore draws on literature on scenario modelling, corporate management strategies for low-carbon transitions, and low-carbon production methods. For this thesis, the aluminium sector is chosen as a specific case to gain insight into criteria for green bonds for the materials sector more generally.

As a result, this paper proposes two sets of criteria for a green bond in the aluminium sector. The first set addresses a company's management strategy. It assesses components like scenario compatibility, management quality, and disclosure requirements. The second set of criteria is concerned with process-related mitigation options such as installation of best available technologies, switching to renewable energy, and circular economy strategies. The technology-related criteria are classified through CICERO's "shades of green" approach, allowing nuances for the classification of different mitigation options.

The green bond market is at risk of implosion if environmental integrity of green bonds through transparent criteria does not improve (Shishlov, Morel, & Chochran, 2016). This thesis makes first steps to address this issue, but procedures and clarity regarding green bonds must be standardised so that this asset class can further develop. Apart from proposing criteria for green bonds in the aluminium sector, this thesis performs the important task of identifying areas for further research in this underdeveloped field. Most importantly, the question of how to develop criteria for green bonds needs further investigation.

Table of Contents

LIST OF FIGURES ..... **II**

LIST OF TABLES ..... **II**

ABBREVIATIONS ..... **III**

1 INTRODUCTION **5**

1.1 BACKGROUND AND SIGNIFICANCE 5
1.2 PROBLEM DEFINITION 6
1.3 RESEARCH QUESTIONS 6
1.4 SCOPE AND LIMITATIONS 7
1.5 AUDIENCE 8
1.6 STRUCTURE 8

2 LITERATURE REVIEW **9**

2.1 CLIMATE FINANCE 9
2.2 GREEN BONDS 9
2.2.1 Characteristics of the bond market *9*
2.2.2 History and development of green bonds *10*
2.2.3 Review and labelling of green bonds *11*
2.2.4 Barriers to issuance of green bonds *13*
2.3 THE MATERIALS SECTOR 14
2.4 THE ALUMINIUM SECTOR 14
2.4.1 Basic characteristics of aluminium production *14*
2.4.2 Applications of aluminium *15*
2.4.3 Barriers to decarbonisation of aluminium production *16*
2.5 LITERATURE REVIEW SUMMARY 16

3 ANALYTICAL FRAMEWORK AND METHODOLOGY **17**

3.1 CASE STUDY SELECTION 17
3.2 ANALYTICAL FRAMEWORK 17
3.2.1 CBI's green bond taxonomy *18*
3.2.2 Approach to classify process-related mitigation options *19*
3.3 RESEARCH DESIGN AND METHODOLOGY 20
3.3.1 Steps to develop green bond criteria *20*
3.4 DATA COLLECTION 21

4 ANALYSIS AND RESULTS **22**

4.1 ANALYSIS OF RELEVANT SCENARIOS 22
4.1.1 Sectoral carbon budget scenarios *23*
4.1.2 Technology mix and price change scenario *26*
4.1.3 Circular economy scenario *27*
4.1.4 Summary of the scenario analysis section *28*
4.2 TRANSLATING SCENARIOS AND SECTOR PATHWAYS INTO BENCHMARKS, ELIGIBILITY CRITERIA AND FIRM-LEVEL METRICS 32
4.2.1 Emission allocation at company level: contraction and convergence *32*
4.2.2 Science based target approaches *33*
4.2.3 Target setting at company-level *34*
4.3 MITIGATION OPTIONS FOR THE ALUMINIUM SECTOR 37
4.3.1 Characteristics of the aluminium sector *37*
4.3.2 Mitigation options in the aluminium sector *41*
4.3.3 Technology-related criteria selection *46*

4.4 ASSESSMENT OF STRATEGY-BASED CRITERIA 50
4.4.1 *Strategy-based criteria* *50*
4.4.2 *Principles of reporting* *53*
4.5 GREEN BOND CRITERIA FOR THE ALUMINIUM SECTOR 53
4.5.1 *Strategy-related criteria for a green bond in the aluminium sector* *53*
4.5.2 *Technology-based criteria for a green bond in the aluminium sector* *54*

5 DISCUSSION 57

5.1 DISCUSSION OF METHODS TO DEVELOP GREEN BOND CRITERIA 57
5.2 DISCUSSION OF RESULTS 58

6 CONCLUSION 61

6.1 SUMMARY 61
6.2 RECOMMENDATIONS AND FUTURE RESEARCH 61

BIBLIOGRAPHY 63

List of Figures

Figure 2.1. Key players in green bond certification. 12

Figure 3.1 Flow-chart to design criteria for a green bond in the materials sector. 20

Figure 4.1 TPI's benchmark scenarios for the aluminium sector. 25

Figure 4.2: Benchmarks for the aluminium sector according to selected scenarios 29

Figure 4.3: Simplified aluminium production processes. 37

Figure 4.4 Average CO_2 *intensity of aluminium production.* 41

Figure 4.5 TPI's framework to measure a company's management quality 52

List of Tables

Table 3.1: Outline of CBI's green bond taxonomy. 18

Table 4.1 Scenarios as used by IEA's 2017 ETP report. 24

Table 4.2: Benchmark values for selected scenarios for the aluminium sector in percent of the reference value for 2014. 30

Table 4.3 Overview of required data to derive emission intensity pathways. 35

Table 4.4: Emission and energy intensity of primary and secondary aluminium. 40

Table 4.5: Classification after CICERO's "shades of green" approach. 46

Table 4.6: Classified mitigation options for the aluminium sector. 47

Table 4.7: List of non-quantifiable mitigation options for the aluminium sector. 49

Table 4.8 List of strategy-related criteria and disclosures. 53

Table 4.9: Green bond taxonomy for the aluminium sector. 54

Abbreviations

2DS	2°C scenario
Al	Aluminium
B2DS	Beyond 2°C scenario
BAT	Best available technologies
BREF	BAT Reference
CBI	Climate Bonds Initiative
CCS	Carbon capture and storage
CDP	Carbon Disclosure Project
CDSB	Climate Disclosure Standards Board
CO_2e	CO_2-equivalent
CPI	Climate Policy Initiative
DIW	Deutsches Institut für Wirtschaftsforschung (German Institute for Economic Research)
EC	European Commission
EIB	European Investment Bank
EJ	Exajoule
EMS	Energy Management Systems
ESG	Environmental, social and economic
ETP	Energy technology perspectives
EU	European Union
FSB	Financial Stability Board
GBPs	Green Bond Principles
GEVA	Greenhouse Gas per Value Added
GHG	Greenhouse gases
GJ	Gigajoule
GRI	Global Reporting Initiative
GSSB	Global Sustainability Standards Board
H-H	Hall-Héroult Process
HLEG	High-Level Expert Group on Sustainable Finance
IAI	International Aluminium Institute
ICMA	International Capital Market Association
IEA	International Energy Agency
IIIEE	International Institute on Industrial Environmental Economics
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
MWh	Megawatt hour
NDCs	Nationally Determined Contributions
NGO	Non-governmental organisation
OECD	Organisation for Economic Co-operation and Development
PFPB	Point Feeder Pre-Bake
PFC	Perfluorocarbons
R&D	Research & development
R&DDD	Research, development, demonstration, & deployment
RTS	Reference Technology Scenario
SASB	Sustainability Accounting Standards Board
SBN	Sustainable Banking Network
SBT	Science-based target
SDA	Sectoral Decarbonisation Approach
SDG	Sustainable Development Goal
TCFD	Task Force on Climate-related Financial Disclosure
TEG	EU Technical Expert Group on Sustainable Finance
TRL	Technological readiness level
TWh	Terawatt hours
TPI	Transition Pathway Initiative

USD	US Dollar
WRI	World Resource Institute
WWF	World Wildlife Forum

1 Introduction

1.1 Background and significance

In the 2015 Paris Accord, world leaders have agreed to limit the global average temperature increase to 2°C compared to pre-industrial levels and pursue efforts to keep the global average temperature below a 1.5°C increase (UNFCCC, 2015). Yet, according to Climate Action Tracker (2018), Altenburg & Assmann (2017), and UNEP (2019), the current efforts to cut greenhouse gas emissions are not enough to reach these targets and avoid catastrophic consequences of climate change.

To reach the targets agreed on in the Paris Accord, efforts need to be directed to sectors that are especially emission intensive, such as the basic materials sector (cement, chemicals, iron, steel, pulp and paper, aluminium, etc.), which alone contributes with 25% to the global greenhouse gas (GHG) emissions (Neuhoff et al., 2018).

At the same time, materials are the literal building blocks of modern life. They are integral to the global economy and infrastructure surrounding us (Material Economics, 2018). With a growing world population, the materials sector will become even more important (Haraldsson & Johansson, 2018; Neuhoff et al., 2018). Growing demand and its central role in the global economy make decarbonising the materials sector a challenging mission.

Like other sectors, the materials sector has been subject to numerous measures that aim to reduce emissions. For example, national rules and regulations aim to limit emissions, and policy programmes, like subsidies for renewable energy projects, have been designed to stimulate transition (Altenburg & Assmann, 2017). These instruments, however, have not been effective enough to reach the necessary levels of decarbonisation (Neuhoff et al., 2018). Therefore, innovative approaches that target the financial dynamics of the sector are gaining attention around the globe (Buchner et al., 2017).

The second article of the 2015 Paris Accord has called for "making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development" (UNFCCC, 2015). The term "climate finance" is generally used to describe actions involving financial resources to aid a transition to a low-carbon economy and to adapt to the impacts of climate change (Falconer & Stadelmann, 2014; Talbot, 2017). To reach climate targets, public and private sectors are gradually starting to develop capacities dealing with climate finance and the mobilisation of capital (Dangerman & Schellnhuber, 2014; Falconer & Stadelmann, 2014). Particularly private investment flows are considered to be a crucial element in the transition towards a low-carbon society (Banga, 2019; Polzin, 2017; SBTi 2019a). In 2015, climate finance flows reached USD 299 billion from private and USD 138 billion from public investors (Buchner et al., 2017).

So-called "green bonds" or "climate bonds" (hereinafter: green bonds) have the potential to play a major role in transitioning the economy but are still an emerging field (Clapp, 2018; Gianfrate & Peri, 2019). Green bonds are bonds which are specifically designed to raise capital for a transition to a more sustainable economy (Laskowska, 2018; Schoenmaker, 2019). Green bonds can be issued by the private sector, banks, and governments. Since 2007, USD 152 billion have been issued in green bonds, and the market is growing rapidly (CBI, 2018; SBN, 2018). There are plenty of examples of global players who use green bonds as a tool, such as the European Investment Bank and the World Bank. Green bonds are praised for having great potential to steer capital towards projects (Gianfrate & Peri, 2019; Laskowska, 2018; SBN, 2018). The UN Secretary-General, for example, has recognised green bonds as one of the "most significant developments in the financing of low-carbon, climate-resilient investment opportunities" in 2015 (UN, 2015). Yet, studies on their effectiveness are still emerging (Agliardi & Agliardi, 2019; Gianfrate & Peri, 2019; Tolliver, Keeley, & Managi, 2019).

Up to date, there is no internationally harmonised definition of what criteria make a bond "sustainable", "climate-friendly", "green", or "low-carbon" (Banga, 2019; Ehlers & Packer, 2017). This lack of clarity inhibits investments into green bonds, as environmental integrity is uncertain (CBI, 2018; Shishlov, Morel, & Chochran, 2016). Several initiatives have emerged aiming to define, review, and certify green bonds, so that they become a transparent, reliable, and effective instrument (Shishlov, Morel, & Chochran, 2016; Talbot, 2017). However, for some emission intensive sectors, like the basic materials sector, criteria for green bonds have not yet been developed.

1.2 Problem definition

Thus far, the renewable energy sector has been attracting the majority of green bonds (Zerbib, 2016). While decarbonising the energy sector is essential, other sectors like the growing basic materials sector are also responsible for a large share of emissions that urgently need to be reduced. Production facilities have lifespans of more than 20 years, meaning that today's investments have a significant influence on the future (Bataille et al., 2018). Despite of this, to date there is no comprehensive set of criteria for green bonds in the basic materials sector, meaning that investments are less likely to be directed accordingly (Shishlov, Morel, & Chochran, 2016; CBI, 2018).

Green bonds are an opportunity for investors to diversify their sustainability portfolio (Schoenmaker, 2019). A lack of clarity on what constitutes effective criteria for green bonds in the basic materials sector bears several risks, such as delaying important investment to decarbonise the sector. Another risk is so-called green (bond)-washing[1], where investors are deceived into putting capital towards projects that are labelled as effectively reducing the sector's emission intensity, but in fact only have limited mitigation potential (Bachelet, Becchetti, & Manfredonia, 2019; EU HLEG, 2018). Therefore, it is crucial to design comprehensive tools that help issue appropriate green bonds and provide investors with reliable information to guide their decision-making process.

This thesis addresses the lack of criteria for green bonds in the basic materials sector. It aims to propose criteria and benchmarks for developing green bonds for the materials sector that effectively and transparently steer investments towards less emission-intensive production. The aluminium sector is chosen as a case study to explore this topic.

1.3 Research questions

The general research problem this thesis seeks to address is how to develop an effective and transparent set of criteria and benchmarks for green bonds in the materials sector. To address this question, a number of sub-questions need to be investigated.

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[1] Greenwashing is defined as the act of promoting an overly positive corporate image, that is in fact founded on limited or no environmental benefits (Lyon & Maxwell, 2011).

Primary Research Question:	
What kind of green bond criteria stimulate transparent and effective investments that reduce GHG emissions in the basic materials sector?	
Sub-Questions:	
i.	What climate and energy scenarios can inform green bond criteria for the aluminium sector?
ii.	How can the emission profile of the aluminium sector be characterised and with which mitigation options can those emissions be reduced? How can mitigation options be developed into criteria for a green bond?
iii.	How can sector- and firm-level benchmarks and eligibility criteria be used to assess individual companies with regards to their emission performance?
iv.	What kind of management strategies support the transition to a low-carbon aluminium sector and how can those be used for the design of green bond criteria?

This thesis project has been developed with researchers from the German Institute for Economic Research (Deutsches Institut für Wirtschaftsforschung, DIW). The research group under Ingmar Jürgens, who co-supervised this thesis, focuses on designing green bonds in the materials sector more generally.

1.4 Scope and limitations

The widespread use of green bonds is just over a decade old, and there is even less experience with green bonds in the materials sector. This makes data availability a major limitation of this paper. For example, academic literature on frameworks for the development of green bonds is largely lacking.

This paper focuses on reducing the aluminium industry's impact on global warming, so it is mainly concerned with GHG emissions and energy consumption, arguably the largest environmental impacts of the sector. Covering all environmental issues connected to the aluminium industry has not been in the scope of this research project.

Furthermore, this paper focuses on aluminium production (e.g. refining and smelting) rather than emissions from mining, transport, use, and end-of life management. This is because it aims to contribute to green bonds potentially financing the production rather than the use of aluminium.

Furthermore, available literature dealing with specific technologies and management practices in relation to decarbonisation of the aluminium sector is limited. For example, data on emission intensities of specific technologies are often outdated or not available in sufficient detail. This limits the accuracy of this research, as calculating emission intensities is an integral part of this work. Due to time constraints, no expert interviews have been conducted for this thesis.

The paper seeks to deliver insights that are applicable to the aluminium sector on a global level and to companies in all forms and sizes. Yet, due to data availability and language barriers, this paper significantly draws on knowledge and data from Europe, which may limit its global applicability.

As this thesis project has supported the research on green bonds in the materials sector at the DIW, parts in the result section of this thesis are in some instances identical to the work the author has contributed the research at the DIW.

1.5 Audience

As this thesis project has been developed with the DIW in Berlin, it aims to contribute to the research at the DIW. Specifically, this thesis has provided the aluminium sector perspective to the DIW's ongoing research on green bonds in the materials sector. This dynamic makes the researchers at the DIW the main audience for this thesis.

To date, criteria for green bonds in the materials sector as well as literature on how to develop criteria are largely missing. The methodology and results of this thesis aim to advance the scholarly debate around the topic and highlight new research areas both in the field of climate finance and the mitigation of the materials sector.

As this work informs the debate on green bonds and provides a comprehensive assessment of the relevant concepts and data, it also aims to be useful for the financial sector. The results and methodology of this thesis may also be useful for stakeholders such as certification bodies. Proposing criteria for a sector that as of now has not been the focus of attention hopefully raises important questions and gives impulses for future development.

According to Shishov, Morel, & Chochran (2016), national and international governmental bodies play an important role, as they are in a position to provide frameworks, criteria and guidelines for the bond market. The results of this paper offer useful insights for these actors to support this process.

Moreover, the results of this thesis aim to be useful for aluminium producing companies. The proposed criteria inform the debate on how low-carbon transitions both in terms of management approaches and technology roadmaps can be realised. It further offers insight into disclosure requirements that are important for a company's management of transitions to a low-carbon economy.

1.6 Structure

Chapter 1 presents the problem addressed by this thesis, outlines the specific research questions, defines the research gap, and explains the rationale behind the topic choice as well as the thesis objectives and limitations. In chapter 2, a literature review provides a more thorough analysis of the field of study. It establishes the context and provides a review of existing literature on climate finance and the materials sector to further justify the research problem. Chapter 3 explains and justifies the methods, analytical framework and research design that guide this thesis. Chapter 4 contains the results of this study, organised in five sub-sections as outlined in the methods section. Chapter 5 presents a discussion of the methodology and results. It is designed to interpret the results, further explain the implications of new insights for the involved stakeholders and reflect on the methodological implications. Chapter 6 contains a summary of this thesis and presents new research gaps and recommendations.

2 Literature review

The literature review contains four sections. The first section (2.1) explores the topic of climate finance and how it can support a transition to a low-carbon economy. The second section (2.2) focuses on green bonds and their relevance to the materials sector. The third section (2.3) reviews the materials sector and its environmental impacts. The final section (2.4) reviews literature on the aluminium sector.

2.1 Climate finance

Climate finance (also referred to as green finance or sustainable finance) is a relatively new approach to tackle environmental problems around the globe. The Climate Policy Initiative (CPI) defines climate finance as “financial resources paid to cover the costs of transitioning to a low-carbon global economy and to adapt to, or build resilience against, current and future climate change impacts” (Falconer & Stadelmann, 2014, p. 4). It is largely recognised that without international, large-scale investment flows that mobilise private funds for sustainable development projects, reaching climate targets is virtually impossible (IPCC, 2018; OECD, 2017; Steckel et al., 2017).

Kolev et al. (2012) describe that there is mostly a “historical lack” of awareness of sustainability issues in large corporations and the financial world. Broadly speaking, climate finance aims to combine the world of finance and business with environmental protection (Clapp, 2018; Wang & Zhi, 2016). Most often, climate finance instruments are specifically designed to lower GHG emissions to mitigate climate change. Investors have the means to provide productive capital, which is why they play a crucial role in raising the financial means for a sustainable future (Butz, Liechti, Bodin, & Cornell, 2018). According to an estimation by McCollum et al. (2013), around USD 800 billion of investments into low-carbon energy projects alone are necessary per year until 2050 to reach the 2°C target agreed upon in the Paris Accord.

Although climate finance is slowly gaining attention around the globe, Steckel et al. (2017) argue that the academic and political debate around climate finance is largely lacking. Albeit targeting the financial sector, also governmental bodies and policymakers on different levels are influential stakeholders in developing the field of climate finance. Public frameworks are important to build capacity and awareness, address legal and administrative barriers, as well as building verification systems (Falconer & Stadelmann, 2014).

2.2 Green bonds

2.2.1 Characteristics of the bond market

Essentially, bonds function much like private loans from banks, but they are considered public debt. A government or a corporation issues public debt in the form of a bond certificate, which indicates the borrowed amount, interest rates, and payment dates. In the case of bonds, the interest payments are called “coupons” and the borrowed amount is referred to as the “principal” or “face value”. The final date of the bond is called the “maturity date” of the bond. In the time until maturity, (also called term), coupons are paid out periodically at pre-determined dates (Choudhry, 2001).

Green bonds offer a variety of advantages to their issuers. They can perform the important task to align business strategy with sustainability agenda, communicate environmental awareness, and may even “expand and improve relationship with debt providers” (Shishlov, Morel, & Chochran, 2016, p. 8). For investors, green bonds are an attractive tool because it allows them to broaden investment portfolios and gain additional information about a project (Schoenmaker, 2019).

As touched upon, bonds can be issued by governments or corporations. Governmental bonds have three sub-classes: municipal, sovereign, and supranational. Municipal bonds are issued by local authorities, sovereign bonds by national governments, and supranational bonds are issues by multilateral institutions such as the World Bank (Schoenmaker, 2019; Shishlov, Morel, & Chochran, 2016).

In the corporate sector, bonds are generally differentiated in secured and unsecured bonds. Holders of secured bonds (also called structured bonds), have direct claims in case of bankruptcy: this type of bond is backed by assets (e.g. real properties). Holders of unsecured bonds have lower priority in case of bankruptcy, meaning holders have the right to claim assets only if those are available (Choudhry, 2001; Schoenmaker, 2019).

The risk of bonds is assessed through credit ratings, which are formulated by private companies. Famous examples include Fitch, Standard & Poor's, and Moody's. Credit rating agencies perform the important task of assessing a government's or corporation's creditworthiness (Baber, 2014; Schoenmaker, 2019).

Generally, both types of corporate bonds carry more risks than government bonds. Corporate bonds are more likely to default, as corporations are much smaller entities than governments. Governments can for instance generate income through taxes before having to default a bond, corporations are much more limited in this regard (Schoenmaker, 2019).

For the materials sector, only corporate bonds are of interest, as corporations are the issuers of bond certificates. Therefore, this paper will only focus on corporate bonds.

As already touched upon, green bonds are praised for their potential to finance the transition to a low-carbon economy and frequently singled out as such (Clapp, 2018; EU HLEG, 2018; Laskowska, 2018; SBN, 2018). Obviously, their market share and therefore success is among other reasons dependent on whether they are financially attractive for investors. Literature on this is still emerging, but a few studies have started to examine their financial attractiveness and report mixed results. In a recent study, Giafrate and Petri reviewed green bonds in the European market and find that "green bonds are more financially convenient than non-green ones" (2019). For the US, Karpf and Mandel (2018) studied municipal green bonds and find that green bonds offer positive premiums and are becoming increasingly more attractive than non-green bonds. Zerbib (2019), on the contrary, finds that green bonds have a slightly lower yield than regular bonds.

2.2.2 History and development of green bonds

The development of green bonds is part of a wider movement within the financial and economic world to act more responsibly. Concepts like socially responsible investing and social and environmental corporate responsibility are becoming widespread, green bonds have emerged as one way to capture this development (Laskowska, 2018; Tolliver, Keeley, & Managi, 2019).

The market for green bonds is just over a decade old, with the European Investment Bank (EIB) issuing the first so called "Climate Awareness Bond" in 2007 (Trompeter, 2017). The

World Bank adopted the concept and issued its first green bond in 2008 (Banga, 2019). Since then, the market has been growing rapidly and spreading from multilateral development banks to other markets, such as commercial banks, institutions, municipalities, companies, and other traditional investors (Banga, 2019; Gianfrate & Peri, 2019). During the first boom of green bonds in 2013, the demand for green bonds was so high that most of them had been heavily oversubscribed (Shishlov, Morel, & Chochran, 2016).

According to Trompeter (2017), particularly the early involvement of international institutions and various government agencies have helped establish credibility in the green bond market. An important milestone in the development of the green bond market has been the publication of the so-called "Green Bond Principles" (GBPs) by the International Capital Market Association (ICMA) in 2014. The GBPs build the foundation of many green bond certifications and labels that exist today (Banga, 2019; Ehlers & Packer, 2017).

Despite the rapid growth, the market share of green bonds in the international bond market is still very small. In 2016, only around 1.6% of debt has been issued in the form of green bonds (Ehlers & Packer, 2017). To date, the market is concentrated in developed and emerging economies. Notably, in 2016 40% of the green bonds have been issued in China alone (Banga, 2019).

2.2.3 Review and labelling of green bonds

Green bonds can be divided into "certified" and "self-labelled" green bonds. Certified green bonds undergo an external certification process, and if successful they receive a green label that indicates that all bond proceeds go to the indicated cause. Self-labelled bonds, on the other hand, are labelled only by the issuer and without external review (Banga, 2019; Talbot, 2017).

Essentially, there are three key players in the process of issuing a certified green bond. Figure 2.1 offers a simplified visualisation of the relationship between them: issuer, independent reviewer, and investor. The issuer (e.g. a company) develops a green project and documents its characteristics and environmental benefits. This documentation then undergoes an independent review, in which the truthfulness of the claims made by the issuer are verified (Banga, 2019). Depending on the independent reviewer, this confirmation process is based on a set of different criteria. Once this process is finished, the issuer can put a certified, labelled green bond on the market to raise capital for the indicated project. Investors then provide capital, and in return they receive coupon payments and eventually the principal (Banga, 2019; Schoenmaker, 2019).

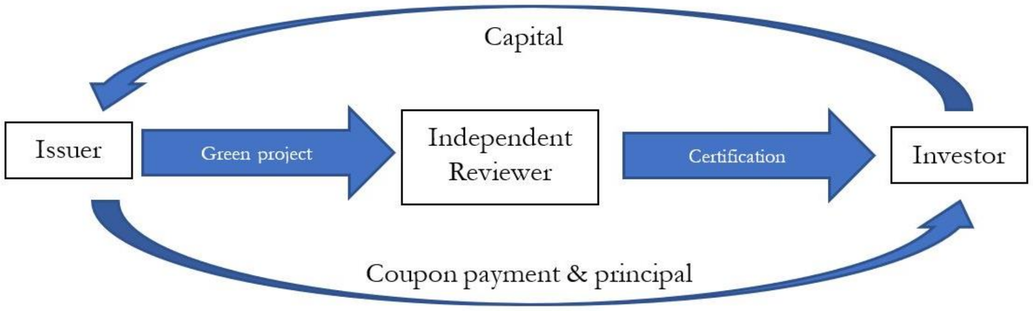

Figure 2.1. Key players in green bond certification.

Source: Adapted by the author from Banga (2019).

It is integral to the environmental integrity of green bonds that issuers, investors, and asset managers have certainty that bonds intended to contribute to a sustainable future actually deliver effective outcomes (Shishlov, Morel, & Chochran, 2016). There are some international initiatives that aim to make it easier for asset managers to identify such bonds themselves, such as the Financial Stability Board's (FSB) Task Force on Climate-Related Financial Disclosure (TCFD). The TCFD promotes increased disclosure of environmental information (TCFD, 2017b). This kind of internal judgement, however, is not considered enough to develop the bond market as a whole. External certification is considered to be crucial, because it increases transparency and allows a company to publicise its engagement towards all kinds of stakeholders (Ehlers & Packer, 2017; Shishlov, Morel, & Chochran, 2016).

There are several organisations that seek to define what a green bond entails and how they can be externally certified. As already touched upon, a first and important step towards defining green bonds was made in 2014 by the ICMA, which published a set of general principles for green bonds. These so-called "Green Bond Principles" (GBPs) are widely used and have four core components (ICMA, 2018):

- *Use of proceeds:* clear and quantified (if applicable) documentation about environmental benefits of the project (e.g. biodiversity conservation, renewable energy, energy efficiency, climate change adaptation, circular economy).
- *Process of Project Evaluation and Selection:* communication of objectives, justification of basis on which project has been identified as green, eligibility criteria, etc.
- *Management of Proceeds:* issuer demonstrates trackability of net proceeds.
- *Reporting:* annual report on the status of proceeds and project development.

In 2016, the European Commission introduced the High-Level Expert Group on Sustainable Finance (HLEG), with the task to explore climate finance instruments and their relevance (EU HLEG, 2018). Important in harmonising the standards and criteria of green bonds is also the Technical Expert Group (TEG) established by the European Commission, which has the task to give clear guidelines for publishing a taxonomy for sustainable finance instruments by 2020 (Bachelet, Becchetti, & Manfredonia, 2019).

The largest organisations that provide certification for green bonds are the Climate Bonds Initiative (CBI), CICERO Second Opinions, Moody's Green Standard Assessments, and Standard & Poor's Green Evaluations. CBI is a non-profit organization solely focused on green bond certification, and CICERO is a research institute. The last two organisations in this listing are private companies and sections of the biggest credit risk agencies in the world (Ehlers & Packer, 2017; Shishov, Morel, & Chochran, 2016).

The Climate Bonds Initiative (CBI) is a non-profit organisation and one of the key players in the green bond market. CBI has developed a sector-specific certification procedure to label green bonds. If an asset meets their criteria, it is eligible to receive external certification through CBI. The CBI uses a binary approach: according to their framework bonds are either green or not. The CBI has not put forward certification procedures for all sectors yet. Especially the industrial sectors, including the materials sector, are largely underdeveloped (CBI, 2018). Furthermore, CBI is criticised for not including continuous monitoring in its certification procedure (Ehlers & Packer, 2017). The CBI and its approach are discussed in more detail in chapter 3.

CICERO is an independent, Norwegian-based climate research institute, which provides a quality check on green bonds if requested by the issuer. The so-called "second opinions" review the criteria and framework the issuer has used to declare a bond a green bond. To do so, CICERO works on a case-by case basis, reviewing each framework separately. The review criteria are based on the GBPs as defined by ICMA. The aim is to ensure integrity of the criteria with which the green bond has been defined as green. CICERO works with a non-binary assessment, allowing for different "shades of green". The final reports on second opinion by CICERO are most often confidential (CICERO, 2016; Shishov, Morel, & Chochran, 2016).

Moody's Green Standard Assessment has been developed in 2016. Moody's is a private company with the core business is to rate credit worthiness. In the case of green bonds, it rates the likelihood that the capital raised through the green bond will support environmentally beneficial projects. Their assessment is largely based on the GBPs (Ehlers & Packer, 2017; Shilling & Cantor, 2016).

Similarly to Moody's, Standard & Poor's offers ratings of green bonds. Their assessment is also based on the GBPs. It is considered to be one of the most extensive assessments, and captures transparency, governance, and technical impact assessments as components (Ehlers & Packer, 2017; S&P, 2017).

Besides private organisations setting out certification criteria, there are also national and international players who provide certification procedures for domestic or regional markets. For example, the Chinese Green Bond Finance Committee has put forward a catalogue of endorsed bonds. Those types of domestic guidelines limit, however, green bonds to the internal investor base (Ehlers & Packer, 2017).

2.2.4 Barriers to issuance of green bonds

As already touched upon, green bonds as a financial instrument are developing rapidly, but still only cover a fraction of the bond market. The literature mentions the slow development of certifications, definitions, and taxonomies as key reasons for the small market share. For sectors like the materials sector, frameworks or criteria that can transparently certify a green bond are missing. This lack of tools and criteria may lead to a lack of investments in the transition of the sector, a lack of credibility, and even to greenwashing (EU HLEG, 2018; Laskowska, 2018; Talbot, 2017).

In the past, cases of greenwashing projects through green bonds have caused harm and have inhibited investments. In 2014, for example, a €2.5 billion green bond issued by the company GDF Brazil to finance a hydro power project has received massive criticism because of its questionable environmental benefits (Shishlov, Morel, & Chochran, 2016). The green bond even received the "Pinocchio du Climat" prize awarded by the NGO Friends of the Earth for greenwashing practices (Tickell, 2014). To avoid such cases in the future, frameworks, criteria, and standards are important to manage expectations and establish trust and transparency.

The harmonisation and development of standards and criteria is especially important for internationally traded goods like basic materials, for example because international supply chains are very difficult to monitor and the understanding of what "green" means can differ across borders. In 2018, for example, the EIB and Chinese government have published a white paper outlining how they will work on harmonising their approaches in the future. International collaboration like this provides further clarity and high-level action creates additional momentum around green bonds (Bachelet, Becchetti, & Manfredonia, 2019).

2.3 The materials sector

The basic materials sector contributes 25% of the global GHGs, and therefore carries a special significance for decarbonising the global economy (Neuhoff et al., 2019). Materials are integral to modern life – virtually everything around us is made out of materials such as steel, plastics, cement, paper, chemicals, copper, and aluminium. Materials are important for construction, transmission lines, manufacturing, transport, and appliances. With a growing world population, more materials are needed to ensure everything from energy production to transportation, buildings to appliances, and electronics to food packaging (Material Economics, 2018). In the European Union alone, the non-ferrous metal industry employs around two million people and is integral to the economy (Cusano et al., 2017).

The materials sector is very capital intensive. Plants and production facilities have an average lifespan of twenty years. According to Bataille et al. (2018), "all new investment must be net-zero emitting by 2035-2060 or be compensated by negative emissions to guarantee GHG-neutrality" (p. 5), implying that investments made today should already incorporate these aspects.

The non-ferrous metal sector (as one of the materials sectors) includes materials such as lead, zinc, cadmium, tin, cobalt, as well as aluminium. For most materials, two streams of production exist: primary and secondary production. Primary production is the production from raw materials, whereas the secondary production route uses end-of-life materials as input (Cusano et al., 2017).

2.4 The aluminium sector

2.4.1 Basic characteristics of aluminium production

Aluminium has only been produced since the 19th century, making it one of the newest materials used by humans. Aluminium does not exist in nature in its pure form and has to be produced through a number of steps. It was not until the advent of electricity that aluminium could be produced, because it has to be refined through an electrolytic process (Cusano et al., 2017; Schatzberg, 2003).

Today, aluminium is produced via primary and secondary production methods. For primary production, the input raw material is bauxite ore. From bauxite ore, alumina (aluminium oxide) is extracted through the Bayer process. Alumina is then refined to aluminium through an electrolysis process (most plants use the Hall-Héroult process). The liquid aluminium is then further processed into a variety of products (Liu & Müller, 2012). The smelting process is very energy-intensive and responsible for more than 80% of the emissions in the aluminium sector (Cusano et al., 2017). Decarbonising the energy sources (e.g. by switching to renewables) used for smelting is therefore considered to be one of the most important transition pathways.

In the secondary production route, scrap aluminium is used as an input for the production process. After collection, sorting, and de-coating, scrap aluminium is remolten for further processing (Cusano et al., 2017). Secondary aluminium production is much less (approximately 98%) emission intensive than primary production, making secondary aluminium an attractive decarbonisation option (Material Economics, 2018).

As touched upon, the energy supply is one of the most important factors influencing the environmental impact of aluminium production. Haraldsson & Johansson (2018) find that the electrolysis process alone can amount to as much as half of the production costs for primary aluminium. On global average, energy costs are estimated to account for approximately 30% of the production costs for primary aluminium (Balomenos, Panias, & Paspaliaris, 2011). Next to drawing from the national energy grid, many firms also have on-site energy production (Dietz, Jahn, & Noels, 2019). Besides CO_2 emissions, so called and perfluorocarbons (PFCs)[2] are one of the main greenhouse gases emitted during aluminium production. With 2% of the global GHG emission, the aluminium sector has a significant impact on global emissions (Neuhoff et al., 2018), while in terms of carbon intensity, it is one of the most carbon intensive sectors. Moreover, it is characterised (in the EU and its emissions trading scheme) by significant CO_2 costs (Jürgens, Barreiro-Hurlé, & Vasa, 2013). According to the EU definition, the aluminium sector is considered to be at risk of carbon leakage (EC, 2018). A full discussion of the processes of aluminium production, its energy consumption, emission profile, and mitigation options are presented in section 4.3.1.

2.4.2 Applications of aluminium

Around the globe, aluminium is a widely used material. In terms of annual production volumes, only steel is more popular (Balomenos, Panias, & Paspaliaris, 2011; Das & Green, 2010). Due to its unique properties like being an excellent conductor and low weight, aluminium finds many applications. In 2016, the transport and construction sectors each accounted for approximately 25% of the global demand. Electrical engineering, machinery, foil stock, packaging, electricity infrastructure (transmission lines), and consumer durables contributed with 5-15% to the global demand (EC, 2019a; ICF, 2015). The demand for aluminium is expected to increase as much as two to three times by 2015 (Haraldsson & Johansson, 2018).

In a finished product, it is usually not possible to determine whether aluminium comes from primary or secondary sources. Aluminium's theoretically infinite recyclability is a major factor of its success and one of the core reasons why it is such an important material in the future (Cusano et al., 2017; Material Economics, 2018).

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[2] Perfluorocarbons (PFCs) are a very persistent greenhouse gas (up to 50,000 years) with high global warming potentials (7,390–12,200) compared to other greenhouse gases (EPA, 2018)

2.4.3 Barriers to decarbonisation of aluminium production

It is obvious that the emissions of aluminium production have to be reduced drastically to achieve climate targets, so there is a growing body of literature dealing with mitigation options. Haraldsson & Johansson (2018), however, find that for example the literature on improving energy efficiency measures in the sector is underdeveloped. A lack of literature on the topic may delay important investments into new technologies.

Due to the energy intensity of aluminium production, availability of cheap energy has historically been the primary factor determining the location of primary aluminium plants. Additionally, it is an advantage if energy production is close to the aluminium plant to avoid losses of electricity transmission (EC, 2019a). Access to cheap, often fossil fuel-based, energy is seen as the key factor influencing a company's success and resilience (Sauvage, 2019).

In the last decades, a shift in production locations can be observed. In the EU, for example, the number of aluminium production facilities has significantly declined, the number of smelting plants has decreased from 26 in 2002 to 16 in 2016 (EC, 2019a). Notably, the emergence of China as the dominant player across the aluminium value chain has influenced the structure of the global aluminium market (Sauvage, 2019).

The primary production of aluminium is dominated by a few large corporations, e.g. only 25 different companies operate in the EU. In 2018, around 55% of the primary production of aluminium took place in China, and this fraction is expected to grow (Material Economics, 2018). Increased competitiveness causes firms to be hesitant when making decisions about new investments.

Secondary production is much more diversified. In the EU, for instance, around 130 smaller companies are active in this industry. Some companies also pursue both primary and secondary production (Cusano et al., 2017).

The literature describes the availability of capital as a major barrier to deploying mitigation options. Retrofitting existing plants, investing in new production facilities and equipment, and especially R&D expenditures are very capital intensive. Companies are therefore hesitant to invest in mitigation options, even though in some cases, investments come with added benefits such as saved running costs (Reddy, Assenza, Assenza, & Hasselmann, 2009; Ruppel & Luedemann, 2013).

The availability of capital as a barrier is among the primary reason why green bonds promise to have potential to steer this capital-intensive sector towards a more low-carbon future.

2.5 Literature review summary

This literature review has investigated relevant aspects of climate finance, green bonds, the materials sector, and the aluminium sector. Where applicable, connections between those four subtopics have been established to further justify the research problem. Climate finance instruments such as green bonds are gaining popularity. However, the literature review also reveals that the lack of guidelines, criteria, and benchmarks for green bonds in the materials sector is a barrier to harness their potential. The review has shown that there is a lack of available academic literature on the topic of green bonds in the materials sector.

3 Analytical framework and methodology

3.1 Case study selection

In order to propose criteria for a green bond in the materials sector, this thesis follows a case-based research design. Gerring (2004) defines case-based research as "an intensive study of a single unit for the purpose of understanding a larger class of (similar) units" (p. 342). For this thesis, the aluminium sector is chosen as a specific case to gain insights into criteria of green bonds in the materials sector more generally.

The aluminium sector is a particularly suitable case for this purpose for a variety of reasons. Aluminium is part of the non-ferrous metals sector, which also includes zinc, lead, and copper (Dessart & Bontoux, 2017). In the EU, aluminium production contributes to more than half of the emissions in the non-ferrous metal sector (EC, 2019a). With a contribution of 2% to the global greenhouse gas emissions, the aluminium sector has a significant impact on global emissions (Neuhoff et al., 2018). Aluminium production is also one of the most energy-intensive industrial sectors, consuming each year approximately the same amount of primary energy that is necessary for global lighting (Material Economics, 2018). Exploring new instruments to decarbonise the aluminium sector offers a significant contribution to mitigation of climate change (Neuhoff at al., 2018). Understanding mechanisms that are powerful enough to decarbonise a sector of this scale offers meaningful insights for other subsectors in the materials sector.

Most metals, like aluminium, can be produced through primary and secondary production processes (Cusano et al., 2017). This division of production methods is also pronounced in the aluminium sector, which is a further reason why aluminium lends itself for understanding the materials sector.

Aluminium is further considered to be representative of the materials sector, as its demand is expected to grow in the future due to a growing world population, and an increased demand for materials in buildings, transport, electronics, and packaging (IEA, 2017; Sahni & Gutowski 2012). More so than other basic materials, however, aluminium is currently an integral material for important low-carbon technologies and products because of its unique properties. Aluminium is recyclable, lightweight, and durable. These properties make it a particularly interesting material for electric mobility, as weight is an important factor when improving the range of electric vehicles. It is, furthermore, projected to play a crucial role for light-weight packaging and energy-efficient buildings (Dessart & Bontoux, 2017). Understanding how to design green bond criteria for a sector that could be an important building block of the low-carbon economy is a crucial step towards understanding the future structure of low-carbon industries.

For all these reasons, the aluminium sector has been selected as a suitable case study to understand how to design effective green bond criteria for the materials sector.

3.2 Analytical framework

As discussed in section 2.2.3, the taxonomy developed by CBI has found widespread application for the certification of green bonds. This thesis bases its analysis on the CBI's taxonomy to propose criteria for green bonds in the aluminium sector. The following sections introduce how the taxonomy as developed by CBI will be used as a starting point in this thesis.

3.2.1 CBI's green bond taxonomy

The taxonomy as developed by the CBI is based on the scientific findings of the International Panel on Climate Change (IPCC), the International Energy Agency (IEA), as well as other scientific literature. The CBI taxonomy is a tool to assess whether a project or asset is consistent with the 2°C target agreed upon in the 2015 Paris Accord based on selected criteria. The CBI has designed its taxonomy to be applicable for a variety of sectors, such as energy, waste, buildings, land use, and industry. The tool was first published in 2013 and is updated annually (CBI, 2018).

3.2.1.1 Elements of CBI's taxonomy

Table 3.1 shows the basic taxonomy as developed by the CBI. In this paper, the basic structure of the taxonomy is kept, but modifications are made where necessary.

Table 3.1: Outline of CBI's green bond taxonomy.

Category	Asset type and specifics	2°C compliant	Screening indicator	Certifiable
Asset category (e.g. solar energy)	(e.g. infrastructure and transmission infrastructure)	Determined through traffic light system ("automatically compatible, compatible if compliant with screening indicator, not compatible, more work required")	Further specifications (e.g. biofuel must be sourced sustainably)	Set of criteria by CBI is available and can be applied

Source: Adapted by the author from CBI, 2018.

The first two rows define the asset category and specify its type and other descriptive details. The CBI has chosen the 2°C target set in the 2015 Paris Agreement as a benchmark for the certification of green projects. This means that assets which are considered as being line with the 2°C goal qualify for green bond certification. The CBI uses a traffic light system to classify the assets. Some assets, such as some renewable energy projects, are "automatically compatible". Other projects need to fulfil additional screening indicators, for instance requirements like sourcing biomass used for biofuels sustainably. If the screening indicator (column 4) is fulfilled, an asset is deemed compatible. A third category consists of projects that are "not compliant" and projects in the final category require additional information before labelled compatible. The last column in Table 3.1 indicates whether the CBI has already developed a set of criteria for this asset category (CBI, 2018).

For this paper, most elements of the CBI taxonomy are used. Adjustments are made for the category "2°C compliant". The mitigation options in the aluminium sector have a wide range of benefits, so a more nuanced approach is necessary to capture this. This study has adopted CICERO's "shades of green approach", which has been introduced in section 2.2.3 and is explained in more detail in the following section. Furthermore, the last column ("certifiable") has been dropped as CBI criteria are not available for any of the asset types discussed in this paper. In fact, the lack of these criteria has led to the development of this research idea in the first place.

3.2.1.2. Advantages and limitations of CBI's taxonomy

For this thesis, the taxonomy by CBI has been chosen over the certification procedures developed by other organisations mentioned in section 2.2.3 for various reasons. First of all, the CBI is a non-profit, independent NGO which receives its funding from a variety of sources, including governmental grants (Ehlers & Packer, 2017). The criteria developed by CBI are publicly available and based on the assumption that investments into green bonds should be guided by "independent, science-driven guidance" (CBI, 2018, p.1). These characteristics make CBI's approach favourable over the certification by private companies such as Standard & Poor's or Moody's.

CBI's green bond criteria are widely applied and based on scientific findings of internationally renowned institutions such as the IEA and IPCC. In addition, they are based on the widely applied GBPs, allowing for comparisons with other taxonomies. The manufacturing sector which the materials sectors pertain is largely under-developed in the CBI taxonomy (CBI, 2018).

The CBI describes the aims of a green bond taxonomy as fourfold (CBI, 2019). Their taxonomy is designed to:

- create an international, uniform and harmonised classification system
- avoid market fragmentation
- prevent greenwashing and ensure transparency
- serve as basis for other policy tools (labels, incentives, standards).

These aims are consistent with addressing the barriers identified through the literature review performed for this thesis. CBI's approach has therefore been found suitable a starting point for this study.

3.2.2 Approach to classify process-related mitigation options

Rather than publishing an overarching green bond framework that can be applied to a sector, CICERO offers reviews of issued green bond frameworks on case-to-case basis (CICERO, 2016). Therefore, CICERO's framework is not suitable for the aims of this thesis project. The results of the reviews for private companies are mostly confidential, making them inaccessible for research projects like this one. This paper will, however, adopt CICERO's "shades of green" approach, where applicable.

As touched upon, the CBI follows a binary assessment: projects are either green (2°C compliant) or they are not. The taxonomy by CBI does not allow for a more nuanced assessments (Ehlers & Peckers, 2017). By adopting CICERO's "shades of green" approach, this paper aims to offer more nuanced assessment criteria. This modification is especially important when discussing process-related mitigation options in the aluminium sector. The available technologies offer improvements in terms of emission reductions and energy efficiency gains ranging from 5-85%. To capture this range, this study classifies the level of improvement per technology into three levels. The classifications are discussed in detail in section 4.3.3. Whereas CICERO's overall framework has been adopted, the specific classifications for the different "shades of green" have been changed in accordance with the sectoral benchmarks for the aluminium sector.

3.3 Research design and methodology

3.3.1 Steps to develop green bond criteria

This paper uses the taxonomy as developed by CBI to design a green bond taxonomy for the aluminium sector. In order to construct suitable criteria for a green bond in the materials sector, several auxiliary steps need to be performed, which constitute the main body of this thesis (Figure 3.1). These auxiliary steps have been developed in collaboration with the research group at the DIW.

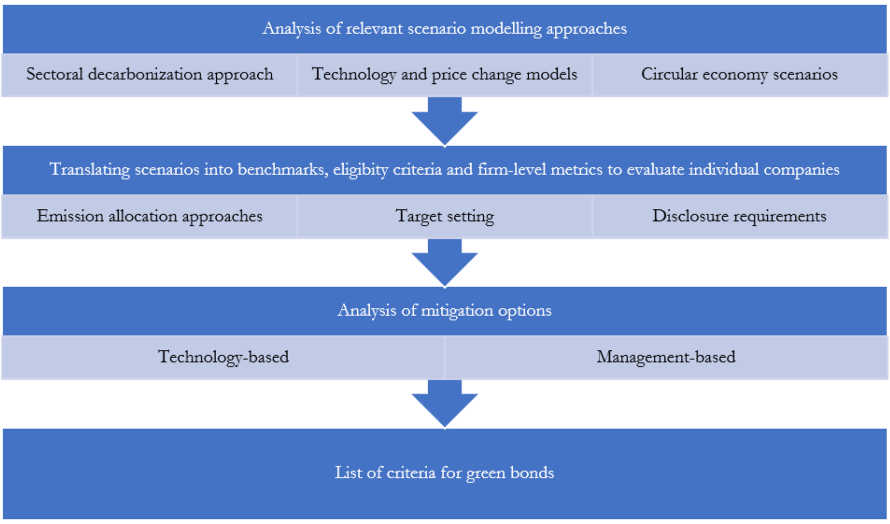

Figure 3.1 Flow-chart to design criteria for a green bond in the materials sector.

Source: Created by the author.

1. *Identify relevant emission scenarios for the sector and derive sectoral emission targets from these scenarios*

Scenario analysis is a powerful tool to understand possible future developments with alternative outcomes (Ruijter, 2014). For the design of green bond criteria, understanding sectoral emission scenarios is an important step as it informs to what extent a sector needs to reduce its emissions to satisfy international targets. Sectoral benchmarks are thus a key variable.

For this thesis, three different approaches to climate change and energy transition scenarios have been analysed: sectoral decarbonisation scenarios, price change and technology scenarios, and circular economy scenarios. These scenarios have been selected for several reasons, with the prerequisite that data for the aluminium sector is published in sufficient detail. A full discussion of the selection is included in section 4.1.

The benchmarks derived from these scenarios form the basis for the classification with the “shades of green” approach as discussed in the previous section (3.2.2).

2. *Translate scenarios and sector pathways into benchmarks, eligibility criteria and firm-level metrics*

As corporate climate action is integral to tackling climate change, the macro-level scenarios and their targets need to be “translated” in order to be useful at company level (Krabbe et al., 2015). This section analyses the so-called science-based target method as a way to translate scenarios into benchmarks, eligibility criteria and other metrics allowing for an evaluation of individual firms in the aluminium sector.

3. *Identify mitigation options*

After having analysed the sectoral benchmarks of the aluminium sector, this step characterises the emission profile of the aluminium sector. It reviews literature on four different mitigation approaches and classifies individual options on the basis of CICERO's "shades of green" approach.

4. *Identify criteria to assess a company's strategy*

This step reviews strategies and disclosure requirements to lower a company's emission intensity and its transition to a low-carbon future.

5. *Final set of green bond criteria for the aluminium sector*

This step presents the proposed framework based on a coherent set of technology- and strategy-related criteria.

3.4 Data collection

Data for this study has been collected through a literature review. Among others, search terms such as "green bond", "green bond certification", "materials sector emissions", "aluminium mitigation options", "sectoral decarbonisation scenario", and "decarbonisation strategy" have been used to search for articles in online resources such as Google Scholar and the IIIEE library.

It is important to note that the volume of academic literature on climate finance and green bonds is limited due to the novelty of the field. Whenever possible, primary documents, such as the CBI framework or GBPs, have been used as a basis for the literature review.

For the chapter on scenario modelling, reports and their underlying data as prepared by international organisations like the IEA, the Transition Pathway Initiative (TPI), and the Joint Resource Centre (JRC) have been used as primary resources. When necessary, the organisations have been contacted to receive additional information.

For the parts of the paper concerning the aluminium sector and its technological mitigation options, technical documents prepared by regional or international organisations have been used as the main source of information. For example, the European Commission (EC), the International Aluminium Institute (IAI), and the IEA have prepared documents that capture the developments in the industry (EC, 2019a; IAI, 2019; IEA, 2017). An important source has been the BAT reference document (BREF) for the non-ferrous metals sector prepared by the Joint Research Centre of the European Commission (Cusano et al., 2017). Further, Haraldsson & Johansson (2018) offer an extensive review of energy efficiency related measures by identifying 52 measures from reviewing more than 120 scientific sources.

4 Analysis and results

This chapter presents the analysis and results of the study. It is designed to investigate the auxiliary research questions as outlined in section 1.3 and follow the steps outlined in the previous section (3.3.1). Section 4.1 analyses relevant scenario models and sectoral roadmaps to understand what type of transition the aluminium sector needs to undergo to meet targets. The following section (4.2.) presents how benchmarks, eligibility criteria, and firm-related benchmarks can be used to assess the emission performance of individual companies.

The next two sections are concerned with the strategy-based and technology-based criteria for green bonds. Section 4.3 analyses the emission profile of the aluminium sector, assesses what kind of mitigation options are applicable for the sector, and presents a list with classified technologies. Section 4.44.3 discusses strategies and required disclosures to manage the emission intensity of the aluminium sector.

On the basis of this analysis, section 4.5 presents the final results. The section contains one list with strategy-related and one list with technology-related criteria for green bonds in the aluminium sector.

4.1 Analysis of relevant scenarios

In order to understand a sector's future development, it is common practice to consult climate and economic modelling and sectoral roadmaps. Such scenario modelling gives information about the plausible pathways to reach climate targets. In the literature, there are multiple approaches to scenario modelling, each with different key assumptions, outputs, and results (Ruijter, 2014; Schoenmaker et al., 2019). The IPCC and other organisations analyse the ranges of scenarios, producing families of climate-compatible pathways (IPCC, 2014).

For this study, three scenario modelling approaches have been analysed to understand the extent to which the aluminium sector has to reduce its emission intensity to satisfy climate targets. This paper works under the assumption that in order to qualify for a green bond, a company must demonstrate that its future performance (e.g. a project) is in line with sectoral benchmarks. This way a firm can demonstrate that it is decarbonising to a sufficient extent. This assumption also underlies the taxonomy developed by the CBI. In their taxonomy, only projects and assets that are compatible with the 2°C target of the 2015 Paris Accord can be classified as green (CBI, 2018). Using sectoral benchmarks as the basis for criteria has the additional advantage that it allows for comparison between different firms in the same sector.

The following sections each examine one of the three scenario modelling approaches:

1) sectoral carbon budget scenario
2) technology and price change scenario
3) circular economy scenario

Section 4.1.4 contains a summary of the benchmarks for the aluminium sector and discusses how those can be applied to green bond criteria.

4.1.1 Sectoral carbon budget scenarios

The global carbon budget can be analysed by breaking down emissions by sector over time. This so-called "Sectoral Decarbonisation Approach" (SDA) builds on the idea that different sectors and regions are confronted with different challenges when facing low-carbon transitions. Based on a set of assumptions, the global carbon budget is broken down by sector and carbon emission pathways for selected time periods are defined. This requires a form of integrated economy-energy model, which allocates emission reductions to sectors over time (CDP, WRI & WWF, 2015a). The models are designed to allocate emissions by optimising against specific time horizons and by minimising abatement costs (i.e. the costs of reducing emissions). A variety of factors enter into the specific set-up of the model and the corresponding assumptions about issues such as public preferences, the speed of innovation and technological learning, and availability of capital can have a strong influence on the modelling outcomes (Dietz, Garcia-Manas, Irwin, Rauis, & Sullivan, 2018).

The SDA requires sector specific benchmark scenarios for emission intensities. Emission intensities are calculated by dividing emissions (e.g. tonnes of CO_2) by a measure of activity or production (e.g. tonnes of aluminium). As this approach "normalises" the emission intensity, the approach allows for comparisons of carbon performances of single companies with the sectoral benchmark pathways. Moreover, the approach allows for comparisons of companies' emission intensity pathways among each other, even if the companies are of different sizes (Dietz, Garcia-Manas, Irwin, Rauis, & Sullivan, 2018).

$$Emission\ intensity = \frac{emissions\ (t\ GHG)}{economic\ output\ (t\ output)}$$

Carbon budget scenarios are relatively straightforward to apply and have a high degree of transparency and are therefore widely used (TCFD, 2016).

4.1.1.1 Sectoral emission scenario: IEA's approach

The International Energy Agency (IEA) supplies sectoral emission scenarios via its biennial Energy Technology Perspectives Report (ETP). The IEA scenarios have the advantage that modelling inputs and outputs are accessible and moreover provided so that they are suitable for applying the SDA (Dietz, Jahn, & Noels, 2019,). The scenario model used in the 2017 ETP report covers around 30 countries and regions in a time period until 2060. The IEA model considers three distinct carbon budget scenarios, which limit global warming to different global average temperatures (

Table *4.1*). The first scenario estimates sectoral carbon budgets and benchmark emission pathways for a "reference technology scenario" (RTS). The RTS is based on the "nationally determined contribution" (NDC) pledges of the Paris Agreement and result in a temperature increase of 2.7°C until 2100. The "2°C Scenario" (2DS) and the "Beyond 2°C Scenario" (B2DS) are "consistent with a 50% chance of limiting the average temperature increase" to 2°C and 1.75 °C by 2100, respectively (IEA, 2017, p. 23). It is important to note that only the 2DS and the B2DS scenario are in line with the aims of the Paris Agreement. The RTS scenario is, however, not comparable to a business as usual trajectory, as it does imply significant shifts (IEA, 2017).

Table 4.1 Scenarios as used by IEA's 2017 ETP report.

		Global average temperature impact range and likelihood in %
Reference Technology Scenario	**RTS**	Average temperature increase of 2.7°C by 2100
2°C Scenario	**2DS**	50% chance of limiting global average temperatures to a 2°C increase by 2100
Beyond 2°C Scenario	**B2DS**	50% chance of limiting global average temperatures to a 1.75°C increases by 2100

Source: Adapted by the author from IEA, 2017.

In the IEA's ETP model, assumptions are made to estimate the global and sectoral economic development until 2060. The estimated global economic growth and historic production shares of the sectors are used to determine the sectoral emission intensities that allow for staying within the global carbon budget (IEA, 2017). The ETP industry sector scenarios are available for five sectors, among which is the aluminium sector. This and the specific industry model (TIMES-based linear optimisation model) are further described in ETP 2017 pp. 399-400 (IEA, 2017).

For all scenarios, the IEA makes the same assumptions on future economic activity and population development. Changes in global energy demand are reflected in energy prices (oil, gas, coal, differentiated by region), depending on the scenario. The applied technologies and policies reaching the 2DS and B2DS scenario have an impact on demand development, e.g. oil demand and therefore oil prices are higher in the RTS than in the 2DS and B2DS scenarios (IEA, 2017).

As with all energy-modelling frameworks, they are based on a set of assumptions and simplifications, and the interpretation of modelling outputs needs to account for these limitations. It is critical to gain an understanding of the underlying assumptions that enter into the modelling frameworks. The assumptions made when designing the scenarios sensitive to different input factors and the corresponding choices and assumptions. For example, the model used by the IEA only includes commercially available technologies, which excludes the possibly disrupting effects of future technological breakthroughs (IEA, 2017). The IEA carbon budget is furthermore very sensitive to changes in the probability achieving certain temperature targets. For example, in the 2DS scenario, moving from a 50% chance to a 66% chance of reaching the targets by 2100 reduces the CO_2 budget by as much as 25% (IEA, 2017). Moreover, results are sensitive to "how quickly capital is turned over, on relative costs of the various technology options and fuels, and on incentives for the use of best available technologies for new capacity" (IEA, 2017, p. 400). It is especially difficult to incorporate factors like social acceptance, political feasibility, and availability of capital in a model that optimises on cost-effectiveness (IEA, 2017).

The overall activity of an economy is defined by a set of socioeconomic factors. In terms of their level and dynamics, six dimensions are particularly critical in the context of modelling GHG emissions: economic activity; climate and energy policies; population; productivity; innovation and technological learning; and natural resources. Emission reduction scenarios are further significantly shaped by energy supply and demand as well as energy technology choices (Ventosa, Baíllo, Ramos, & Rivier, 2005). For a recent discussion of related modelling frameworks, see for example Jürgens, Piantieri, Hessenius, & Rusnok (2019).

4.1.1.2 Transition Pathway Initiative's use of IEA's ETP model

The Transition Pathway Initiate (TPI) assesses companies' performance and preparedness for the transition to a low-carbon economy. The initiative has been established in 2017 and is led by asset owners. It assesses both management quality (discussed 4.4) and carbon performance. The carbon performance of individual companies is compared to the sectoral benchmark. This comparison aims to support the decision-making process of investors. The results are published in the form of an open access tool in collaboration with Grantham Research Institute on Climate Change and the Environment at the London School of Economics (Dietz, Jahn, & Noels, 2019).

Based on the scenario modelling performed by the IEA, the TPI produces sector specific benchmark scenarios to which individual firms are compared (Dietz, Garcia-Manas, Irwin, Rauis, & Sullivan, 2018). The benchmarks created by TPI for the aluminium sector can be seen in Figure 4.1. On top of CO_2 emissions, the TPI approach also takes other greenhouse gases such as PFCs into account. Based on the share of CO_2-equivalent[3] (CO_2e) PCF emissions in 2014, the TPI adds 4.27% to the benchmark values calculated by the IEA (Dietz, Jahn, & Noels, 2019). Here, it is assumed that PFC emissions are equal across companies and do not change significantly in the future.

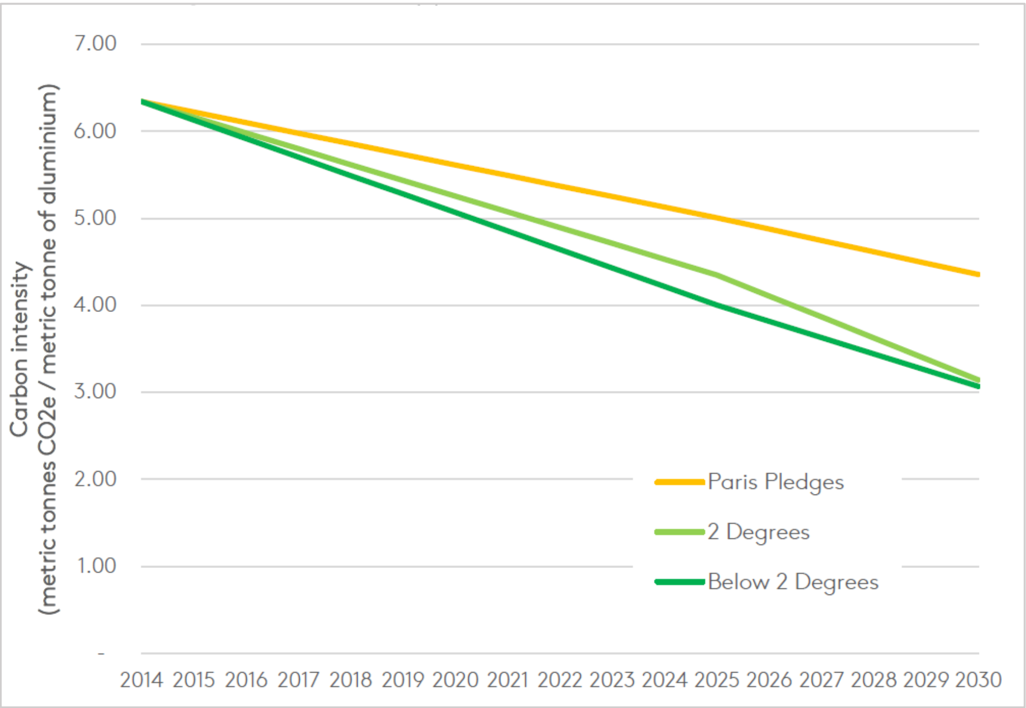

Figure 4.1 TPI's benchmark scenarios for the aluminium sector.

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[3] CO_2-equivalent is a universal unit expressing each of the six greenhouse gases global warming potentials in terms of one unit of CO_2 (Smith, WBCS, & WRI, 2004).

Source: Dietz, Jahn, & Noels, 2019.

The TPI has chosen 2030 as a target year, which is relatively short considering that the average lifespan of a primary aluminium plant is around 20 years (Bataille et al., 2018).

Similarly to the IEA approach, the TPI approach is built on several assumptions. For example, the TPI orients the future emission intensity of companies by the targets they have set (Dietz, Jahn, & Noels, 2019). This, of course, assumes that companies meet the targets they have set, which is not always the case.

The TPI further makes a number of assumptions regarding scope 2[4] emissions in the aluminium sector. As mentioned, the aluminium sector is very energy intensive, which is why these estimations have a strong effect on the sectoral emissions. They estimate the emission intensity of the global electricity gird is "an average of the emissions intensity of the electricity grid in OECD and non-OECD countries" (Dietz, Jahn, & Noels, 2019, p.8). As non-OECD countries have a higher emission intensity, the TPI weighs the emission intensity by region. The TPI further adjust for the fact that most aluminium plants generate a part of the energy needed for the production on site. To take this factor into account, they rely on data disclosed by aluminium producing companies (Dietz, Jan, & Noels, 2019).

Compared to the scenario of IEA's ETP 2017 report, the TPI approach makes it even easier to assess individual companies against the sectoral benchmark. The tool is also very useful when comparing the performance of individual companies against each other. The open access online tool is very assessible and straightforward to use. It is further an advantage that the TPI also takes PFC emissions into account. Yet, TPI's approach to factor in PFC emissions is very inflexible, as it simply adds the average share of the reference year 2014 to all future years. This approach does not take any kind of technological improvement or other factors into account.

4.1.2 Technology mix and price change scenario

Modelling can also pursue different aims like showing sectoral mitigation potential or effects of technological upgrades. There are several scenarios and roadmaps for the aluminium sector which focus on technology and price developments. The Joint Research Centre of the European Commission (JRC) constructs scenarios for the aluminium sector (Moya et al., 2015; Pardo et al., 2015). The JRC constructs energy consumption and GHG emission scenarios for the aluminium sector in the EU and Iceland until 2050 based on technological developments and cost effectiveness. This approach allows an assessment of the cost-effectiveness of investments into new technologies under different price scenarios (Moya et al., 2015).

The input data (e.g. energy consumption and costs per production step, GHG emissions, installed technologies, material in- and output) is mostly supplied by individual production facilities. The model is thus dependent on the disclosure of companies and the quality of supplied data. As data disclosed by companies is limited, the model relies on assumptions and estimates (e.g. costs of technologies, on-site electricity generation costs). Other input data, such as electricity price developments and future aluminium demand are derived from a variety of sources. The JRC approach uses the simplification that national electricity costs equal

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[4] In carbon accounting, emissions are categorized in scope 1, 2, and 3. Scope 1 emissions are direct emissions by a company (e.g. from combustion) and scope 2 emissions are indirect emissions from purchasing electricity. Scope 3 are all other indirect emissions that are a consequence of a company's activity but are not directly controlled by the company (e.g. use of sold products) (Smith, WBCS, & WRI, 2004).

production costs, as on-site electricity costs are rarely disclosed. Since the model optimises for cost-effectiveness, electricity prices largely determine where production is allocated. The regional focus on the scenarios does not allow for incorporation of developments in the global market (Moya et al., 2015).

From their scenario modelling, the JRC draws the conclusion that innovative technologies currently in their development phase will play a central role for decarbonising the sector. Therefore, the JRC advises to give these technologies effective pushes and put the right conditions in place for innovation (Moya et al., 2015).

4.1.3 Circular economy scenario

Scenarios focused on circular economy strategies are highly relevant for the aluminium sector. An increased share of secondary aluminium has great impact on the overall emissions of the aluminium sector, because secondary aluminium production is associated with up to 98% less emissions (Material Economics, 2018). The European Commission, for example, defines the circular economy concept as an "economy, where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimised" (EC, 2015).

For this paper, a circular scenario as developed by the Swedish consultancy firm "Material Economics" has been analysed. Their model has been developed together with various partners, such as the European Climate Foundation, the Ellen MacArthur Foundation, Climate-KIC, Energy Transitions Commission, ClimateWorks, the MAVA Foundation, and SITRA (Material Economics, 2018).

Their approach has a focus on the EU and takes the most emission intensive materials sub-sectors into account (cement, steel, aluminium, and plastics). It largely builds on IEA's ETP scenario modelling approach. Material Economics further builds on a dynamic material flow analysis model developed by Liu, Bangs, and Müller (2013).

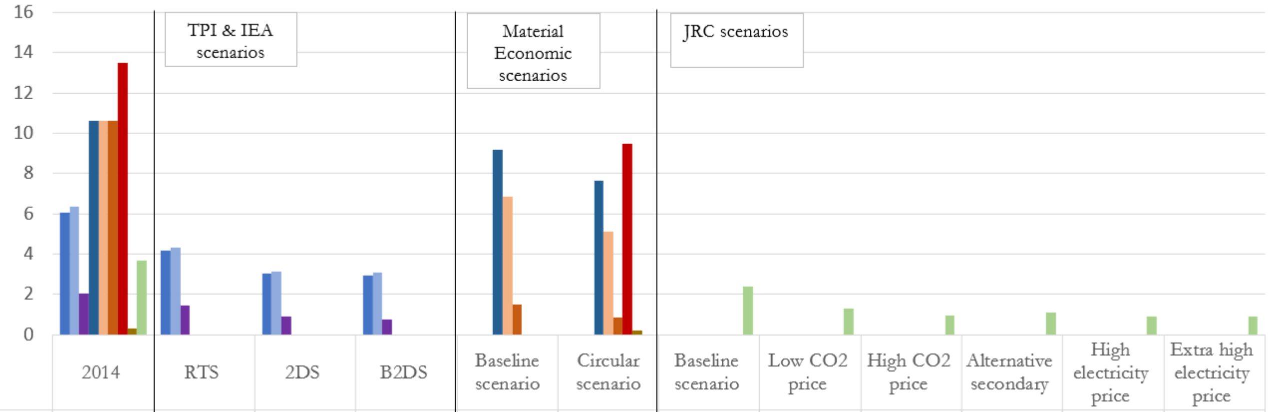
Liu, Bangs, and Müller (2013) model the demand for the main applications of aluminium: machinery, electrical equipment, transport, consumer goods, and construction. Future stock flows are modelled through a stock-driven approach and computed backwards from assumed product lifetimes and stocks (Liu, Bangs, & Müller 2013).

The Material Economics' model is designed to show the effects of three circular economy strategies: circular business models, materials recirculation, and material efficiency. Their analysis concludes that these strategies can cut up to 56% of the CO_2 emissions of the aluminium sector in the EU by 2050 (Material Economics, 2018). As the report by Material Economics does not specify whether PFC emissions have been included, it is assumed that those emissions are not assessed.

Material Economics considers a baseline and a circular scenario. Both scenarios assume a gradual decarbonisation of the energy system by 2100, meaning that all energy-related emissions are assumed to be equal to zero by 2100. The scenarios differ in the extent of collection, sorting, and separation of secondary aluminium. Whereas the baseline scenario considers gradual improvements, the circular scenario models more extensive and faster improvements. Both scenarios have the same production levels for each year, but a different share of primary and secondary aluminium (Material Economics, 2018).

4.1.4 Summary of the scenario analysis section

The analysis of the three modelling approaches shows different sectoral benchmarks as summarised in Figure 4.2. It is important to note that the benchmarks derived from the scenarios are not directly comparable, because they refer to different time frames, processes of aluminium production, or take different emissions into account.



		TPI & IEA scenarios			Material Economic scenarios		JRC scenarios					
	2014	RTS	2DS	B2DS	Baseline scenario	Circular scenario	Baseline scenario	Low CO2 price	High CO2 price	Alternative secondary	High electricity price	Extra high electricity price
■ tCO2/t al (TPI 2030 scenario)*	6.08	4.18	3.02	2.94								
■ tCO2e/t al (TPI 2030 scenario)	6.34	4.35	3.14	3.07								
■ tCO2/t al (IEA 2060 scenario)**	2.06	1.44	0.92	0.75								
■ tCO2/t al (Material Economics 2030 scenario)	10.6				9.17	7.67						
■ tCO2/t al (Material Economics 2050 scenario)	10.6				6.84	5.11						
■ tCO2/t al (Material Economics 2100 scenario)	10.6				1.52	0.88						
■ tCO2/t primary al (Material Economics 2050)	13.5					9.50						
■ tCO2/t secondary al (Material Economics 2050)	0.3					0.20						
■ tCO2/t al (JRC 2050 scenario)	3.7						2.4	1.3	0.95	1.1	0.9	0.9

*excl. PFC emissions
** only direct C02 emissions
highlighted in grey: only direct GHG emissions for primary production, values only for EU and Iceland

Figure 4.2: Benchmarks for the aluminium sector according to selected scenarios

Sources: Created by the author, data based on IEA, 2017; Dietz, Jahn, & Noels, 2019; Material Economics, 2018.

For easier comparison of the different benchmark values for the aluminium sector, Table 4.2 shows an overview of the emission reductions in percent relative to the 2014 reference value.

Table 4.2: Benchmark values for selected scenarios for the aluminium sector in percent of the reference value for 2014.

	Reference value: 2014	**RTS**	**2DS**	**B2DS**	**Baseline scenario**	**Circular scenario**
IEA 2060 scenario* (tCO_2/t al)	2.06	1.44	0.92	0.75		
Emission reductions		**30.1 %**	**55.3 %**	**63.6 %**		
TPI 2030 scenario (tCO_2e/t al) **	6.34	4.35	3.14	3.07		
Emission reductions		**31.4 %**	**50.5 %**	**51.6 %**		
TPI 2030 scenario* (tCO_2/t al)	6.08	4.18	3.02	2.94		
Emission reductions		**31.3 %**	**50.3 %**	**51.6 %**		
Material Economics 2030 scenario (tCO_2/t al)	10.60				9.17	7.67
Emission reductions					**13.5 %**	**27.7 %**
Material Economics 2050 scenario (tCO_2/t al)	10.60				6.84	5.11
Emission reductions					**35.5 %**	**51.8 %**
Material Economics 2100 scenario (tCO_2/t al)	10.60				1.52	0.88
Emission reductions					**85.7 %**	**91.7 %**
Material Economics 2050 (tCO_2/t primary al)	13.50					9.50
Emission reductions						**29.6 %**
Material Economics 2050 (tCO_2/t secondary al)	0.30					0.20
Emission reductions						**33.3 %**
***only direct (scope 1) CO_2 emissions** ****incl. PFC emissions**						

Source: Compilation by the author.

While other 2014 reference values for the aluminium sector as a whole range from 10 tCO_2e/t in 2014 to 10.6 tCO_2e/t al (Material Economics 2018), it is noteworthy that the 2014 values published by TPI are significantly lower with 6.34 tCO_2e/t. After reaching out to TPI for an explanation for this, they reported the reliance on the IEA model as a reason for the lower values. As TPI uses the ETP model, "it is not initialised using observed values but is based on model outputs. The ETPs internal validity relies on these model outputs and hence they cannot be modified in hindsight" (TPI, personal communication, May 9, 2019). According to their own statement, this does not, however, influence the accuracy of the intensity "as the ratio between total production and emissions is accurate" (TPI, personal communication, May 9, 2019).

The JRC scenario only presents results for direct (scope 1) emissions from EU and Iceland-based primary aluminium facilities. Direct emissions only contribute between 10-20% to the CO_2 emissions of primary aluminium production (Cusano et al., 2017). The benchmarks are thus not useful for the scope of this paper and will not be further discussed. Nonetheless, JRC's analysis highlights the importance of energy prices and the development of technologies on the emission intensity pathways of aluminium production.

Similarly, the IEA only makes data about direct (scope 1) emissions available. The IEA does, however, cover global primary and secondary production. The emission reductions presented by the IEA for 2060 are 30.1% in the RTS scenario, 55.3% in the 2DS scenario, and 63.6% in the B2DS scenario. The IEA analysis does not take PFC emissions into account. The TPI approach is largely based on the IEA approach, but has extended its models to take scope 1 and scope 2 emissions as well as PFCs into account.

The Material Economics approach covers global primary and secondary aluminium production as well as scope 1 and 2 emissions. In the 2030 scenario, the models suggest moderate reductions of 13.5% in the baseline and 27.7% in the circular scenario. In the Material Economics 2100 scenario, however, emissions are steeply reduced by 85.7% in the baseline and by 91.7% in the circular scenario. Interestingly, Material Economics also makes separate values for primary and secondary aluminium production available. Until 2050, both production lines are projected to reduce their emissions by approximately 30%.

The TPI scenario benchmark (incl. PFC emissions) suggests that the aluminium sector as a whole has to reduce its emission intensity by 31.4% under the RTS, 50.5% under the 2DS, and 51.5% under the B2DS scenario until 2030 relative to 2014 levels.

The sectoral benchmarks of IEA and TPI are roughly aligned with each other, as they all fall within a 30% range for the RTS scenario, around 50% for the 2DS scenario, and between 51.5-63.6% for the B2DS scenario. The benchmark presented by Material Economics for 2050 in their circular economy scenario is comparable to the 2DS scenario of TPI. Of course, it is important to note that target years of each scenario are different.

For the year of 2030, only the benchmark values for TPI's RTS scenario and Material Economics' Circular economy scenario are of a comparable level (approx. 30%).

As the TPI and the Material Economics approach deliver the most comprehensive sectoral benchmarks of all reviewed scenarios, these benchmarks are used for the further analysis in this study. It is important to note, however, that the scenarios in the TPI scenario only proceed until 2030, which is a very short time horizon. As investments in the capital-intensive aluminium sector are usually made for a time horizon that exceeds 2030, this is a limitation of this paper.

It is important to note that almost all benchmark values as shown in Figure 4.2 are for aluminium production as a whole. This means that the emission levels of primary and secondary production are not discussed separately. This leads to problems, as the emission intensity of the two are widely different, secondary production has 98% less emissions than primary production (Material Economics, 2018). This issue is also discussed in a study on life-cycle assessments in the aluminium sector by Liu and Müller (2012). They find that combined assessment of primary and secondary aluminium production is a challenge because it is "very sensitive concerning whether primary or recycled aluminium is applied, and the consequent allocation issue becomes a crucial and contentious challenge" (Liu & Müller, 2012). A discussion of emission levels as a whole is therefore misleading when assessing the performance of an individual firm. Nonetheless, TPI and Material Economics decide in their approach to assess individual firms against the emission intensity of the combined aluminium production.

Of course, this raises the question how specialised companies are expected to satisfy the sectoral average benchmark. A company that is, for example, specialised in the production of primary aluminium has potentially much more difficulties in reaching the sectoral benchmark, as primary aluminium production has much higher emissions.

4.2 Translating scenarios and sector pathways into benchmarks, eligibility criteria and firm-level metrics

Scenario models, as described in section 4.1, are generally designed to inform on a global or regional level and allow for macro assessments. In order to make scenario modelling relevant for designing green bonds, more specific data needs to be extracted (Krabbe et al., 2015). This section will discuss how the scenarios can be translated into benchmarks, eligibility criteria, and other metrics that allow for an evaluation of individual firms in the aluminium sector. The aim of this section is to show how individual firms can use the scenarios described in the previous section to develop their decarbonisation pathways.

The science-based target (SBT) method is the underlying approach for companies to satisfy sectoral benchmarks. The Science-Based Target Initiative (SBTi) is a collaboration between a number of organisations like the United Nations Global Compact (UNGC), Carbon Disclosure Project (CDP), World Resources Institute (WRI), and the World Wide Fund for Nature (WWF) to promote the setting of climate-related targets among companies. The SBTi aims for science-based target setting to become the norm for businesses before 2020 (SBTi, 2019a).

The SBT method consists of three components: an overall carbon budget, an emission scenario, and an allocation approach at company level (SBTi, 2019a). As described in the Fifth IPPC Assessment Report, the global carbon budget is set to limit the rise of global temperatures to well-below 2°C compared to pre-industrial levels (IPCC, 2014). Emission scenarios are constructed to define how GHG emissions are allocated and reduced over time. At company level, a target is considered science-based if it is designed to keep the GHG emissions of a specific company aligned with the global carbon budget (CDP, WRI & WWF, 2015a; Krabbe et al., 2015). The following sections presents methods to allocate the carbon budget at company level.

4.2.1 Emission allocation at company level: contraction and convergence

To allocate emissions on company level, science-based targets are built on two different approaches, convergence and contraction (SBTi, 2019a).

The convergence approach can only be applied if the emission scenario is based on a sectoral carbon budget. It assumes that the carbon intensities of all companies in certain sectors converge towards the sectoral target without exceeding the overall sectoral carbon budget. To calculate the rate of convergence for an individual company, the initial carbon intensity consistent with the sectoral carbon budget, the initial carbon intensity of the individual company, and “the growth of the company relative to the growth of the sector” is determined (SBTi, 2016, p. 14). For instance, a company with a higher growth rate than the sectoral average has to reduce its emission intensity more rapidly than one with a lower growth rate (SBTi, 2019a).

In the contraction approach, it is assumed that all companies in a sector reduce their emissions in parallel to reach the sectoral carbon budget (SBTi, 2016). For absolute targets, this means that companies reduce their emissions at a uniform rate, eventually reaching the sectoral emission target. For intensity-based targets, the reduction is a "function of a decreasing carbon budget and the expected level of activity for the sector or region" (SBTi, 2016, p. 15).

4.2.2 Science based target approaches

The sectoral decarbonisation approach (SDA) was developed by the Carbon Disclosure Project (CDP), the World Resource Institute (WRI) and the World Wildlife Forum (WWF) as partners of the Science Based Targets Initiative and is based on the IEA scenarios. The SDA approach has been introduced in 4.1.1. For the SDA approach, both contraction and convergence can be applied.

The SBTi identifies many different methods to set science-based targets, such as the "Absolute Emission Contraction", "Autodesk's Corporate Finance Approach to Climate stabilising Targets (C-FACT)", "Greenhouse Gas Emissions per unit of Value Added (GEVA)", the "Sectoral Decarbonisation Approach" and many more (SBTi, 2016). It is dependent on the sector which of the methods is best-suited. For the materials sector, three of the approaches are particularly relevant: the intensity-based approach, the absolute-based approach and the economic-based approach (SBTi, 2019a).

Intensity-based approach
For homogenous sectors, it is useful to calculate a company's emission intensity pathway, as it can then be compared to sectoral emission intensity pathways. The SDA is useful for homogenous, emission and energy intensive sectors, like the aluminium sector. (CDP, WRI & WWF, 2015a). The SBTi uses the IEA scenarios to determine a method for companies to set an emission target in line with the remaining carbon budget. A free and publicly available excel tool is published that supports companies in setting emission targets for a commitment period (SBTi, 2019a).

Absolute-based approach
The absolute-based approach is useful for heterogenous sectors. Here, a company sets its absolute emission targets, e.g. Mt CO_2 per year. As all companies are assumed to reduce their emissions at the same rate as required for a given scenario the contraction of absolute emissions is used to allocate the emission reduction on the company level (SBTi, 2019a). The approach is considered to be straightforward to apply, but not particularly useful for the aluminium sector. The aluminium sector is homogenous and is expected to grow in the future. This makes setting absolute-based targets challenging. It is thus more useful to choose an intensity-based approach for the aluminium sector.

Economic-based approach
The economic-based approach calculates the contraction of emission intensity per value added and is intended for scope 1 emissions. Instead of using a physical output like tonnes of aluminium, the economic-based approach relates emissions to value added (Randers, 2012). The Greenhouse Gas per Value Added (GEVA) approach is one of the most famous

examples, it uses the contraction of economic intensity. The GEVA method recommends reducing tonnes of CO_2 per value (e.g. Euro or USD) by at least 7% per year (SBTi, 2019a).

4.2.3 Target setting at company-level

A company has to choose a methodology with which it is setting targets, i.e. contraction or convergence, absolute or intensity based, and by physical or economic output. Once set, a target can then be compared to the sectoral benchmark (see discussion in Section 4.1.4). As already touched upon in the previous section, all of the approaches have advantages and disadvantages. Absolute targets, for example, highlight a company's absolute contribution and are thus more environmentally robust (SBTi, 2019a). Yet, they poorly capture growth related emissions, as a decline in total emission could also stem from a decline in production rather than efficiency gains. Comparisons between companies is very difficult due to varying sizes. When applying a pure economic-based approach, there is a risk of exceeding the carbon budget. According to the SBTi (2019a), economic-based approaches are not favourable over intensity-based targets, as "volatility of economic metrics, economic intensity target-setting methods are considered less robust than absolute and physical intensity methods" (p.23).

For the aluminium sector, an intensity-based target after the sectoral decarbonisation approach is the most suitable. It captures growth of the sector and allows for comparisons (SBTi, 2019a).

For setting a target, boundaries, like the emission scopes, the greenhouse gases, and geographical operations, must be set. The SBTi suggests the inclusion of emissions of scope 1 and 2, and a target for scope 3 emissions if these indirect emissions cover over 40% of the total emissions (SBTi, 2019a). Companies are free to choose a single target for all emission scopes, or separate ones for emission scope 1 and 2. One single target has the advantage of ensuring the inclusion of emissions along the entire value chain. It also grants more flexibility for the company to reach targets, as it can set priorities. Yet, setting one single target decreases transparency, as it does not distinguish between the two emission scopes (SBTi, 2019a).

The SBTi further requires that the base and target year must be chosen precisely. Credible emission data of the base year must be disclosed, and the base year should be classified as a representative one for the company. The SBTi suggest a time horizon of five to fifteen years. (SBTi, 2018). Table 4.3 provides an overview of the disclosures required from companies in order to derive meaningful emission intensity trajectories. The last column of the table indicates the frameworks which require disclosures of the firm-related data. The frameworks which have not been introduced yet are covered in section 4.4.

Table 4.3 Overview of required data to derive emission intensity pathways.

Theme	**Data**					**Reference framework**
	Benchmark Input Data	**Unit of Measure**	**Required Disclosure from Company**	**Unit of Measure**	**Comment**	
GHG emissions	Total scope 1	MtCO$_2$e	Total scope 1*	MtCO$_2$e	per production step if possible	SBTi, TCFD, CDP, GRI 305-1
	Total scope 2	MtCO$_2$e	Total scope 2*	MtCO$_2$e	per production step if possible	SBTi, TCFD, CDP GRI 305-2
	Total scope 3	*MtCO$_2$e*	*Total scope 3*	*MtCO$_2$e*	*only necessary if scope 3 emissions cover over 40% of the total emissions*	SBTi, GRI 305-3
**if data has to be estimated: method for estimation and reason for lack of data to be disclosed*						
Energy consumption	Total energy consumption	MWh	Total energy consumption	MWh	per production step if possible	GRI, TCFD
	Electricity consumption	MWh	Electricity consumption	MWh	per production step if possible	GRI 302-1/2
Future energy consumption			Future energy consumption	MWh	per production step if possible	SBTi
Emission factor of purchased electricity	National electricity mix and emission factors	tCO$_2$e /MWh	Emissions factor for the purchased amount of power from specific generation facility	tCO$_2$e /MWh		TPI, SBTi
Activity / production	Sectoral physical production levels	tons per year	Physical production	tons per year		SBTi
Emission intensity			Emission intensity	tCO$_2$e /MWh		GRI 305-4
Future emission Intensity	Future production levels (based on models)	tons per year				TPI, SBTi
	Future GHG emissions (based on targets set by companies, scenario models, business strategies)	tCO$_2$e				TPI, SBTi
GHG emission target			Base year	Year		SBTi
			Target year	Year		SBTi
			Absolute Target	MtCO$_2$e or % reduction (base year)		SBTi

			Intensity (scope 1 + 2 combined or separately)	$MtCO_2e$ per activity or % reduction of intensity measure		SBTi
Energy efficiency & energy reductions			Energy efficiency (total energy consumption divided by production output)	MWh/t		GRI 302-3
			Energy reductions achieved as result of conservation efforts	J	per fuel type if possible	GRI 302-4
Emission reductions			Emissions reductions achieved as result of initiatives	tCO_2e/t	per emission type is possible	GRI 305-5
Technology Mix	Data on technology developments		BATs installed			TCFD

Sources: Created by the author, based on reference frameworks as indicated in the last column.

4.3 Mitigation options for the aluminium sector

4.3.1 Characteristics of the aluminium sector

Section 2.4 of the literature review has introduced key characteristics of the aluminium sector. Before going into detail about the mitigation options, it is important to gain an in-depth understanding of the processes as well as energy and emission profile of the aluminium sector, which is presented in the following sections 4.3.1.1-4.3.1.3.

4.3.1.1 Aluminium production processes

For primary production, the most significant production steps are bauxite mining, alumina refining from bauxite, and smelting. In addition, a carbon anode needs to be produced for the smelting process. The secondary aluminium process includes scrap pre-treatment, melting, and refining. Both primary and secondary aluminium production includes downstream processing such as rolling, intrusion and casting (EC, 2019a; Haraldsson & Johansson, 2018). Figure 4.3 shows a simplified version of the aluminium production process.

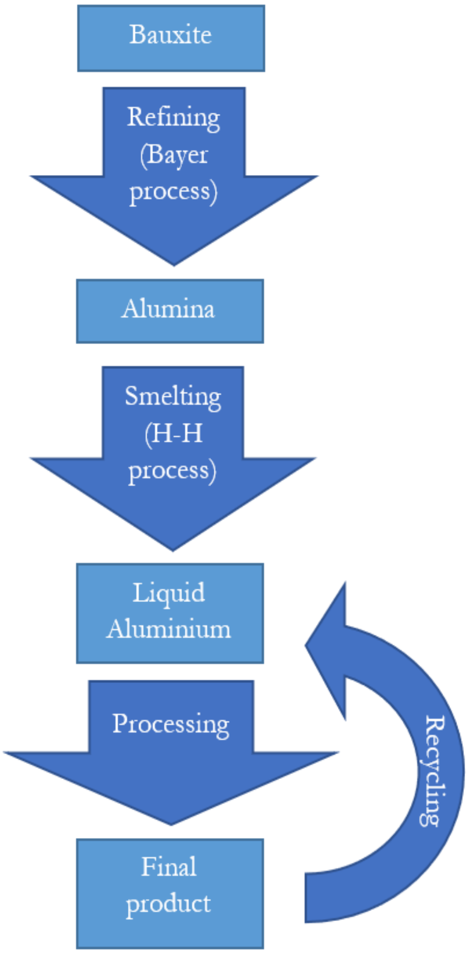


Figure 4.3: Simplified aluminium production processes.

Source: Adapted from: EC, 2019a.

Primary aluminium production

Primary aluminium production begins with the mining of bauxite ore. Nearly all facilities around the globe use the so-called Bayer-process, which has been invented in 1887, to extract alumina (aluminium oxide) from bauxite ore through a chemical process (EC, 2019a). Around 100 tons of bauxite ore are necessary to produce 40-50 tons of alumina (Cusano et al., 2017).

Alumina, in the form of white powder, then constitutes the main raw material for the primary aluminium production. From 40-50 tons of alumina, 20-25 tons of aluminium can be produced (Cusano et al., 2017). In smelting plants, alumina is reduced to pure aluminium through electrolysis. In almost all production facilities the Hall-Héroult process (H-H process) is used for the electrolysis, which separates the oxygen atoms from the alumina by passing of a high-intensity electrical current. In most cases, the smelting plant is not at the same site as the alumina refining, which is usually linked to the availability of cheap energy (Cusano et al., 2017). The electrolysis process is performed at high temperatures of approximately 950°C. The H-H process produces liquid aluminium, which is then further processed (EC 2019a).

The smelting process requires an anode that is consumed during the process and has to be renewed about once per month (Haraldsson & Johansson, 2018). The consumed anodes (20% the weight of original anode) are recycled for the production of the new carbon anode.

Typically, the anode is made from carbon that is processed through a "baking" process. In most cases, the anode production is located at the same site as the smelting process (Cusano et al., 2017).

Secondary aluminium production
Secondary aluminium is produced through re-melting used aluminium products. First, used aluminium products (e.g. aluminium cans) need to be collected and prepared for re-melting. The aluminium products are then washed and sorted. Once prepared for the re-melting process, a melting furnace is melting the aluminium at around 700-760°C (EC, 2019a).

Downstream production processes
In the downstream processes (also referred to as fabricating), liquid aluminium is processed into its form as a final product. There are three main mechanisms to bring liquid aluminium into its final form: rolling, casting and extrusion (Haraldsson & Johansson, 2018). The rolling process is mainly used to produce thin sheets of aluminium, such as foil or plates. The aluminium is pressed through two or more rolls until the desired thickness is reached. Application of heat is optional in the rolling process, but often heat treatment is used to achieve additional strength of the final product (ICF, 2015).

Casting is the most widely used from of downstream processing. Here, the liquid aluminium is poured into a casting mould, which may take the form of the final product or intermediaries like ingots or billets (Haraldsson & Johansson, 2018).

In the extrusion process, the solidified aluminium (e.g. in the form of ingots or billets) is formed into its final shape through the application of pressure. The aluminium is forced through a die opening and compressed into its final form. Heat treatment can be applied to facilitate the compression process (ICF, 2015).

4.3.1.2 Energy and emission intensity of primary aluminium production

The primary aluminium production is very energy intensive, demanding roughly 4% of the global industry energy demand (about 6.2 EJ) in 2014 (IEA, 2017).

Alumina refining is with approximately 15% of final energy demand the second-most energy intensive step, requiring mostly thermal energy (IFC, 2015). The Bayer process has required 3.5 MWh/t al (12.6 GJ/t Al) in 2014 (IAI, 2019), the current BAT level is at 2.88 MWh/t al (10.4 GJ/t al) (IEA, 2017).

For primary aluminium, the smelting process is by far the most energy-intensive (approximately 80% of final energy demand). Smelting has demands of 14.3 MWh/t al as global average 2014 (IEA, 2017; IAI, 2019). Using best available technologies (BATs), the H-H process has needs of 13.6 MWh/t al (IEA, 2017).

So-called anode effects increase energy demand, lower operating efficiency and can cause direct emissions of greenhouse gases such as CO_2, carbon monoxide, and perfluorocarbons (PFCs). Anode-effects are process upset conditions where alumina is insufficiently dissolved during the electrolysis (EC, 2019a). In 2014, the total PFC emissions amounted to the equivalent of 34 Mt of CO_2 and mean PFC emission intensity of 0.61 tCO_2e/t al (IAI, 2019).

The other production steps only contribute with 2% to the energy needed for primary production processes (EC, 2019a). As downstream processing only contributes to such a small extent to the energy and emission intensity of the aluminium sector, it is mostly neglected in this paper.

Annually, around 60 million tons of primary aluminium are produced, implying an emission intensity of about 13.5 tCO_2 per tonne of primary aluminium (Material Economics, 2018). In 2014, direct, process-related CO_2 emissions from primary production (mainly from consumption of anode) have amounted to 1.53 t CO_2/t of primary aluminium (Cusano et al., 2017; IEA, 2017).

Obviously, the emission-intensity of primary aluminium production varies greatly depending on the fuel used for energy production. The TPI has reviewed the emission intensity of selected firms and found that the emission intensity per tonne of aluminium differs not only per region or country, but also per company. Whereas the companies Rio Tinto (UK/Australia) and Norsk Hydro (Norway) have respective emission intensities of 5.18 and 3.45 tCO_2e/t al in 2015, the companies UC Rusal (Russia) and Alumina (Australia) have respective emission intensities of 7.81 and 19.90 tCO_2e/t al. Reportedly, Norsk Hydro's primary electricity source is hydro power, whereas Alumina mainly sources from fossil fuels (Dietz, Jahn, Nachmany, Noels, & Sullivan, 2019). These examples indicate that companies perform very differently, but also that aluminium production with comparatively low emissions is possible under certain circumstances.

4.3.1.2 Energy and emission intensity of secondary aluminium production

Secondary production of aluminium is around 95% less energy-intensive than primary aluminium production, requiring only 1.3 MWh/t al on average in 2016 (EC, 2019a). The carbon intensity is only 0.3 tCO2/t of secondary aluminium, only a fraction of the emission intensity of primary production (Material Economics, 2018). Around 25 million tons of secondary aluminium are produced annually. The share of secondary aluminium has been increasing steadily in the last decades (IEA, 2017). Globally, the share of secondary aluminium production is estimated to be around 30%, in regions with high recycling rates like the European Union, the share is estimates to be as high as 50% (Moya et al., 2015).

4.3.1.3 Emission profile of aluminium production

Aluminium industry as a whole (approx. 80Mt per year) has been demanding approximately 30 EJ of energy in 2014 (IEA, 2017). The total emissions of aluminium production in 2014 have been equivalent to around 800 $MtCO_2e$ (Material Economics, 2018; Dietz, Jahn, & Noels, 2019), including PFC emissions which were equivalent to 34 Mt of CO_2 (IAI, 2019). The average CO_2 intensity per tonne of aluminium varies in the literature, Material Economics (2018) reports 10.6 tCO_2/t aluminium, Carbon Trust (2011) reports 11.99 tCO_2/t al. On the basis of the reported annual production volumes (80Mt) and reported total emissions (800 $MtCO_2e$), an average of 10 tCO_2/t aluminium can be calculated for the year 2014.

Table 4.4 provides an overview of energy and emission intensities for both primary and secondary production.

Table 4.4: Emission and energy intensity of primary and secondary aluminium.

	Process step	**Annual Production**	**Energy intensity**	**Total energy demand**	**Emission intensity**	**Total emissions**
Primary Aluminium	Annual production	55 million tons (2014)		6.2 EJ (2014)	13.5 tCO_2/t al	766 $MtCO_2$
	Electrolysis		14.3 MWh/t al (2014)	2.8 EJ in (2014)		
	Electrolysis with H-H under BAT conditions		13.6 MWh/t al			
	Anode effects (electrolysis) – PFC emissions				0.61 tCO_2e/t al (2014)	34 $MtCO_2e$ (2014)
	Process-related (direct) emissions				1.53 tCO_2/t al (2014)	
	Alumina refining (Bayer process)		3.5 MWh/t al (2014)			
	Alumina refining (Bayer process) under BAT conditions		2.88 MWh/t al			
Secondary Aluminium	Total production process	25 Mt (2014)	1.3 MWh/t al (2014)	32 $MtCO_2$	0.3 tCO_2 / al (2018)	7.5 $MtCO_2$
	Downstream processes (rolling, casting, extrusion)		0.28 MWh/t al			
Primary and secondary production	Aluminium sector as a whole	80 Mt 2014			10-12 tCO_2e/t al	800 $MtCO_2e$

Sources: Created by the author based on EC, 2019a; IEA, 2017; IAI, 2019; Material Economics, 2018.

Figure 4.4 visualizes the great variations of CO_2 intensity of aluminium production, indicating that especially the production with coal and gas has a high emission intensity. Remarkably, the emission intensity of secondary (recycled) aluminium is only a tenth of the production with low-carbon energy sources (Material Economics, 2018).

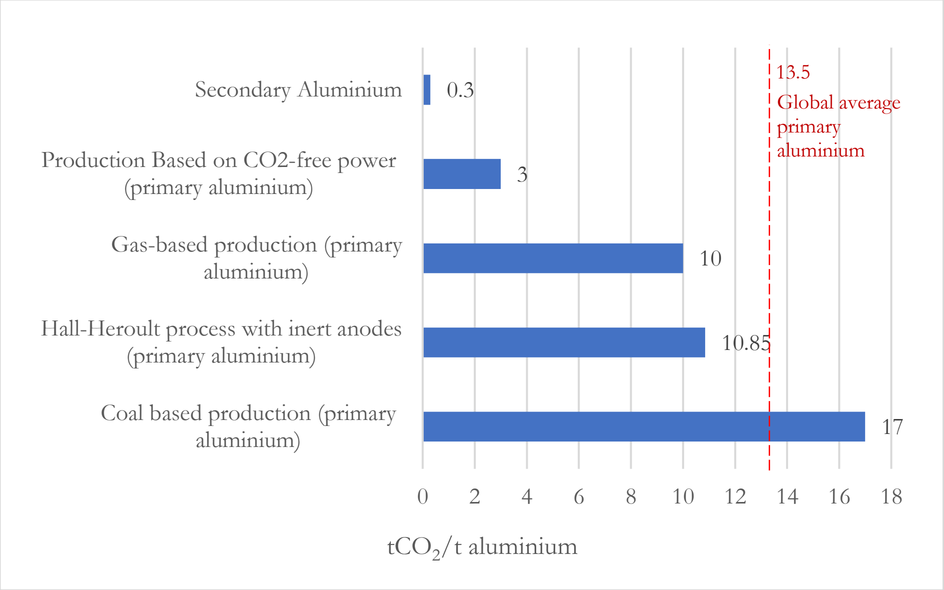


Figure 4.4 Average CO$_2$ intensity of aluminium production.

Sources: Created by the author, based on Material Efficiency, 2018; Dietz, Jahn, & Noels, 2019; IEA, 2017.

4.3.2 Mitigation options in the aluminium sector

The aluminium sector has halved its greenhouse gas emissions since 1990, mainly through process improvements and the reduction of PFC emissions (EC, 2019a). To further decarbonise the aluminium sector, four mitigation pathways are presented below.

1. Processes improvements
2. New production methods
3. Increased share of secondary production
4. Fuel switch

The choice of categories is based on the analysis of mitigation options by the IEA (2017), EC (2019a), Neuhoff et al. (2018), and Bataille et al. (2018).

4.3.2.1 Processes improvements

The implementation of best-available technologies (BATs) to improve energy efficiency and reduce emissions is an important and wide-spread approach (IEA, 2017). BATs are technologies, processes, equipment and practices that are currently available on the market and offer improvements to other technologies. It is important to note that the concept of BATs is dynamic, as new and improved approaches are continuously being researched and tested (Cusano et al., 2017). Most aluminium production sites are continuously optimising their processes to save costs and reduce their impact, so deploying BATs is already the industry norm. In the last decades, less efficient processes like Søderberg smelters have been phased out, the IEA describes the aluminium sector as mature when it comes to deploying BATs

(IEA, 2017). It is important to note that BATs are region, process, and on-site specific, meaning that the real energy or emission reductions are dependent on the specific context. A discussion of BATs offers, however, an indication of the potential of reductions and improvements (IEA, 2017).

Overall plant management

A wide-spread energy efficiency improvement approach is for companies is to apply energy management systems (EMS). Here, energy efficiency is improved through monitoring and optimising consumption at the production site. Increasingly, plants obtain EMS certification through ISO50001 (Cusano et al., 2017; IEA, 2017).

Alumina Refining

For the alumina refining, the Bayer process can be improved by upgrading rotary kilns with fluidised bed calcination, which can lead to energy savings in the Bayer process of up to 15%. This technology has a TRL[5] of 9 and is already widely applied (EC, 2019a). The installation of innovative tube digesters can keep the energy demand of the Bayer process around 2.8 MWh/t of aluminium (current BAT level). Although they have a high TRL of 8, tube digesters are, however, only compatible with very few plants. Another option is installing a CHP and waste-heat co-generation plant (TRL level 9), which can reduce fuel consumption of the Bayer-process by up to 15% (EC, 2019a).

Anode related improvements

With design upgrades of the anode used for the electrolysis, efficiency gains are possible with technologies that already have a high TRL of 8. Electricity and emission can be saved for the anode (electrolysis process), e.g. by installing slotted anodes (Haraldsson & Johansson, 2018). The use of "Point Feeder Pre-Bake" (PFPB) anodes is already widespread (TRL of 9). With this technology, electricity savings between 10-30% are possible (EC, 2019a).

Heat recovery

In nearly all production steps of primary and secondary aluminium, excess heat is produced, e.g. from the alumina refining, smelting and melting. Waste heat can be recovered and if possible, re-used for other processes in order to reduce the amount of energy used to produce heat (Haraldsson & Johansson, 2018). This is possible with recuperative and regenerative burners, boilers or heat exchangers, which already have a high TRL (Cusano et al., 2017). The range of technology options improving energy efficiency is particularly high in facilities whereas many production steps as possible are combined. With installation of a heat recovery system, which makes heat from the electrolysis available for the Bayer process, between 0.8 and 1.3 MWh/t aluminium can be saved (EC, 2019a).

If not applicable for the aluminium production itself, recovered heat can also be used for other purposes. District heating is a widely applied technique to make heat from industrial processes useful, but applications can also be found for other production sites (e.g. greenhouses). Heat recovery for other processes than aluminium production does not, however, directly reduce the emission intensity of aluminium (Haraldsson & Johansson, 2018).

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[5] On a scale from 1-9, the technology readiness level (TRL) assesses the maturity of technologies. A TRL of 1 indicates "basic principles observed" and a TRL of 9 means "actual system proven in operational environment" (Mankins, 2009).

Secondary production

Improved pre-treatment of scrap with new de-coating equipment can lead to fuel savings up to 50% of fuel with a high TRL of 9. Energy efficiency gains through the installation of recuperative or regenerative burners have a high TRL of 8-9, enhanced furnace design can save up to 30-50% of energy use (EC, 2019a).

If all available BATs were implemented in the global primary aluminium production, the energy demand would only decrease by a maximum of 4% (IEA, 2017), by far not enough to achieve the necessary emission reductions. It is therefore important to consider technologies that are currently in their R&D phase, as well as increasing the share of renewable electricity for the primary aluminium production.

Moreover, if all available BATs for secondary production were implemented, the final energy consumption would decrease by around 28% (IEA, 2017). As the energy demand of secondary production is only around 5% of the energy demand for primary production, implementing all BATs alone would not be sufficient to achieve significant energy demand and emission reductions.

4.3.2.2 New production processes

Whereas BATs offer significant reduction potential and have the major advantage that they are already commercially available, deploying BATs is not far-reaching enough to decarbonise the sector. The IEA concludes that without developing new technologies that go beyond current state-of-the-art, reaching sufficient transitions is not possible (IEA, 2017).

Decarbonisation with CCS

Carbon Capture and Storage (CCS) is an end-of-pipe solution designed to capture and remove CO_2 (EC, 2019a). Capturing carbon requires point-sources of CO_2 in order to effectively capture emissions. As the CO_2 emissions from the bauxite mining and electrolysis are diluted, CCS is not applicable (IEA, 2017). Especially for plants with the Hall-Héroult process, which is most plants, CCS is not commercially viable (IEA, 2017). The TRL for CCS is only 3-4 (EC, 2019a).

Alumina reduction: alternatives to the H-H process

As an alternative to the H-H process, carbo-thermic reduction of alumina does not use electrochemical processes. Instead, alumina and carbon are reacted at very high temperatures to form aluminium (Haraldsson & Johansson, 2018). The technology could reduce energy demand by up to 30%, but only has a TRL of 2-3 and is not expected to be available before 2050 (EC, 2019a)

An alternative to the H-H process is also the reduction of Kaolin, an alumina-containing clay that is less expensive than Bauxite and widely available. Kaolinite reduction an energy saving potential of 12-46% but is only at the R&D stage with a TRL of 1-2 (EC, 2019a).

The use of ionic liquids (organic solvents, salts and electrolytes) instead of the H-H process allows for lower temperatures with energy savings between 30-85%. It is uncertain, however, whether the technology is suitable for large-scale production facilities and only has a TRL of 1-2 (EC, 2019a).

Anode-related improvements
Conventional anodes are carbon based and as the anode gets consumed during the smelting process, process-related emissions occur. Inert anodes are made from other materials than carbon have the potential to eliminate process-related CO_2 and PFC emissions (IEA, 2017; Haraldsson & Johansson, 2018). Inert anodes are still in their testing phase (TRL of 5) but are highly likely to find widespread application (EC, 2019a; Moya et al. 2015). Once available, inert anodes have the potential to reduce emissions of the H-H process by as much as 1.65 tCO2/t aluminium (IEA, 2017).

Less developed approaches during the electrolysis include wettable cathodes. Wettable cathodes lower the anode-cathode distance and achieve energy consumption by up to 20% (EC, 2019a; Haraldsson & Johansson, 2018). The inert anode and wettable cathode technologies are combinable into the so-called "Elysis" process. This process allows for a smelting process without direct carbon emissions and lower energy demand (up to 55%). The process is in its demonstration phase and is likely to be commercially available within the next five years (TRL of 6) (EC, 2019a).

Other electrolysis technologies
Technologies that allows for lowering the temperature of the H-H process promises energy savings around 5% and is starting to become commercially available with a high TRL of 7 (EC, 2019a).

Secondary production improvements
Secondary aluminium production can be made technologically more efficient by installing innovative sorting technologies (up to 12% energy savings) and has a TRL of 5 (EC, 2019a; Cusano et al., 2017). Another approach is the introduction of so-called "Aluminium Mini Mills" in urban areas. As they are both close to the areas where scarp is produced and collected as well as to areas where new aluminium products are necessary, the number of energy-intensive steps is reduced. For example, Aluminium Mini Mills avoid the shipping of scrap oversees for sorting purposes. This technology can save up to 84% of primary energy and has a TRL of 6 (EC, 2019a).

Another option is to use so-called "Oxy-fuel" combustion is secondary aluminium plants. The technology uses pure oxygen for combustion and has been demonstrated to reduce energy reduction by as much as 60% (Haraldsson & Johansson, 2018).

4.3.2.3 Increased share of secondary production

As it only requires around 5-6% of the energy necessary for primary aluminium production, increasing the share of secondary aluminium is a priority (IEA, 2017). Secondary aluminium has up to 98% less emissions than primary aluminium, making it a very attractive decarbonisation strategy. As secondary aluminium offers such substantial reductions, it needs to replace as much primary production as possible in the future (Material Economics, 2018).

Secondary aluminium is often further divided into "new" and "old" scrap. New scrap is generated during the downstream processes (e.g. casting) at the production facilities. The recycling rate for new scrap is almost 100%, as it is directly collected and recycled. Old or used scrap is recovered from consumed articles (Cusano et al., 2017; Haraldsson & Johansson, 2018). The challenge with old scrap is increasing collection rates. Currently, 20-30% is lost (land-filled) in each use-cycle (Material Economics, 2018).

Collection rates and quality of collected aluminium play a significant role. Whereas in some parts of the world collection rates are already relatively high, improvements are necessary in others (EC, 2019a). It if furthermore crucial to improve product design, so that end-of-life management can be facilitated (Material Economics, 2018). Another barrier to increased secondary aluminium production is that a large proportion of aluminium has just entered its use phase and is not yet available for recycling (Dessart & Bontoux, 2017; IEA, 2017).

The significance of secondary aluminium production is further highlighted in IEA's ETP report. According to the B2DS scenario, the share of secondary aluminium should increase from 30% in 2014 to 70% in 2060 (IEA, 2017).

The circular economy concept offers great opportunities for increased aluminium recycling in the future, which will lower the emission intensity of the aluminium sector as a whole. In the future, new technologies such as increased automation, mobile apps, information technology and advanced sensors are expected to further promote the increase of available aluminium scrap (Material Economics, 2018).

As touched upon when describing the so-called "Aluminium Mini Mill" technology in 4.3.2.2, increased recycling also has the added benefit of avoiding the transport of aluminium raw materials and final products. Scrap can be re-melted into secondary aluminium close to where aluminium products are consumed, e.g. close to urban areas. This does not only offer efficiency gains, but also has the co-benefit of decreasing international dependencies and emissions from transport (Material Economics, 2018).

In secondary aluminium production, a greater efficiency can also be achieved by increasing alloy separation through improved collection systems. Alloying refers to a process were pure aluminium is mixed with other metals in order to achieve specific properties (Haraldsson & Johansson, 2018). With increased alloy separation in aluminium collection, downgrading can be avoided. Careful alloy separation is especially important regarding the future of recycling, as a limited availability of aluminium with a specific alloy content could reduce the usefulness of secondary aluminium production in the long run. The recycling system for beverage cans made from aluminium is a good example for a so-called "closed-loop" system, were aluminium is re-used for the same purpose, which avoids downgrading. In order to avoid primary production as much as possible, careful alloy-separation is crucial (Material Economics, 2018).

4.3.2.4 Fuel switch

Although low-carbon electricity sources are commercially available (e.g. hydro, nuclear, wind and solar power) and become increasingly advanced, it will remain a challenge to fully switch to low-carbon electricity sources for primary aluminium production. In some estimates, the primary aluminium demand will grow so rapidly until 2050 that the amount of electricity that India uses today per year (1335 TWh) would be necessary to cover the future demand of low-carbon electricity (Material Economics, 2018), indicating that switching to electricity-based processes will only prove viable when combined with other measures.

Alumina refining

For the alumina refining, the Bayer process can be improved by upgrading to natural gas as fuel, which can save up to 5% of carbon emissions and has a TRL of 9. There are also pilot projects testing the integration of solar thermal for the alumina refining process as a low-carbon alternative (IEA, 2017).

Smelting

As electricity is required for the electrolysis (smelting) process, switching to low-carbon electricity sources has a big influence on the emission intensity of aluminium. There are several facilities which are already using hydro power or nuclear power as an electricity source, resulting in an improved emission performance (EC, 2019a).

Virtual battery concept

Efficiency load management in the aluminium sector has the potential to support the integration of renewables into the grid. Some facilities, like the TRIMET facility in Germany, can increase or decrease their production by 25%, allowing them to manage the amount of electricity drawn from the grid (Philibert, 2017). By lowering the energy consumption at peak demand, the facility can save costs and facilitate grid integration of intermittent power sources, such as wind and solar power. The "virtual battery" concept has concluded its test phase in 2017 and is expected to be widely applied (Depree, Düssel, Patel, & Reek, 2016; IEA, 201).

4.3.3 Technology-related criteria selection

The four mitigation pathways discussed in the previous sections offer a variety of options to reduce the emission intensity of the aluminium sector.

As outlined in section 3.2.2, this study adopted the "shades of green" approach from the green bond second opinion framework developed by CICERO to classify the different options. The previous section (Table 4.2), presents the sectoral benchmarks for the aluminium sector, the levels of improvement in percent are based on those sectoral benchmarks. The scheme also includes the classification "not qualified" (1-30%) because their level of added benefit is too low for significant improvements. Table 4.5 includes the mitigation options falling into this category, even though they are by themselves not sufficient enough for two reasons. First of all, the presented percentages represent average potentials, the real impact may be higher at specific companies. Secondly, some of the approaches could be used in combination with each other which would make them more powerful.

The mitigation options are classified in three categories and presented in Table 4.5. The mitigation options as discussed in 4.3.2 according to this classification scheme are presented in

Table 4.5: Classification after CICERO's "shades of green" approach.

	% of emission reduction (2014 reference level)	**Reasoning**
Grey-green	1-30%	All improvements between 1-30% are not significant enough to offer improvements strong enough to reach any of the sectoral benchmark scenarios.
Green	30-60%	In this range, most of the sectoral benchmarks may be reached (e.g. all IEA 2050, Material Economics 2030 and 2050 benchmarks, almost all TPI 2030 benchmarks)
Dark green	Min. 65%	With a minimum of 65% the more ambitious sectoral benchmarks may be reached (Material Economics 2100 & TPI 2030 B2DS benchmarks)

Source: Author.

Table 4.6: Classified mitigation options for the aluminium sector.

		Reference level 2014	**Production step**	**Measure**	TRL	**Incremental Benefits** 1-30%	**Significant improvements** 30-60%	**Ambitious improvements** min. 65%
Primary Aluminium	**Emission intensity**	Global average CO_2 intensity: 13.5 tCO_2/t al						
			Alumina Refining	Natural gas as fuel	BAT	5% reduction (12.8 tCO_2/t al)		
			Smelting	Inert anode	5	14% reduction (11.61 tCO_2/t al)		
			Gas-based production	Fuel switch	BAT	16% reduction (11.34 tCO_2/t al)		
			Production-based on CO_2-free power	Fuel witch	BAT			88% reduction (3 t CO_2/t al)
Primary Aluminium	**Energy intensity**	Global average energy intensity (approx.) 18 MWh/t al	Alumina refining	Carbo-thermic Reduction	2-3	20-30% (14.4-12.6 MWh/t al)		
			Alumina Refining	Fluidised bed calcination	9 (BAT)	15%* (17.4 MWh/t al)		
			Smelting	Lower temperature electrolytes	7	6% (16.92 MWh/t al)		
			Smelting	PFPB	BAT	10-30% reduction (16.2-12.6 MWh/t al)		
			Smelting	Elysis process	6		Up to 55% (8.1 MWh/t al)	
			Smelting	Kaolin Reduction	1-2		12-46% (15.84-9.7 MWh/t al)	
			Smelting	Ionic Liquids	1-2			30-85% (12.6-2.7 MWh/t al)
			Combined plant (Alumina Refining & Smelting)	Cogeneration	BAT	15% reduction (15.3 MWh/t Al)		

Secondary Aluminium		Global average: 4 MWh/t al	Aluminium Mini-Mills	Lean production	6			86% reduction (0.56 MWh/t al)
			Oxy-fuel combustion	Melting process	-		60% (2.4 MWh/t al)	
			Preparation	Economic sorting	5	12% (3.52 MWh/t al)		
			Melting	Recuperative or regenerative burners	BAT		30-40% (2.8-2.6 MWh/t al)	
*for Bayer-process								

Sources: Created by the author, based on Cusano et al., 2017; EC, 2019a; Haraldsson & Johansson, 2018; IEA, 2017; Material Economics, 2018.

As already discussed in the previous chapter, the emission intensity and energy efficiency values are averages based on the data found in the literature. The actual improvements a technology can achieve is highly dependent on the specific plant and context.

Furthermore, it is important to note that emission intensity and energy efficiency improvements have been classified under the same approach (Table 4.5). The sectoral benchmarks concern, however, only emission intensities and not energy efficiency gains. Achieving some percentage of energy efficiency improvement does not necessarily directly translate to the same extent of emission intensity reductions. Yet, this study has chosen to adopt the same classification system for energy efficiency gains as for emission intensity improvements for several reasons. Firstly, for the sake of simplicity and clarity, as developing an additional classification system for energy efficiency improvements would add another layer to the methodology of this paper, decreasing its comprehensibility.

Secondly, calculating the emission intensity improvements from energy efficiency gains is hardly possible due to a lack of data. Calculating reliable emission intensity improvement would require knowing the energy intensity of national and regional energy mixes, as well as the site-specific energy mix, as most firms produce at least a share of the energy necessary for the production on site. Taking this into account would mean having to abandon generalisability of Table 4.6. The green bond criteria designed for this paper do, however, aim to be universal.

Another option of dealing with this issue would be to exclude all technologies for which no quantification of the corresponding emission savings potential is available in the literature. This would, however, lead to only very few remaining options and the exclusion of options with promising potential (e.g. the "Elysis process"). For all these reasons, it has been chosen to simply apply the same classification methodology to emission intensity improvements and energy efficiency gains.

Other mitigation options

Notably, not all the mitigation options discussed in section 4.3.2 are represented in Table 4.6 This is due to two main reasons. Firstly, for the applications of some of the mitigation options, the aluminium industry and individual companies have very little agency. It is, for example, difficult for an individual company to have impact on the collection of scrap aluminium from consumers to improve recycling rates. In many countries, this would be a measure directed by a local or national authority through policy instruments.

Secondly, for some mitigation options quantifying effects is very complex and specific. For example, the mitigation potential resulting from the installation of an EMS are site-specific to such an extent that it could not be included in Table 4.6.

The benefits of other mitigation options mentioned in this section are very difficult to quantify, as they not directly reduce the emission intensity of aluminium. Using excess heat outside of the aluminium sector (e.g. as district heat), for example, reduces GHG emissions overall, but does not directly reduce the emission intensity per ton of aluminium. Similarly, the "virtual battery" concept is very hard to quantify, as it supports grid integration of renewables, but does not directly reduce the emission intensity of the produced aluminium.

It is especially difficult to include increased secondary aluminium production, as it is difficult to quantify to what extent secondary aluminium can replace the production of primary aluminium. Increasing the share of secondary aluminium has been identified as the single most effective measure to decarbonise the aluminium sector as a whole (EC, 2019a; IEA, 2017; Material Economics, 2018). Yet, it is obviously only reducing emissions if secondary production is replacing primary reduction. This dynamic makes simply listing secondary aluminium production as a decarbonisation method problematic.

Despite these issues, it is arguably very important to include as many mitigation options as possible into the criteria for a green bond. If not included, there is a risk that raising capital through green bonds is inhibited or delayed. Thus, Table 4.7 presents a list of those mitigation options that are not easily quantifiable. The "shades of green" approach by CICERO has not been adopted in these cases due to the lack of data.

Table 4.7: List of non-quantifiable mitigation options for the aluminium sector.

		Production step	**Measure**	**Environmental Benefits**
Primary Aluminium	**Emission intensity & Energy efficiency**			
		Overall process	Energy Management System	Incremental improvements (energy efficiency)
		Smelting	Slotted anodes	Incremental improvements (energy efficiency)
		Multiple	Heat recovery for use outside the production plant	Potential emission savings (non-plant level)
		Smelting	Efficiency load management	Facilitates grid integration of renewables
Secondary Aluminium		Circular Economy strategies	Increased scrap collection, design for recycling	Increased secondary aluminium production
		Collection	Increased alloy separation	Improved secondary aluminium production

Source: Compiled by the author.

4.4 Assessment of strategy-based criteria

4.4.1 Strategy-based criteria

This section answers the question what is required from a firm's management to show its commitment to a low-carbon future and environmental integrity. Four broad categories have been identified which will be discussed in the following sections.

For this purpose, the most important standards and recommendations regarding a firm's management of low-carbon transitions and climate-related reporting are reviewed. The consulted literature includes publications by the Taskforce on Climate-Related Financial Disclosures (TCFD), the Global Reporting Initiative (GRI), the Transition Pathway Initiative (TPI) and others. As all of these standards aim to be applicable on a global scale and across industries, they are in most cases aligned or based on each other. For example, the widely used four elements of disclosure published by the TCFD are aligned with several other reporting frameworks, such as the G20/OECD Principles of Corporate Governance, the Carbon Disclosure Project (CDP) Climate Change Questionnaire, the GRI principles, Climate Disclosure Standards Board (CDSB) frameworks and the International Integrated Reporting Framework (SASB & CDSB, 2017).

4.4.1.1 Four elements of climate-related disclosure

In its 2017 "Recommendations Report" the TCFD proposes four fundamental elements that are to be disclosed by individual companies. The four thematic core elements are governance, strategy, risk management, and metrics and targets (TCFD, 2017b).

1. Governance

Recognising the risk and opportunities that come with climate-related issues, the TCFD argues that a company must have an internal governance structure designed to deal with such risks and opportunities of climate change. A company is therefore required to disclose governance structures within the company's board, e.g. how they oversee climate-related matter. Moreover, a company needs to disclose how the company's management is concretely managing climate-related risks and opportunities (TCFD, 2017b).

2. Strategy

TCFD outlines that a company should make sure to directly link climate-related risks and opportunities to their business strategy as well as financial planning. Here, it crucial to take both actual and potential impacts into account. TCFD outlines a stepwise approach for this disclosure process. First, companies are asked to identify short-, medium- and long-term risks and opportunities related to climate issues. Then, companies should disclose the expected impact on the business strategy and financial planning. Finally, the company should disclose how it is planning to cope with the identified risks. The company should hereby relate its resilience strategy to different climate and energy scenarios, e.g. to B2DS, 2DS and RTS. The TCFD specifically requires that the disclose includes a strategy relating to B2DS scenarios (TCFD, 2017b).

For developing the company's strategy, TCFD recommends using scenario analysis. A company should demonstrate that the identified strategy is resilient when tested against different climate scenarios. For this, the company is required to test its strategy against a range of scenarios. The strategy should further be tested under different key assumptions (e.g. policy scenarios, macroeconomic parameters) to demonstrate robustness (TCFD, 2017a).

In the materials sector, a disclosure about a company's strategy on the current and future use of innovative technologies (see 4.3) is essential. Financial and strategic planning of the company's production facilities is central, as most new technologies require substantial amounts of capital. The TCFD highlights that specifically a company's strategy regarding R&DDD (research, development, demonstration, and deployment) is a crucial disclosure (TCFD, 2017a).

3. Risk Management

Under this theme, the TCFD requires company to disclose the internal procedures to identify, assess and manage risks and opportunities specific to their company. Here, a company is furthermore required to show how it is embedding the management of climate-related risks and opportunities into its risk management regarding other topics (Dietz, Garcia-Manas, Irwin, Rauis, & Sullivan, 2018). According to the 2018 TCFD Status Report, especially companies in the materials sector tend to disclose insufficiently on their risk management (TCFD, 2018).

4. Targets and Metrics

When attempting to assess a company's carbon performance and compare it with benchmark scenarios, the disclosure of targets and metrics is especially important. Section (4.2) has discussed data disclosure requirements that are necessary to calculate emission intensity pathways from firms (Table 4.3).

4.4.1.2 TPI's approach to include TCFD elements

In the science-based target approach, assets are evaluated based on expected pathways. For instance, to derive a future emission pathway of a company, emission and production targets must be considered. To classify a bond as "green", carbon management quality and target reliability must be ensured. The TPI has developed a method to capture the disclosure elements of governance, strategy and risk management, so that a company's performance can be compared. TPI highlights that a company's carbon performance is not necessarily indicative about a company's performance in the management-related disclosure elements. For example, a company could have a carbon performance in line with the sectoral benchmark, but that does not imply the quality of its management around climate-related issues is compliant to standards such as the TCFD. According to TPI, a poor management performance could imply that the company will not be able to stay compliant in the future (Dietz, Garcia-Manas, Irwin, Rauis, & Sullivan, 2018).

Besides carbon performance relative to the sectoral benchmark, the TPI is therefore also reviewing a company's management quality. TPI bases its assessment on the approach of multiple initiatives, such as GRI, CDP, CDS and TCFD. TPI derives the data for the assessment from FTSE Russel, but lets the assessed companies cross-check during the quality control process (Dietz, Garcia-Manas, Irwin, Rauis, & Sullivan, 2018).

TPI has developed a so-called "Management Quality Framework" that places the management quality of companies on five levels, ranging from "unaware" to "strategic assessment" (see Figure 4.5). The assessment is built on a set of 17 indicators (questions), the companies are placed according to their respective performances (Dietz, Garcia-Manas, Irwin, Rauis, & Sullivan, 2018).

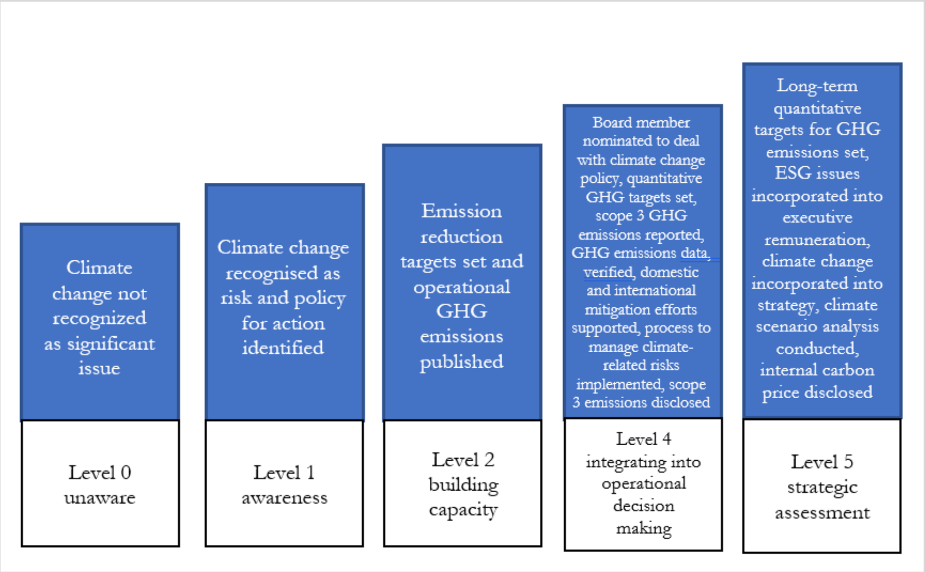

Figure 4.5 TPI's framework to measure a company's management quality

Source: Created by the author adapted from Dietz, Jahn, Nachmany, Noels, & Sullivan, 2019

4.1.1.3 Global Reporting Initiative's approach

The Global Reporting Initiative (GRI) Standards are another widely used set of guidelines for companies to perform sustainability reporting. They are regularly updated by the Global Sustainability Standards Board (GSSB) and include guidelines to universal, economic, social as well as environmental topics (GRI, 2018). For this paper, especially the GRI standards on emissions (GRI 305), renewable energy (GRI 103, 302-1) and energy efficiency (GRI 103, 302-3, 302-4) are relevant. Similarly to the TCFD framework, the GRI specifically highlights disclosure of a company's management approach (GRI 103). The GRI standards for management disclosures are very extensive, as they for example also include requirements for companies to report on the evaluation procedure of their management approach (GRI, 2018).

The emission reporting guidelines specified in section 305 outline requirements to report on scope 1, 2 and 3 GHG emissions (305-1, 2, 3) and how to report on emission intensity (305-4). GRI 305-5 also discusses reporting guidelines on GHG reductions (GRI, 2018).

The sections on renewable energy and energy efficiency (GRI 302-1, 302-2, 302-3, 302-4) further separate total energy consumption, e.g. by separating by energy consumed inside (GRI 302-1) and outside (302-2) the organisation. Companies are required to disclose detailed reports of energy consumptions, e.g. split by fuel type. The GRI also requires a disclosure of energy efficiency (302-3), which is calculated by dividing the total energy consumption by the output metric of the company (see Table 4.3). Furthermore, GRI principle 302-4 outlines how companies should report on their energy efficiency improvements resulting from conservation efforts. Here, the company should also report on calculation method, including baselines, fuel types etc. (GRI, 2018).

4.4.2 Principles of reporting

While climate-related disclosure should be in line with all TCFD principles for disclosure (TCFD, 2017b), principles 2 and 6 refer explicitly to scenario-based and future-oriented information. Both the SASB and CDSB have very similar principles (SASB & CDSB, 2017), a comprehensive overview of the alignment of different reporting principles can be found in CDSB (2018) on p. 33.

TCFD's principle 2 stresses the requirement of reported data to be complete as well as specific. It states that companies should disclose on all climate-relevant dimensions of the company according to the previously discussed four elements of disclosure (section 4.4.1.1). Disclosures must include historic data as well as future-relevant information where necessary. When disclosing information about the future, all key assumptions should be described in detail. Principle 2 two further states that whenever scenario modelling is used, the underlying assumptions and data should be sound with the general financial and strategic planning of the company. A company is furthermore required to demonstrate how altering the key assumptions would affect the outcomes of scenario modelling (TCFD, 2017b).

Principle 6 stresses the importance of reliability and objectiveness. Disclosed data should be as neutral as possible. This point is less straightforward for future projections, as assumptions have to be made. Here, a company is required to base assumptions on objective data sources as much as possible (e.g. industry-wide standards), communicate the reasoning behind all judgements in detail and make sure all data is verifiable. For this process, it may be useful for company to orient this disclosure process on the already established financial disclosure processes of a company (TCFD, 2017b).

4.5 Green bond criteria for the aluminium sector

4.5.1 Strategy-related criteria for a green bond in the aluminium sector

Having analysed the most important management quality elements in Section 4.4, this paper has come up with four overarching components to assess a company's management quality. The criteria are summarised in Table 4.8.

Table 4.8 List of strategy-related criteria and disclosures.

Topic	**Sub-category**		**Based on**
Scenario compatibility	Vision	Vision of firm transition to net carbon neutral technology / practices	TCFD, TPI
	Targets	In line with sectoral benchmark, ambitious, realistic, measurable	TPI
	Technology Roadmap	(Financial) planning of technology roadmap in line with targets	TCFD
Management Quality	Governance	Internal governance structure to oversee climate-related risks and opportunities	TPI, GRI 103, CFD

	Strategy	Directly link climate-related risks and opportunities to business strategy and financial planning	TPI, GRI 103, CFD
	Risk management	Internal procedures to identify, assess and manage risks and opportunities specific to the company	TPI, GRI 103, CFD
Reporting/disclosure requirements	Management related disclosures	Disclosure in line with GRI 103	TPI, GRI, CFD
	Emissions	See Table 4.3 & GRI 305	TPI, GRI, CFD
	Renewable energy	See Table 4.3 & GRI 302-1	GRI, CFD
	Energy efficiency	See Table 4.3 & GRI 302-3, 302-4	GRI

Source: Created by the author, based on various sources as indicated in the last column.

For a company to be eligible for a green bond, the criteria as presented in Table 4.8 are a pre-requisite. Without these elements being recognisable in a firm's management strategy and disclosures according to the principles outlined in section 4.4, a company's commitment to a low-carbon future cannot be considered credible.

4.5.2 Technology-based criteria for a green bond in the aluminium sector

This section presents a taxonomy for the aluminium sector based on the analysis in section 4.3. As explained in the methods section (3.2), it is based on the taxonomy developed by the Climate Bonds Initiative and the "shades of green" approach developed by CICERO. Table 4.9 presents the mitigation options discussed in this report. The taxonomy uses the classification system for the benchmarks presented in Table 4.5. Where possible, screening indicators have been identified.

Table 4.9: Green bond taxonomy for the aluminium sector.

Asset type	**Asset specifics**	**Technology**	**Benchmarks**			**Screening indicator**
			Incre-mental	***Majority reached***	***Ambitious***	
			1-30%	***Min. 30%***	***Min. 65%***	
Primary Aluminium	**Generation of Power & Heat**	Fuel switch to renewable power sources			✓	Total emissions less than 3 t CO2e/t al
		Natural gas as fuel (Bayer process)	✓			
		Gas-based production	✓			
		Cogeneration				

		Heat recovery for use outside the production plant	✓			
		Virtual battery concept	✓			
	Alumina Refining Technology	Carbo-thermic reduction	✓			
		Rotary kilns	✓			
	Smelting Technology	Inert anodes / PFPB	✓			PFC emissions eliminated
		Lower temperature electrolytes	✓			
		Elysis process			✓	PFC emissions eliminated
		Kaolin Reduction			✓	
		Ionic Liquids			✓	
Secondary Aluminium Production	**Circular Economy Strategies**	Increased scrap collection / secondary production			✓	As alternative to primary production
	Heat & Power Generation	Fuel switch to renewable power sources			✓	No carbon leakage
		Oxy-fuel combustion		✓		
	Process Improvements	Economic Sorting	✓			

	Process Improvements	Recuperative/ regenerative burners	✓	🟩	🟩	

5 Discussion

The aim of this study has been to develop an analytical framework and propose criteria and benchmarks for a green bond in the aluminium sector. Building on the CBI taxonomy, this paper has found that two sets of criteria are most useful to develop an effective and transparent taxonomy for green bonds in the aluminium sector. One set of criteria is focused on strategy-based criteria (Table 4.8) and one on technology-based criteria (Table 4.9). The two sets are complementary to each other. In the following, the methods, results, and further implications of this paper are discussed.

5.1 Discussion of methods to develop green bond criteria

To develop criteria for a green bond taxonomy for the aluminium sector, methodological choices have been made. The paper has adopted the green bond taxonomy developed by CBI as its point of departure, which has proven to be useful to answer the research questions. CBI's taxonomy has provided a simple yet clear structure to guide the research. Adopting this widely used framework allows for a comparison with other sectors, which is an important basis for future research in the field. Nonetheless, the CBI approach also has shown several shortcomings. For example, CBI's binary approach has proven to be too narrow to capture the variety of mitigation options in the aluminium sector. Therefore, this paper has decided to combine CBI's approach with elements of CICERO's "shades of green" method. As other sectors also have a range of mitigation options to choose from, this methodological choice is likely to be useful for other industrial sectors. Yet, it is important to note that this methodological choice makes the development of green bond criteria a more complex task.

When developing and defining the methodological approach for this paper, it has been a major challenge that the literature on green bonds does not suggest methods on how to develop green bond criteria. This is why one of the contributions of this paper lies in the development of a methodological framework, which benefitted, among others, from a close collaboration and exchange with the research team at the DIW. While the stepwise research method has delivered robust outcomes, the lack of literature and primary data on the topic may limit comparability and generalisability of this research. Further research should be undertaken to establish general methods for the development of green bond criteria.

This thesis has relied on scenario modelling to understand how emissions in the materials sector may develop in the future. The analysis of scenarios has built the foundation of the subsequent chapters. It is thus very important to discuss the advantages and shortcomings of this methodological choice.

Drawing on scenario modelling to understand a sector's development path has proven to be very helpful for proposing criteria in the aluminium sector. It allows to make informed decisions on what kind of mitigation options are effective enough to decarbonise a sector. Furthermore, connecting the proposed criteria to widely used and scientifically robust scenario modelling further makes the method more transparent. As lack of transparency is one of the key barriers for the development of the green bond market, this advantage of scenario analysis is crucial. Therefore, this paper recommends the use of scenario modelling for future research on this topic.

Yet, the use of scenario modelling for this paper also bears several limitations. Only a limited number of scenarios have been reviewed for this research, mostly due to a lack of available literature. While the three scenario modelling approaches have been selected very carefully, analysing more scenarios would have provided additional insights that may have affected the outcome of this thesis.

Furthermore, the analysed scenarios have only been comparable to a limited extent. As already touched upon in section 4.1.4, for some scenarios only benchmarks for selected emissions or regions have been available whereas others present data for the overall emission intensities of the aluminium sector. As the sectoral benchmarks have formed the basis for the classification after CICERO's "shades of green" approach, these inconsistencies may have led to over- or underestimation of the mitigation options. In future work on this topic, it would be very useful to perform scenario modelling for the targeted sector and compare it to the published literature. This would allow for more robust results and alleviate data availability issues. Performing scenario modelling would furthermore allow for more detailed results, such as modelling of energy intensities or separate benchmarks for primary and secondary production methods.

As discussed in section 4.1, scenario modelling is always dependent on a number of simplifications and assumptions, making carbon budgets by default somewhat arbitrary. This means that ultimately, only setting carbon-neutrality as a benchmark would be reliable.

Furthermore, a step in deriving the green bond criteria has been to propose ways to translate scenarios into benchmarks, firm-level metrics, and other eligibility criteria (4.2). The strength of this step is its strong foundation in internationally used frameworks, such as the approaches of TCFD, GRI or CDP. Connecting the macro-level scenarios to the context of individual firms has proven to be very useful for further analysis. This section has intentionally been kept very general (i.e. not specific to the aluminium sector), which makes it more useful for similar research into other industrial sectors. Table 4.8, for example, outlines disclosure requirements that are not specific to the aluminium sector but may just be as applicable for other materials sectors.

A similar approach has been chosen for the section on management approaches (4.4), which is based on the most widely referenced international frameworks and recommendations in order to deliver generalisable results. In future work on green bond criteria, a division between strategy-based and technology-based criteria is strongly recommended. This recommendation reflects those of the TPI, who argue that a company's emission performance and management approach are not necessarily correlated and therefore need to be treated separately (Dietz, Jahn, & Noels, 2019).

5.2 Discussion of results

Mitigation options for the aluminium sector

After having analysed the aluminium sector in detail, this paper clearly indicates that strengthening efforts to mitigate emissions in the aluminium sector is crucial. Investments into cleaner production methods and increased secondary production are necessary to transform the sector. This finding further justifies the research question, as green bonds have potential of supporting this pathway.

While outside of the scope of the primary research question pursued in this paper, this study has nonetheless highlighted that mitigation of industrial sectors like the aluminium sector should be a top priority in order to avoid catastrophic climate change. This paper has demonstrated that a variety of options powerful enough to mitigate sectors are already available today. Timely implementation and targeted investments have been identified as major barriers, which highlights once more that tools and incentives need to be put in place to transform industrial sectors.

Yet, the list of presented mitigation options is by no means exhaustive. It has been outside the scope of this study to offer a detailed and conclusive list of mitigation options. The idea of this section has merely been to conceptualize how research on mitigation options may be used for the development of green bond criteria. To support a firm's decision-making process in what kind of technological upgrade to invest in, a lot more details need to be considered. For example, this thesis has not offered any information on costs or compatibility of measures.

When designing the method for developing green bond criteria for the materials sector in this thesis, it has been considered to simply take the installations of BATs as criteria. Yet, BATs do not offer emission reductions to the necessary extent and this method could therefore not be adopted (see section 4.3.2.1). For other sectors, however, this approach could be considered as an orientation along BATs may be more effective.

Strategy-related criteria

For this paper, a transparent and committed management strategy has been defined as a prerequisite for the issuance of a green bond. To ensure lasting impact of the investment in green bonds, a company's management strategy towards decarbonisation is crucial. The disclosure and reporting requirements as outlined in Table 4.3 and Table 4.8 are important starting points to evaluate a company's management strategy, but this thesis lacks details on how exactly a company can be evaluated. In future research, developing clear, sector-focused guidelines would be very important to ensure transparency and effectiveness. For this, TPI's management review approach (Figure 4.5) could serve as a starting point.

Technology-related criteria

The technology-related criteria raise several issues. First of all, in the section focusing on mitigation options (4.3), accessing recent literature with a necessary level of detail has proven to be a major challenge. It is inherent to the concept of best available technologies that they are state-of-the-art, analysing reference documents that are even only a few years old is thus a major shortcoming. While this paper has only considered literature on technologies that are published after 2015, this factor nonetheless may limit the accuracy of the results. Therefore, the findings in Table 4.6 must be interpreted with caution. It has furthermore been a challenge to find quality data with a suitable level of detail. For example, it has been unclear in some cases to what reference value energy efficiency improvements have been compared. Those kinds of issues limit the accuracy of green bond criteria. For future research, it would be important to conduct primary research and expert interviews.

It is furthermore a major limitation that some mitigation options could not be quantified and therefore not properly be included in the criteria list. To properly include these options (Table 4.7), future work is required.

Importantly, the aim of this thesis has not simply been to develop criteria and benchmarks, but to ensure that the selected criteria lead to green bonds that are also transparent and effective. As touched upon in the previous section, several methodological choices aim to ensure transparency, such as establishing links to the most widely used reference frameworks. Yet, it is important to note that transparency of the criteria could be improved through further research. Ultimately, only testing of the criteria in practice is the only way to find out whether they are perceived as transparent.

In terms of effectiveness, this thesis offers mixed results. On the one hand, the technology-related criteria have been chosen very carefully, the analysis is mostly based on state-of-the-art literature. Adopting the "shades of green" approach by CICERO categorises the mitigation options in terms of effectiveness, aiming to offer additional nuances. Yet, it can be argued that the classification approach chosen for this paper has been too arbitrary, as it takes a variety of scenario modelling approaches into account. In future research, this can be overcome by conducting original and tailored scenario modelling.

It is also questionable whether all of the listed technologies should be included in the criteria list. Arguably, marginal improvements (e.g. by upgrading to BATs) is not enough to decarbonise the sector. One could argue that those process-related technology upgrades should not be included at all because they risk a carbon lock-in. More radical approaches (e.g. switching to 100% renewable energy) have certainly a bigger impact on the emission intensity. Yet, this paper has decided to also include marginal improvements with the assumption that any kind of improvement is better than none. However, emission reduction options that only offer marginal improvements need to be evaluated as to whether they are compatible with the sector's and company's path to reach sectoral benchmarks. Any useful green bond taxonomy should carefully avoid incentivising investments in stranded assets and carbon lock-in.

It is further important to highlight the fact that every plant is different, the mitigation options are highly context dependent. As aluminium production is very energy-intensive, the regional or national energy mix also has an impact on the emission reductions a technology can offer. While global applicability of green bonds criteria offers a variety of advantages, it may be necessary for the sake of accuracy to also conduct research into region-specific criteria.

Another crucial area for future research is the screening indicators for the final green bond taxonomy (Table 4.9). This paper has presented some indicators, but details were outside of the scope of this paper. Screening indicators are very important for the effectiveness of green bonds, and additional studies will be required to solely focus on this aspect.

Nonetheless, the technology-related criteria offer important insights into how investments under green bonds could steer capital in the direction of a low-carbon future.

6 Conclusion

6.1 Summary

The current emissions of the materials sector as a whole and the aluminium sector in particular are incompatible with the goals of the Paris Agreement. This paper suggests that green bonds (as one of a range of climate finance tools) could be developed and hence eventually contribute to raise capital for the decarbonisation of the sector. The literature review has revealed that to date, green bond criteria are not available for the materials sector. The objective of this thesis has been to address this research gap by proposing effective and transparent criteria for a green bond. The aluminium sector has been chosen as a case study. Elements of the green bond taxonomy by the Climate Bond Initiative and CICERO have been adopted. The research question and methodology have been developed with a research group at the DIW Berlin. As a result, this thesis proposes two complementary sets of criteria for the aluminium sector: one focused on management quality and one focused on technology options.

Overall, this study strengthens the idea that it should be feasible to develop a transparent, quantifiable and verifiable framework for green bonds in the materials sector. This paper has made important first steps to find out how criteria of a green bond can be developed, the aluminium sector has proven to be a suitable case study for this. Besides proposing two sets of criteria, the results add to the rapidly expanding academic field of green bonds. This thesis has provided deeper insight into how to develop green bond criteria, findings that may be useful for criteria developments in a variety of sectors.

6.2 Recommendations and future research

This study argues that transitioning the materials sector is of major importance to reach climate targets and prevent catastrophic impacts of climate change. As conventional approaches such as rules and regulations have not been powerful enough to transition the sector in the past, new approaches such as climate finance instruments need to be considered. The green bond market "risks implosion" if environmental integrity of green bonds through transparent criteria is not ensured (Shishlov, Morel, & Chochran, 2016). This thesis has made some first steps to address this issue, but procedures and clarity regarding green bonds must be standardised so that the market can develop further.

Here, not only obvious stakeholders such as companies, investors, and certification bodies play a crucial role. Exploring climate finance instruments is also important for players like governments, policymakers, and academia. As touched upon, those play a crucial role for establishing credibility and transparency of the instrument. The lack of academic literature on creating green bond criteria has been a major issue for this research. There is, therefore, a definite need for academia to start studying green bonds in more detail.

The discussion section of this paper has already touched upon important areas for future research. The lack of data on scenarios and mitigation options is especially pressing, as this kind of research is also important for decarbonisation strategies other than green bonds.

It is important to note, however, that several international initiatives, which have been consulted for this research, are already doing important work on the topic of green bonds, sectoral decarbonisation, and management approaches for low-carbon transitions. Therefore, the results of this thesis suggest that future collaborations between organisations such as the

Transition Pathway Initiative, the Science Based Target Initiative, the Climate Bond Initiative, and others are very important for the development of green bonds in the materials sector.

Green bonds as an instrument certainly have potential to support the low-carbon transition. It is important to note, however, that they are by no means a silver bullet solution. Building a low-carbon, sustainable and just future in which people and planet prosper requires strengthened efforts from all players including governments, producers, international institutions, consumers, and many more.

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