DOCTORAL THESIS

Embedding Environment and Sustainability into Corporate Financial Decision-Making: The Business Case for a Novel Carbon Capture Technology.

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Embedding Environment and Sustainability into Corporate Financial Decision-Making: The Business Case for a Novel Carbon Capture Technology

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ABSTRACT

This thesis is comprised of two main parts. The first part investigates the potential of a novel CO_2 sequestration method, carbon mineralisation, which utilises mineral waste from mine sites, namely mafic and ultramafic rocks. The idea is to utilise this method, seeing that the pledges made under the Paris Agreement force countries around the globe to search for pathways that help reduce the impact their economies have on climate change through their greenhouse gas emissions.

Chapter 3 looks at the potential of carbon mineralisation from an Australian perspective. Australia has a long history as a mining country and is one of the top worldwide producers of nickel. Furthermore, utilising feedstock from mining companies is ideal due to the granulated rocks which facilitate the chemical reactions. The mining feedstock potential from both abandoned and currently operational mine sites, as well as estimates from future reserves, are taken into account. The gathered data is then crossed with a CO_2 sequestration table, which identifies sub-types of mafic and ultramafic feedstock and their inherent potential for CO_2 absorption. It was found that a total of 2,171 Mt of CO_2 could be absorbed from nickel mine feedstock. Australia, with annual CO_2 emissions of approximately 500 Mt of CO_2, aims to reduce their output by twenty-six to twenty-eight percent by 2030. Using carbon mineralisation could serve as a contributor to decarbonise the Australian economy as part of an array of solutions.

Chapter 4 expands the search for ideal mine sites from Australian to a global scope and also includes kimberlite rocks, which host diamonds, due to their similar reactivity with CO_2. Here, a total of seventeen countries and 145 mine sites are assessed for their potential feedstock to facilitate the carbon mineralisation method. In addition, future estimates of nickel and diamonds are taken into consideration in order to give a more accurate estimate. Furthermore, a net present value (NPV) model with simple underlying assumptions is deployed in order to gauge the economic potential of this method. The global potential is estimated at 7,254 Mt of CO_2. Furthermore, the NPV model estimates a present value of approximately US$13.3 billion, assuming a price on carbon of US$20, with a break-even of US$7.311.

Chapter 5 consists of the second part of this thesis and looks into reasons and obstacles that prevent firms from adopting methods such as carbon mineralisation.

Building on insights gained from the literature review, a model is developed that aims at overcoming said obstacles and enable firms to take a long-term view. Having adequate executive compensation systems, moving away from quarterly reports as well as utilising adjusted decision-making models, would enable the firm to embed sustainability. It is recognised that in the absence of clear, governmentally mandated rules and regulations, it is the informal institutions that become more relevant, manifested through individuals that push firms to become industry leaders.

KEYWORDS

CO_2, Carbon Mineralisation, Corporate Social Responsibility, CSR, Carbon Markets, Carbon Capture and Sequestration, CCS, Sustainability, Decision-making, Short-termism.

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G18, G31, H41, L72, P28, Q01, Q15, Q28, Q51, Q54, Q55, Q57

DECLARATION BY AUTHOR

This thesis is submitted to Bond University in fulfilment of the requirements of the degree of Doctor of Philosophy.

This thesis represents my original work towards this research degree and contains no material that has previously been submitted for a degree or diploma at this university or any other institution, except where due acknowledgement is made.

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ABBREVIATIONS

Carbon Capture and Storage	CCS
Carbon Dioxide	CO2
Carbon Dioxide Equivalent	CO2e
Enhanced Gas Recovery	EGR
Enhanced Oil Recovery	EOR
Intergovernmental Panel on Climate Change	IPCC
Greenhouse Gasses	GHG
European Union	EU
28 countries in the European Union	EU28
Gigagram, 1,000,000 kg or 1,000 metric tonnes	Gg
Gross domestic product	GDP
Net present value	NPV
Social cost of carbon	SCC
Emission trading system	ETS
Weighted Average Cost of Capital	WACC
United Nations Framework Convention on Climate Change	UNFCCC
(Intended) Nationally Determined Contribution	(I)NDC

GLOSSARY

CCS	Carbon capture and storage is the process of capturing carbon dioxide from large point sources, such as power plants or factories and transporting it to a CO_2 storage site. Here, the CO_2 can be deposited in a way that it will not enter the atmosphere. This could be a saline aquifer, a depleted oil and gas field, or an underground geological formation.
EGR / EOR	Enhanced Oil and Gas Recovery through gas injection, thermal injection, or chemical injection to extract oil or gas that cannot otherwise be extracted. Gas injection, which uses gases such as natural gas, nitrogen, or carbon dioxide (CO2), accounts for nearly sixty percent of EOR production in the United States
INDC / NDC	INDCs are Intended National Determined Contribution. They are country-specific post-2020 climate action commitments made in the lead-up to the 2015 climate conference. With the ratification of the Paris Agreement, the INDC turned into Nationally Determined Contributions (NDC).
IPCC	The Intergovernmental Panel on Climate Change is an intergovernmental body of the United Nations dedicated to providing the world with an objective, scientific view of climate change and its political and economic impacts.
SCC	The marginal economic damage cost to society associated with the release of CO_2 or other Greenhouse Gasses.
Paris Agreement	A global agreement within the United Nations Framework Convention on Climate Change (UNFCCC) that deals with the mitigation, financing and adaptation of GHG emissions, ratified by 185 parties.

Chapter 1: Thesis Introduction

1.1 Introduction

Society faces an environmental problem with a constantly warming planet caused by increasing CO_2 concentration in the atmosphere (Metz et al., 2005; NASA, 2016). Anthropogenic greenhouse gas (GHG) emissions cause an externalised cost borne by society and not by the emitter (Linnenluecke et al., 2016; Stern, 2007). The majority of countries committed to reducing their GHG emissions at the Conference of the Parties (COP21) in Paris in November 2015, henceforth called the 'Paris Agreement' (UNFCCC, 2015b). The emission reduction goals were defined on a country-specific basis (Meinshausen and Alexander, 2017; UNFCCC, 2015a; World Resources Institute, 2015). The Paris Agreement officially came into play by November 2016, after it had been ratified by at least fifty-five parties which contribute at least fifty-five percent of the worldwide emissions (UNFCCC, 2017a).

The Paris Agreement is a consequence of the conclusion mentioned above that warming the planet causes a cost to society (Linnenluecke et al., 2016; Stern, 2007). Therefore, the marginal social cost of carbon per additional quantity of GHG emitted or prevented can be derived. The loss in net social welfare, based on various models, assumption and time frames, ranges from US$9 up to US$220 (Kelly and Marshall, 2010; Moore and Diaz, 2015; Murphy, 2009; Tol, 2011, 2013). Due to the absence of a clear, consensual and legally binding framework, resulting in mostly absent or broken carbon markets, firms lack the knowledge on how to value carbon and how to incorporate the currently externalised cost into their financial decision-making framework. Subsequently, there are no clear incentives to stop, reduce or optimise emissions, which leads to the creation of a circular problem: firms continuing to emit emissions due to the absence of a framework for the valuation of carbon and therefore, emissions levels continue to rise.

Australia has pledged to reduce its GHG emissions twenty-six to twenty-eight percent by 2030, while not impeding a two percent annual economic growth (Denis et al., 2014b). This grand challenge to reduce global emissions while simultaneously keeping up economic growth will not be solved on a global level as a whole but needs to be broken down into a three-tiered approach. First of all, a globally unifying goal needs to be established on a high-level. Putting the Paris Agreement into effect was a

step in the right direction, as previously mentioned (UNFCCC, 2015b). Secondly, each country is given the authority to define their individual goals as well as create specific pathways to achieve said goals. The Paris Agreement gave countries, such as Australia, the freedom of identifying various methods to achieve their self-set goal on how to decarbonise their economies, laying out various pathways that includes a wide range of methods (Australian Government, 2015b; Deep Decarbonization Pathways Project (2015), 2015; Denis et al., 2014a; Sachs and Tubiana, 2014). Thirdly, the national approach is further divided into industry and firm levels. The thesis recognises that while pivotal change can be achieved on a firm level, the initiatives need to stem from choices and strategies made by individuals. This change can come in various forms and is spurred through pressure along the value chain from various stakeholders such as clients, producers, legislators and policymakers. A focus lies on the individual executives at a firm-level who can evoke ground-breaking change and turn a firm into an industry leader, shaping the institutional sphere as a whole and incentivise an entire industry to follow suit.

The mining industry, which is responsible for ten percent of energy consumption in Australia, inclusive of fossil fuels (Australian Government, 2018a; SunSHIFT Pty Ltd., 2017), is considering utilising carbon mineralisation to tackle its emission contributions. This method, discussed in detail in the literature review, has the potential to 'genuinely and permanently sequester the necessary quantities of CO_2 for centuries' (Burgess et al., 2011). However, the usefulness of the carbon mineralisation method for human or industrial timescales is impeded due to the slow absorption speed of CO_2 (Zevenhoven et al., 2011), and has since been dismissed as a contributor to the decarbonisation of economies (Deep Decarbonization Pathways Project (2015), 2015). Applying heat and pressure can speed up the absorption rate. Unfortunately, the costs associated with this method renders the process economically unviable (Zevenhoven et al., 2011). A developing technology that uses naturally occurring soil bacteria (Cyanobacteria) to induce and accelerate the carbon mineralisation process without the need of external energy sources overcomes many of these obstacles (Power et al., 2009). Building on these novel sequestration methods, this thesis aims at understanding what the potential and usefulness of the carbon mineralisation process are, and what the current obstacles in the firm's financial decision-making framework are which prevent them from valuing and incorporating carbon.

1.1.1 Motivation

Academic motivation

This thesis aims to understand the underlying reasons why firms continue to underestimate the potential inherent in a particular carbon dioxide sequestration technology that has the potential to absorb substantial amounts CO_2 and store it safely for centuries. However, real options dictate, that there are situations where firms are better of to delay investing into carbon sequestration, seeing that in most countries, such as Australia, CO_2 regulations are not particularly strict, despite being one of the top-polluter on a per-capita basis (Schiermeier, 2014). In this case, the absence of governmental or competitive pressure, firms can economically justify a delayed investment approach with high pioneering cost and uncertain outcomes of the first-mover advantage (Boulding and Christen, 2003). Real options are discussed in chapter 2.3.3. Furthermore, due to the absence of prices on carbon or broken carbon markets, it is perfectly justifiable for companies to buy carbon certificates in the short run until the market has corrected. This topic is further discussed in Chapter 2.2.5.

Carbon mineralisation, however, appears to be a potentially viable future investment for the abatement of CO_2 emissions, apart from being a useful and inexpensive method for the rehabilitation of abandoned mines. While various articles (Fagerlund and Zevenhoven, 2011; Power et al., 2007; Pronost et al., 2011; Wilson et al., 2006) describe both the natural mineral carbonation process as well as the artificially-induced method (accelerated carbon mineralisation), there is a lack of research quantifying the economic impact of bacterially-mediated method of sequestering CO_2.

This thesis aims to investigate what the country-specific potential is to absorb CO_2 via carbon mineralisation. Picot et al. (2011) assess the worldwide potential for ex-situ mineral carbonation and identifies eight major mine sites that are within a 300-kilometre radius of a large CO_2 point source (>1 megaton of CO_2 per year). However, the self-imposed restrictions of having to be within a sizeable CO_2 point source narrows potential mine sites tremendously. Moreover, the carbonation methods discussed by Picot et al. (2011) use heat and pressure, which vastly differs economically from the biologically-induced method discussed in this thesis. Bodéan et al. (2014) describe how mineral waste could be used to sequester large amounts of CO_2. However, their

paper also assumes the utilisation of heat and pressure to facilitate the chemical reaction (aqueous direct carbonation of rocks). Their article concludes that this method could be used as an addition to pumping and storing CO_2 underground, which is considered to be the 'traditional' carbon capture and storage (CCS) method.

This thesis aims at closing some gaps in the literature. In particular, research needs to be done to estimate the sequestration potential from mineral waste resulting from mine site operations accurately. This thesis will focus on nickel and diamond mines. The first chapter investigates the Australian potential while the second chapter estimates carbon sequestration feedstock (suitable material) on a worldwide scale. Traditional carbon mineralisation methods have previously been dismissed as a means to help decarbonising economies (Burgess et al., 2011). However, marginal changes in the process, such as bacterially mediated carbon mineralisation, might justify a reassessment of this method.

Societal innovation

From a governmental and policy-making perspective, the motivation of this thesis is to understand to what degree carbon mineralisation could contribute to the decarbonisation of an economy. As stated in the introduction, Australia's goals are to implement 'an economy-wide target to reduce greenhouse gas emissions by 26 to 28 per cent below 2005 levels by 2030' (Australian Government, 2015b). When taking population growth into account, this represents an approximate cut of fifty percent in emissions per capita and a sixty-five percent reduction per unit of GDP by 2030 (Australian Government, 2015b). Australia plans to tackle this reduction of emissions via a portfolio of policies. Amongst others, it plans to decarbonise its energy production by promoting the deployment of renewable energy as well as the overall improvement of energy efficiency. Part of the solution is the National Energy Productivity Plan, which targets to improve productivity by forty percent between 2015 and 2030 (Australian Government, 2015b).

The Deep Decarbonization Pathways Project (DDPP), which published the 'Pathways to Deep Decarbonization Report' (Deep Decarbonization Pathways Project (2015)), is a collaborative global research initiative which develops individual pathways for its member countries so they can transition to a low-carbon economy from a technological, socio-economic, and policy perspective. The decarbonisation of

electricity is a longer-term proposition. DDPP envisions reducing the carbon content of all energies: electricity, heat, liquids, and gases. Aside from switching to renewable energy (hydro, wind, solar and geothermal), the report also proposes combining fossil fuel energy production with CCS.

Carbon mineralisation, which is also considered a CCS method, has the potential to be a substantial contributor to the decarbonisation of a country with adequate feedstock from mine sites. However, due to the aforementioned unfavourable energy economics, it has been largely dismissed as a means to be an effective and cost-efficient contributor. Seeing how novel approaches to overcome said obstacles have emerged, carbon mineralisation could become a useful instrument for governments to support their CO_2 reduction goals. This thesis aims at giving an insight into the CO_2 sequestration potential on a country-specific basis on the back of adequately identified nickel and diamond mine site feedstock.

The primary motivation from an industry and firm perspective are to push smart decisions. The thesis researches why projects, such as mineral carbonation, are not on the radar of mining firms that emit large amounts of CO_2. It highlights the opportunity costs of deploying carbon mineralisation on otherwise fallow mine tailings, utilising them to make mining operations carbon-neutral or even carbon sinks. In doing so, this would not only support a country's goals to decarbonise an economy but also serve as a marketable 'green mining' feature that could contribute to the betterment of the overall public impression of the mineral industry. The thesis aims at understanding what is necessary with regards to policy and incentives to spur investments into this technology.

1.1.2 Structure

This dissertation presents an extensive literature review as well as three main chapters, each with an introduction, methods, and findings. The author has decided to structure the thesis in a way that identifies the sequestration potential of this novel approach on a local and global level via chapter 3 and 4 first. After that, chapter 5 offers insights as to why companies fail to incorporate the said sequestration method and identifies current roadblocks as well as pathways forward.

Chapter 2 is the literature review, which is split into two parts. The first part

revolves around the conundrum on how to build a rationale for a price on carbon as a consequence of social costs currently borne by society. Social cost of carbon (SCC) suggests that preventing CO_2 from emitting, or sequestering previously emitted CO_2, can be assigned a value. Having appropriate policies to ensure a price on carbon lead to the creation of carbon markets, a concept that currently seems broken or insufficient for existing markets. Furthermore, current and proposed economic instruments, as well as solutions to tackle the emissions, are identified. Carbon sequestration methods are examined as are existing technologies and methods that are currently used or planned to tackle the sequestration of CO_2 in various ways. The method of utilising feedstock from past and future nickel and diamond mine sites is also explored.

The second part of the literature review revolves around corporate financial decision-making. Here, a comprehensive review of existing literature is given to understand the theory of the firm as well as the goals of the firm. The drivers of short-termism and the surrounding literature are explored. It identifies critical reasons that support the current, unsustainable business model, preventing firms from investing in such methods as carbon mineralisation. Furthermore, the changing context in corporate sustainability, with its increasingly holistic approach encompassing various stakeholders, is addressed.

Chapter 3

Main question

What is the total CO_2 sequestration potential via a novel mineral carbonation method from Australian nickel mine sites?

Outcome

This chapter analysed a total of 23 nickel mine sites across Australia. This subset of mine sites was utilised and extrapolated to quantify the total Australian feedstock. In doing so, the sequestration potential via mineral carbonation is quantified at 2.171 Gt of CO_2. To put this into perspective, Australia's annual CO_2 output was quantified at approximately 0.5 Gt of CO_2 in 2016.

Recommendations

Australia's pledge to reduce its emissions will require a multitude of solutions to help achieve that goal. This chapter highlights that CO_2 sequestration via this novel mineral carbonation method shows potential to be part of the solution and make sizeable contribution.

This chapter is dedicated to the Australian potential of carbon mineralisation as

a mean to improve the sustainability of the mining industry. This chapter addresses a theoretical gap which has been identified in the literature, as there is data of Australian (or worldwide, see chapter 4) nickel mine sites with estimates of their CO_2 sequestration potential. The geological setting of Australia, in combination with its extensive historical and current mining activity, poses an ideal setting for the estimation of sequestration feedstock. Tailings from mine sites are leveraged since during the process of extracting the precious minerals, the mafic and ultramafic rocks, necessary for the carbon mineralisation process, are conveniently crushed up. Granulated rocks are ideal as they facilitate the CO_2 absorption rate during the process. For the data collection, therefore, key nickel mine sites were identified, which include both active and abandoned mines, beginning with the largest to cover as much of the potential as possible. In order to estimate the sequestration potential with high confidence, the geological setting of the subtype of rocks at every mine is analysed and researched individually, to establish their compatibility with the carbon mineralisation process. Due to the secretive nature of the mining industry and the scarce publicly available resources, the author of the thesis had to rely on a multitude of scientific geological journal articles, company announcements, governmental site surveys as well as lexica and various atlases.

Identifying the main geological composition of each mine on an individual basis is an arduous, essential and necessary step, due to the individual reactivity of feedstock of the geological hosting. Once all suitable sites have been identified and geologically categorised, the past and future feedstock are estimated using similar sources as described above, which are then crossed with a sequestration conversion table, determining how much feedstock of each subtype of rocks is necessary to sequester one tonne of CO_2. In doing this, a total of 23 mine sites have been deemed useful and were assessed for their potential. When extrapolating from this subset of mine sites for the total Australian feedstock of suitable material, the sequestration potential is quantified at 2.171 Gt of CO_2.

Chapter 4

Main questions

What is the worldwide total CO_2 sequestration potential via a novel mineral carbonation method from nickel and diamond mine sites?

What is the net present value of the worldwide sequestration potential, assuming a price on carbon of USD 20 and what is the break-even price on carbon?

Outcome

This chapter analysed a total of 145 nickel mine sites across more than 17 countries. Extrapolating from this subset of mines to estimate the total available feedstock, the sequestration potential via mineral carbonation is quantified at 7.254 Gt of CO_2. The financial model returns a net present value of USD 13.289 billion, with a break-even price on carbon of USD 7.311.

Recommendations

Australia's pledge to reduce its emissions will require a multitude of solutions to help achieve that goal. This chapter highlights that CO_2 sequestration via this novel mineral carbonation method shows potential to be part of the solution and make sizeable contribution.

Chapter 4 builds on the data collection methods utilised and described in more detail above, under chapter 3 introduction. In addition to the Australian sequestration potential, the largest nickel mine sites from around the world are identified. While the Australian data collection was an arduous process, the worldwide data proved to be even more difficult. In part, this was owed to the fact that all countries have different obligations with regards to the publication of mining data. The assessment of global nickel mine sites by Mudd (2014) proved to be a great starting point, facilitating the overall selection of sites, as they are categorised by total output and estimated reserves. A total of seventeen countries and 145 mine sites are assessed for suitable feedstock for the carbon mineralisation process. Aside from nickel, diamond mines (kimberlite rock) are assessed due to their ideal CO_2 sequestration potential. Additionally, this chapter introduces a simple net-present-value (NPV) model to understand the financial viability of the carbon mineralisation method. In order to estimate the economic impact of said sequestration method, a present monetary value is derived assuming a hypothetical price on carbon.

When extrapolating from this subset of worldwide mine sites, including the total Australian feedstock identified in chapter 3, the sequestration potential is quantified at 7.254 Gt of CO_2. Furthermore, the carbon pricing model estimates an NPV of USD

13.289 billion, with a break-even cost of carbon of USD 7.311.

Chapter 5

Main questions

What are the main drivers of short-termism that prevent the firm from implementing sustainability into their corporate financial decision-making framerwork?

What suggestions to the business case can be made to focus on the long-term creation of sustainable shareholder value?

Outcome

Mapping the business case for embedding environment and sustainability onto four underlying value drivers, namely, cost-reduction through efficient resource utilisation, revenue enhancement, risk management and the valuation of intangible assets. However, executives often adopt a short-term perspective which is owed to executive compensation, investor pressure and outdated decision-making criteria.

Recommendations

Chapter 5 proposes an integrated framework that highlights how companies could embed environment and sustainablity into their long-term financial decision-making framework:

I) Longer-term executive compensation systems
II) Longer-term financial reporting
III) Modified financial decision-making models that embed intangible values

Chapter 5 identifies key reasons that prevent the firm from embedding sustainability into their existing corporate financial decision-making framework. Assuming that the goal of the firm is the creation and maximisation of long-term shareholder value, various myopic factors, such as management compensation and quarterly pressure, lead executives to make decisions that undermine the long-term vision of said goal. This chapter suggests a sustainable business model that is built on four main pillars (revenue, expenses, risks, and intangible values) as proposed by Esty and Winston (2009). Furthermore, key measures that can be taken to encourage executives to adopt a longer-term perspective to create sustainable shareholder value are identified.

Chapter 2: Literature Review

2.1 Introduction to the Literature review

Calls for a price on carbon continue to emerge following the Paris Agreement (Grantham Research Institute, 2017; Swartz, 2016; Tuck, 2016; UNFCCC, 2015b). In order to be prepared for the challenges ahead, firms need to understand how to value carbon and be aware of potential abatement solutions within their respective economic realms. In doing so, firms can build resilience and create long-term value for shareholders (Linnenluecke et al., 2015; Winston, 2017). The literature review aims to understand how firms can better integrate sustainability into financial decision-making.

The first part explores the idea that society in general, and on a firm-level specifically, 'the lack of willingness to value carbon,' as its price and incorporation are ambiguously represented in the political and legislative landscape. On a macro-level, the task needs to be addressed two-fold: first, there is the revenue-side that can be derived from establishing a price on carbon. Enforcing a price on carbon can be done via various methods which will be explored. Secondly, the question needs to be raised as to what solutions can be utilised to tackle the absorption of GHG emissions from a practical point of view. Here, a brief historical overview of GHG emissions is given, as well as various practical absorption methods that could help facilitate the transition to a more decarbonised economy. A particular focus will be on carbon mineralisation as well as the bacterially mediated variation. Understanding both the revenue and cost side and also the practical application of absorbing emissions could help raise societal awareness of the problem while simultaneously giving firms a better insight and understanding on how to fit carbon pricing into their corporate financial decision-making framework.

The second part of the literature review gives insights into short-termism behaviour that is prevalent and fostered in the current landscape of the firm (Winston, 2017, 2018a). It identifies various points of friction that might prevent the implementation of a price on carbon into the corporate financial decision-making framework of firms and could subsequently lead to the decarbonisation of the economy. On a micro-level, various realms are identified and described with regards to their contribution to the ongoing short-termism. The individual, the firm, and the institutional realm all play a significant role. Intersections of these realms are identified, and the caused friction is researched within the literature. A particular focus is put on the

individual, as it is seen as a significant factor to drive change towards a more sustainable business model which encompasses all stakeholders (Ernst & Young, 2017a; Fink, 2018; UNFCCC, 2015b).

2.2 Part 1: How to Value and Absorb Carbon Dioxide

With the Paris Agreement ratified, countries are exploring solutions to start decarbonising their economies to reach their intended, albeit non-binding, country-specific goals (Denis et al., 2014a, 2014b; UNFCCC, 2015b). Having achieved the first important step, a unifying framework and agreement on a global level, solutions need to be broken down to local and firm-specific goals to evoke adequate results. The reasoning is that due to the diverse nature of economies, countries, states, and regions, it is necessary that decarbonising incentives, such as taxes, subsidies, or prices on carbon, are adjusted to fit the respective economies and industry-landscapes. The economic incentives proposed come in the form of subsidies or taxes to change individual and firm behaviour, spur innovation, increase efficiency, or prevent emissions (Pachauri and Meyer, 2014).

Furthermore, there is an array of practical solutions available to sequester CO_2 to deal with undeterrable emissions (Metz et al., 2005). Seeing that there are currently no unified global solutions to tackle emissions as well as no unified, global price on carbon (See: 2.2.6 and Table 4), these absences leads countries to struggle to find adequate legislation to tackle the problems. The scenario of missing global prices on carbon resembles the prisoner's dilemma, whereby rational parties do not choose to cooperate although it would be in their best interest to do so (Axelrod, 1980). Free-riding under global CO_2 abatement is problematic since governments that choose not to participate still get to enjoy the efforts of other governments without incurring any expenses. This problem arises for both rich countries that have the political power to disagree with the consensus (such as the United States of America withdrawing from the Paris Agreement), as well as with emerging countries, who can justify their non-participation through a lack of resources (The Economist, 2007; UNFCCC, 2017c). Firms find themselves in a situation that makes it hard to price carbon and subsequently incorporate it into their financial decision-making framework. Therefore, emissions continue to rise.

Here, the literature review explores the rationale behind a price on carbon and why SCC is an externality that subsequently should be treated in a pay-as-you-pollute manner (Ackerman and Stanton, 2012; Hänsel and Quaas, 2018; Tol, 2011). Furthermore, some of the current global solutions are analysed, both from a perspective as economic instruments as well as from a practical point of view on how to sequester CO_2. Moreover, the topic of carbon mineralisation, a promising method with an abundance of storage capacity for CO_2, is examined to understand whether it could serve as a means to support the decarbonisation goals of some economies. Lastly, the literature examines why understanding the potential of the carbon mineralisation method is relevant, how it compares to other ways of sequestering CO_2, and what the driving motivation for its utilisation could be.

2.2.1 Paris Talks

The 2015 United Nations Climate Change Conference was held in Paris, France (Paris Talks). It was the 21st session of the Conference of the Parties, referred to as COP21 (UNFCCC, 2015b). Participating countries negotiated a global agreement on the reduction of climate change, named 'Paris Agreement.' Before the conference, countries submitted their 'Intended Nationally Determined Contributions' (INDCs): national climate action commitments intended to achieve overall objectives of reducing GHGs (UNFCCC, 2015a). Australia's 2015 INDCs state a commitment to reduce greenhouse gas emissions by twenty-six to twenty-eight percent below 2005 levels by 2030 (Australian Government, 2015b). Taking population growth into account, this represents an approximate cut of fifty percent in emissions per capita and a sixty-five percent reduction per unit of GDP by 2030 (Australian Government, 2015b).

Together, with all other policies currently in place worldwide, the mean temperature would increase by +3.4˚C (+/- 0.9˚C) in 2030, whereas with the pledged (I)NDCs, the increase is projected to be +3.2˚C (+/- 0.9˚C); both scenarios are well above the Paris Agreement, which states an increase of +2.0˚C (Climate Action Tracker, 2017; UNFCCC, 2017a). Before the agreement, each country defined specific goals to reduce emissions. The agreement officially entered into force after at least 55 countries representing a minimum of fifty-five percent of global emissions joined the Paris Agreement, which was achieved in November 2016 (UNFCCC, 2017a).

2.2.2 Greenhouse Gas Emissions

Systematic measurement of CO_2 concentration started in 1958, with levels around 315 parts per million (ppm) while pre-industrial revolution levels were estimated to be 278 ppm in 1750 (Australian Bureau of Meteorology, 2018; Indermuehle et al., 1999). However, with the advent of the industrial revolution, CO_2 levels started to rise rapidly, averaging at 410 ppm in April and May 2018 (NOAA, 2018). The level of 400 ppm is seen as a critical physical barrier, and scientists argue that this might be the point of no return once this barrier is broken (NOAA, 2016b). If humanity wants to preserve a planet on which our civilisation developed and to which life is adapted, it is suggested that the CO_2 concentration needs to be reduced to 350 ppm or less (Hansen et al., 2008).

Annual anthropogenic (human-made) CO_2 emission from fossil fuel burning and industrial processes increased to an all-time high of 35.3 billion tonnes of CO_2-e in 2013, which is approximately double the amount from 1970 (Olivier et al., 2014). The average annual growth rate was 1.93 percent over the last forty-three years. Table 1 shows the most significant emitters (EU28, USA, China and Australia) of 2013, which accounted for approximately 19.2 billion tonnes of CO_2 which is the equivalent of more than half (fifty-five percent) of total global emissions in said year.

Table 1: Emissions Data by Country

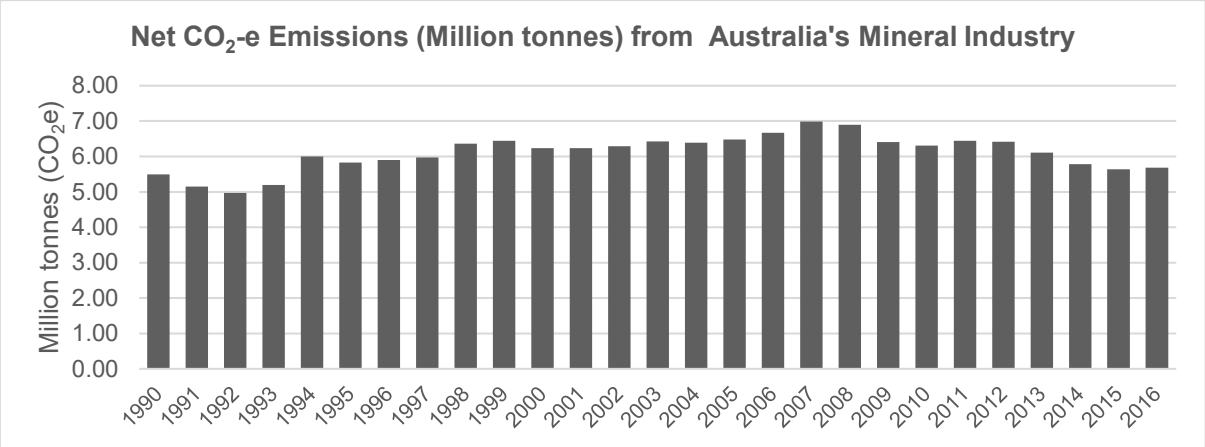
Country/Region	Total Emission of bn tonnes CO_2	Emissions share in %	Emissions per Capita	Average growth rate per capita (2003-13)
USA (2013)	5.3 bn	15%	16.5 tonnes	-1.85%
China (2013)	10.3 bn	29%	7.4 tonnes	8.12%
Australia (2016)	0.5 bn	1.5%	21.6 tonnes	-1.01%
EU28 (2013)	3.7 bn	11%	7.4 tonnes	-1.62%

(Australian Government, 2017c; Olivier et al., 2014; The World Bank, 2014)

While China and the EU28 have very similar emissions per capita, their average growth rates over the last decade differ largely. China has been growing at more than eight percent per annum, while the EU28 had a negative growth rate. The USA and Australia have both very high per-capita emissions, with Australia having one of the highest in the world. The USA has a per-capita which is more than double compared to China, while the USA, EU and Australia all have negative growth rates (Olivier et al., 2014; The World Bank, 2014).

Australia's emissions in 2016 were 532 million tonnes of CO_2e, a share of approximately 1.5 percent globally (Australian Government, 2017c). However, on a per-capita basis, primarily owed to the extensive use of coal for electricity-generating purposes, Australia claims one of the top-polluter ranks globally (Schiermeier, 2014). The mining industry is of particular interest, being a significant polluter in Australia, accounting for approximately ten percent of Australia's energy consumption (SunSHIFT Pty Ltd., 2017). The methods explored in this thesis aim at giving the mining industry the capacity to become a net sink for CO_2 emissions via carbon mineralisation (See section 2.2.8). In 2016, the Australian Department of the Environment and Energy attributed 5.7 million tonnes of net CO_2e emissions to the Australian mineral industry, approximately 1.1 percent of the country's emissions (Australian Government, 2017c). Figure 1 below shows the development of emissions of the mineral industry over time.

Figure 1: CO_2e emissions from the mineral industry in Australia



(Australian Government, 2017c; IEA, 2015)

All gases that trap heat in the atmosphere are classified as greenhouse gases (GHGs). The most common ones which originate from human activities are carbon dioxide (CO_2, which is most widely discussed in this thesis), methane (CH_4), nitrous oxide (N_2O) (EPA, 2016). The reason these various greenhouse gases are distinguished is due to their difference in effect on the atmosphere. The concentration (e.g., ppm), the lifespan (ranging from a few months to a few thousand years) as well as their impact (See Global Warming Potential below) are of importance. Methane and hydrofluorocarbons, known as Near-Term Climate Forcers (NTCFs), contribute strongly to global warming even though they do not last very long, as they trap relatively

more heat (Salter and Yuill, 2016).

CO_2 enters the atmosphere through various channels: burning fossil fuels, industrial processing such as cement manufacturing, wood products, and others. On the other hand, CO_2 is removed through plants and wooden products, through the (bio)geological carbon cycle where it is formed into carbonate minerals. Approximately a quarter of CO_2 released into the atmosphere every year dissolves in the oceans, contributing to ongoing acidification (NOAA, 2016a). Methane gets released into the atmosphere because of livestock and agricultural practices, thawing permafrost, as well as through the production and transportation of coal, natural gas, and oil. Fluorinated gases are synthetic gases that are amongst the most potent and harmful GHGs. These are emitted from a range of industrial activities (EPA, 2016). Table 3 depicts the share of each gas for global emissions in 2014.

The 'Global Warming Potential' (GWP) is a relative measure to indicate how much heat GHG traps in the atmosphere by comparing the amount of heat trapped by the respective mass of gas to the amount of heat by an equivalent mass of CO_2. Therefore, in the example of methane, the net effect of the shorter lifetime and higher energy absorption is reflected in a higher GWP. CO_2, as the baseline, has a GPW 1 across all timelines. Since GWP is calculated relative to CO_2, GWPs based on a shorter timeframe will be more significant for gases with lifetimes shorter than that of CO_2, and smaller for gases with lifetimes longer than CO_2 (EPA, 2017). Derived from the baseline, a range of GWP values for some GHG have been calculated in Table 2: Global Warming Potential, including a specific time interval potential over the long run (Elrod, 1999; Metz et al., 2005). Therefore, the GWP takes into consideration how fast the GHG decays over time. If a gas decays fast, it may initially have a more significant effect but will fade quickly. In the table below, methane has a higher GWP (56) during the first twenty years and a lower GWP over one hundred years (28). On the other hand, sulphur hexafluoride, which has a residence of ca. 3200 years, has an increasing GWP from 20 (16,300) to 100 (22,800), to five hundred (34,900) years (Stocker et al., 2014). It is crucial noting that the GWP values have changed over time as new evidence and scientific measurements have arisen (Greenhouse Gas Protocol, 2016; UNFCCC, 2014).

Table 2: Global Warming Potential

GHG	Lifetime in years	GWP		
		20 years	100 years	500 years
Carbon Dioxide	variable	1	1	1
Methane	~12	56	28	6.5
Hydrofluorocarbon (F-gas)	14.6	3400	1300	420
Nitrous oxide	120	280	265	170
Sulfur hexafluoride (F-gas)	3200	16,300	22,800	34,900

(Stocker et al., 2014; UNFCCC, 2014)

Reports, journal articles, and statistics often mention CO_2e, which is the CO_2 tonne equivalent to help increase readability and comparability across all GHGs. This is achieved by converting all GHG into the equivalent of carbon dioxide, by multiplying the tonnage by the GWP, usually with the twenty years or one hundred years coefficient (See Table 3). Note, GHG emissions typically do not include water vapour, the most abundant greenhouse gas in the atmosphere (NOAA, 2016c). As an example, from Table 2 and Table 3, it can be derived that the effect of releasing one tonne of methane into the atmosphere at GWP100 is 28-fold compared to releasing one tonne of CO_2.

Table 3: GHG emissions by gas (2014)

Gas type	Percentage	Gt effective	GWP	Gt CO_2e (GWP100 years)
Carbon dioxide (Fuel & Industry)	65%	31.9	1	31.9
Carbon dioxide (Forestry & other land use)	11%	5.4	1	5.4
Methane	16%	0.282	28	7.9
Nitrous oxide	6%	0.011	265	2.9
F-gases	2%	0.00005	20,000 (average)	1.0
Total	**100%**	**37.59**	**-**	**49.10**

(Edenhofer, 2014; EPA, 2016; Greenhouse Gas Protocol, 2016)

2.2.3 Effect of Greenhouse Gas Emissions

Over time, the theory has been refined. However, almost all scientists have reached the same conclusion: releasing greenhouse gases into the atmosphere warms up the Earth (NASA, 2016):

The Third Assessment Report (TAR) by the Intergovernmental Panel on Climate Change (IPCC) stated that 'there is new and stronger evidence that most of the warming observed over the past 50 years is attributable to human activities' (Metz et

al., 2005). It went on to point out that 'human influences will continue to change atmospheric composition throughout the 21st century.' The most significant contribution from human activities is carbon dioxide (CO_2). It is released into the atmosphere through the combustion of fossil fuels such as coal, oil, natural gas, and renewable fuels like biomass. It is also released by the burning of forests during land clearance and from certain industrial and resource extraction processes. As a result, 'emissions of CO_2 due to fossil fuel burning are virtually certain to be the dominant influence on the trends in atmospheric CO_2 concentration during the 21st century' and 'global average temperatures and sea level are projected to rise under all scenarios' (Metz et al., 2005).

There is disagreement on how much of a contributor global warming is, an issue that is referred to as 'climate sensitivity,' the amount by which the temperature will increase if CO_2 is doubled compared to pre-industrial levels (Pachauri and Meyer, 2014). Climate models predict up to plus 4.5°C versus pre-industrial levels with less than plus 1.5°C being highly unlikely (Pachauri and Meyer, 2014). Furthermore, climate feedback effects are observed, which accelerate ongoing climate change. The melting of the ice caps can serve as an example: while the rising temperature warms the ice and the extent of the ice caps reduce over time, more water is subsequently released. With the expansion of open water, more of the sun's energy is absorbed, further raising the temperature and accelerating the effect (Stocker et al., 2014). Moreover, the rising temperature induces releases of CO_2 from the biosphere as well as methane from permafrost, which is the carbon-cycle feedback (Stocker et al., 2014).

The background on GHG emissions and their causing effect on climate change build a segue into the following section about a price on carbon. Here, the negative and potentially positive externalities that derive from changes in climate change are assessed and quantified. Due to their overwhelming net-negative external effect, a price on carbon has often been called into existence around the world, which was further confirmed by the Paris Agreement. Implementing a price on carbon has the intention to curb emissions and establish a pay-as-you-pollute principle.

2.2.4 Price on carbon

The following section discusses the need for and determinants of carbon pricing. The social cost of carbon is explained and explored, providing insights and reasoning as for the need for internalising the net-negative cost to society. The literature is in disagreement about the true price on carbon, producing various estimates ranging from approximately US$10 to US$220. Furthermore, this part looks at the net-negative economic implications of climate change, considering both positive and negative effects. As a consequence of having a price on carbon, said costs are eventually passed onto the end consumer, who would potentially see an overall increase in prices of goods and services. This is explored in one sub-section to gain an appreciation of the true cost of economic activity if priced by their emissions. Furthermore, to give a holistic view of this section, a critical perspective questioning a price on carbon is added as well.

It needs to be made clear that while prices on carbon have existed in some countries as early as 1990, there is yet little evidence of economic effects on a global scale. Most economic models are based on theoretical assumptions with unknown implications for global trade, productivity, and economically hierarchical consequences for countries and regions. These are some of the reasons why it is politically difficult to impose a carbon tax on a country or region as has been exemplified in the Australian case (See 2.2.5).

Furthermore, the case against a price on carbon can be made. Patt et al. (2018) argue that the time for having a price on carbon has passed, suggesting focusing on policy, infrastructure, and technology instead.

Rationale for a price on carbon

‘The world’s transition to a low-carbon and climate-resilient economy is the story of growth for this century,’ said Carbon Price Leadership Coalition (CPLC) co-chairs Joseph Stiglitz and Nicholas Stern. ‘We’re already seeing the potential that this transformation represents in terms of more innovation, greater resilience, more liveable cities, improved air quality and better health. Our report builds on the growing understanding of the opportunities for carbon pricing, together with other policies, to drive the sustainable growth and poverty reduction which can deliver on the Paris

Agreement and the Sustainable Development Goals.' (CPLC, 2017).

Sir Nicholas Stern, one of the most vocal advocates of a price on carbon, argues that economic actions need to be guided positively through the provision of sound market signals about the underlying cost of goods, services, and activities in order to overcome market failures (Stern, 2007). This can help support an efficient allocation of resources and achieve equity and climate change risk mitigation (Stern, 2007). By providing correct signals, markets would price good, services, and activities in a way that reflects the true cost that they impose on society. Policymakers can help operate markets more efficiently when it is ensured that the price of fossil fuels and the subsequent release of GHG emissions reflect their true cost (Stern, 2007). Stern estimated that the price per tonne of carbon must be between US$40 – 80 by 2020 and between US$50 – 100 by 2030 to be able to achieve the goals of the Paris Agreement (Grantham Research Institute, 2017). In 2018, carbon schemes around the globe had prices varying from US$1 to US$139 per tonne of CO_2e, with forty-six percent of the emissions covered having a price below US$10 (World Bank and Ecofys, 2018).

The Climate Change 2014 Synthesis Report states that climate change is expected to contribute significantly to environmental and economic consequences, both for present and future generations. The subsequent net negative externalities can be in the form of altered physical (sea level effects, land loss and alteration of hydrological systems), biological (marine and terrestrial ecosystems), and human-managed systems (food production, health, and livelihoods) (Pachauri and Meyer, 2014). Since the emission of carbon is currently too cheap in comparison to the social costs associated, or completely unregulated, markets fail to reflect those risk adequately, and firms are unwilling or unable to price the cost of carbon into their corporate financial decision-making framework. Therefore, to internalise these social costs, economists argue that putting a price on emissions is one of the most effective ways to mitigate global emissions and achieve agreed-upon targets (Keohane and Olmstead, 2016).

Social Cost of Carbon

Emitting CO_2 into the environment can be associated with an economic cost or loss of economic welfare by means of estimating the cost of emitting CO_2. One approach is to calculate the value of future climate change impacts that the emission of one marginal tonne of CO_2 has today by discounting future cash flows to the present values (Net Present Value, NPV - for a detailed explanation, see section 2.3.3). If the emitter of CO_2 is not paying for polluting the environment, referred to as external costs, these economic costs are becoming social costs as paid by society (Chomsky, 2006). Therefore, these marginal global damage costs associated with CO_2 emissions are, as mentioned before, called 'Social Cost of Carbon' (SCC) (Tol, 2011).

In his study, Nobel Laureate William Nordhaus (1993) wrote about the optimal tax policy for the reduction of GHG emissions in his dynamic integrated climate-economy (DICE) model. It weighs benefits and costs to slow the greenhouse gas process and has been widely used by governmental bodies such as the U.S. EPA (Environmental Protection Agency, 2012). In his latest paper, due to the delay of effective policies, Nordhaus argues for an even higher price on carbon ranging from US$30 (2015) to US$98 in 2050 (Nordhaus, 2016). At a three percent discount rate, the cost of carbon under Nordhaus' SC-CO_2 model was estimated at US$37.2 per tonne (IWG, 2016).

Moore and Diaz (2015) extended Nordhaus' DICE model and implemented empirical estimates what effect temperature has on GDP growth, both in rich and poor regions. Their findings show a range of loss in net social welfare from US$33 in the year 2020, up to US$220 by the year 2100. This large discrepancy can be explained by the differing economic growth rates as well as region-dependency ('rich' vs. 'poor').

Critical voices, such as Murphy (2009), predicted that GHG concentrations might be overstated, as they are not adequately adjusted for natural sinks such as oceans. Another controversy questioned is the so-called 'feedback effects,' whereby changing one parameter (CO_2 emissions) subsequently changes a second parameter (raising average temperature), which consequently sets further warming in motion through increasing amounts of water vapour in the atmosphere (Solomon, 2007). While Murphy accepts the consensus of direct temperature increase from CO_2 concentration, he disagrees with the chosen climate sensitivities in Nordhaus' model as they tend to be

far more pessimistic than historical trends suggest (Murphy, 2009). The last area of uncertainty concerns the economic damage from temperature increase. Murphy argues that the foundation for Nordhaus' argument is very fragile, questioning the chosen estimates which are a mixture of findings in the literature rather than a particular estimate. By adjusting Nordhaus' DICE models, Murphy ends with social costs of carbon ranging from US$9.46 (2015) to US$30.62 (2075). These are significantly different from Nordhaus' figures, which range from US$41.90 to US$137.82 for the respective years (Murphy, 2009; Nordhaus, 1993).

It needs to be noted that an array of models exist, aside from what is mentioned above. Thompson (2018) conducted a study in which she compared and contrasted 10 of the most important models of global carbon and climate systems that have the aim to estimate the social cost of carbon. Thompson's study, which included the DICE mentioned above model, intended to analyse these models for their transparency and scientific design (Thompson, 2018). Her findings concluded that while various models are fit for the intended purpose, all of the use different metrics and assumptions, leading to varying results (Thompson, 2018). Pezzey (2019) furthermore noted, that any concluded cost of carbon, irrespective of what the underlying model is, will be disputed. The reason for this can be found in the often dozens of assumptions made by all models, most of which are highly uncertain (Baranzini et al., 2017; Beck and Krueger, 2016). Pezzey (2019) therefore suggests, that instead of trying to model social costs of carbon, the marginal abatement costs of a ton of CO_2 should be used. Chapter 4 of this thesis is following up on this idea, estimating what the break-even abatement cost of carbon is utilising bacteria-mediated carbon mineralisation could be.

This wide span of the assessed SCC by various researchers, institutes, and countries are further contributing to the uncertainty for firms to take actions and price their frameworks adequately. Investment in carbon mitigation technologies (afforestation, CCS, others) requires either an economic penalty (e.g., carbon tax) or an incentive (e.g., the premium on low carbon goods, subsidies). While some researchers favour a mandated bonus-malus system, others conclude that this is best achieved by having a market-driven mechanism (Hise, 2016).

Legal looting

According to Akerlof et al. (1993), the failure to charge externalised costs to the emitter represents an implied subsidy or society grant and is therefore defined as the 'looting amount.' In finance and economics, the term looting is used to describe a situation whereby society agrees to permit a government to legally and contractually binding inefficiencies which persist through time. At its core, looting is a moral hazard problem (Kahn and Winton, 2004). Profits are privatised whereas the losses are paid by the public and are therefore socialised (Chomsky, 2006), allowing investors to engage in higher-risk without having to pay the consequences in full. Early examples of looting can be found in the Chilean financial crisis during the 1980s, or the United States junk bond market (Akerlof et al., 1993). Legal looting is usually more common in countries with weak institutions such as the case of Tanzanite mining in Tanzania, where mining policies in place during the 2000s were so weak that only the (foreign direct) investors benefitted (Helliesen, 2012). Local miners and communities only benefitted marginally while left bearing the externalised costs on the environment.

Linnenluecke, Smith et al. (2017) quantified the legally looted amount by the fossil fuel industry operating under the legal umbrella. The externalised cost, incurred by their CO_2 emissions and due to the absence of a cost of carbon, are not paid. While direct subsidies are known to the public, the paper aims at estimating the indirect or implied subsidies of the fossil fuel industry. To achieve the quantification, the total amount of emitted CO_2 from fossil fuel related activities (petrol, gas, and coal) were summed up in two ranges: from 1959 to 2013 and from 1995 to 2013. The next step was multiplying said CO_2 emissions with a selection of carbon taxes per tonne of CO_2e, ranging from US$1 in Poland to US$130 in Sweden. The same was done for emission trading schemes which vary from US$2 (Shenzhen, China) to US$36 (Tokyo, Japan). Furthermore, the DICE model assumption (Moore and Diaz, 2015) was added, which suggests a price per tonne of CO_2e of US$220[1]. A wide range of looting amounts was established from US$1,118 billion to US$246 trillion from 1959 to 2013, and US$525 billion to US$115 trillion from 1995 to 2013 (Linnenluecke, Smith, et al., 2017).

[1] (Linnenluecke, Smith, et al., 2017)

Economic Implications

The impact of past and predicted future climate change has been widely discussed in the literature with a range of findings and magnitudes. Environmental input factor consumption has seen an ever-growing increase, most significantly since the Industrial Revolution. However, society has only recently started to consider what the environmental impacts of these actions have on global environmental change, and what the financial consequences thereof could be for companies operating in vulnerable industries (Linnenluecke et al., 2016; Winn and Kirchgeorg, 2005). One of the most significant, albeit controversial, climate change reports to date is the 'Stern Review' (Stern, 2007) which served as a 'call to action,' predicting that a failure to do so promptly would result in an equivalent reduction of five to twenty percent of global gross domestic product (GDP) each year.

However, the Stern Review also pointed out that some developed countries could have a net-benefit from moderate climate change, mainly stemming from higher agricultural yields, lower winter mortality, and lower energy use (Stern, 2007). Other researchers have confirmed these two-sided implications but differ on the amount of net loss of GDP. Tol (2013) suggests that global warming and higher CO_2 concentrations in the atmosphere has had a net-benefit in the agricultural production in the past and will continue to have a benefit in the future due to 'carbon dioxide fertilisation.' On the other hand, other areas such as health and water resources tend to have overall detrimental net economic effects (Tol, 2013). It was concluded that the negative impacts had outweighed the positive effects by the second half of the 20th century, with a significant variation depending on the geographical location. Most developing countries are overall negatively affected while wealthier countries can see both positive and negative economic impacts. Tol assessed the average implications of the 20th century for each of the 207 countries in his model. The net impact on GDP ranged from -19 percent for Timor-Leste to +6 percent for China, approximately one order of magnitude larger than the mean (Tol, 2013).

2.2.5 Impediments: Broken Solutions

Having established a rationale for a price on carbon, as demonstrated in the preceding paragraph, the implementation of national strategies to tackle the problem remains a challenging undertaking. Political discord, as well as rapid changes of

reigning governments, have made the case more complex. These fragile political decisions have led to the abandonment of the Australian carbon market, which can be seen in the following paragraph. The Paris Agreement has been put under further pressure when the United States of America decided to recede from their pledge under the Obama administration (UNFCCC, 2017c). Due to the politicisation of the carbon topic and the subsequent ongoing disagreement, firms, regions, countries, and the global community has been left under uncertain terms.

The Australian Carbon Market Case

Australia's emissions in 2016 were 532 million tonnes of CO_2e and represented approximately 1.5 percent of global emissions (Australian Government, 2017c). However, on a per-capita basis, primarily owed to the extensive use of coal for electricity-generating purposes, Australia claims one of the top-polluter ranks globally (Schiermeier, 2014).

Under the Gillard Labour Government, the 'Clean Energy Act (CEA) 2011' was introduced in Australia (Australian Government, 2011). This act, proposed in 2011, was a carbon pricing scheme which came into effect on the 1 July 2012. Liable entities had to purchase carbon credits from the Clean Energy Regulator at a fixed price of AUD 23 (FY 2012-13) or AUD 24.15 (FY 2013-14). If a liable entity was unable to surrender enough credits for the respective period, a 'unit shortfall charge' incurred at one hundred thirty percent of the fixed price. The CEA covered approximately sixty percent of Australia's GHG emissions and included most large businesses and industrial facilities. The vast majority of smaller businesses, as well as households, were excluded (Australian Government, 2015a). In its first year of operation, the CEA raised AUD 6.6 billion. The tax contributions came mainly from the 350 high-polluting companies. Subsequently, the emissions from the power sector were reduced by five percent in that year (Schiermeier, 2014).

Under the Tony Abbott Government (September 2013 to September 2015), the carbon tax was subsequently removed on 17 July 2014. This came after the legislation which requested to abolish it was passed by the Senate and was sanctioned through a Royal Assent and thereby becoming an Act of Parliament (Australian Government, 2014a). The repeal got rid of both the tax and the proposals to turn the CEA it into an emission-trading scheme (ETS). This would have provided more flexibility, and it would

have allowed joining forces with the EU ETS to create a large, market-based pricing (Schiermeier, 2014). The reasons behind the abolishment of the CEA were manifold. The Australian Government, as well as critics of the system, claimed that it would reduce the cost of living for all citizens by an average of AUD 550 in the year 2014-15. Furthermore, it was quoted that the cost of electricity would have risen by nine percent while the gas prices would have been increased by seven percent with the carbon tax in place (Australian Government, 2014a).

Subsequently, the CEA was replaced with the Emission Reduction Fund (ERF). The ERF aims at helping to achieve Australia's 2020 emission reduction goals and reduce emission by five percent compared to the year 2000 baseline. Furthermore, the ERF has the goal to reduce Australia's emissions by twenty-six to twenty-eight percent by 2030 versus 2005. These goals are in accordance with the (I)NDCs declared by Australia at the Conference of the Parties (Australian Government, 2015b). Initially, a budget of AUD 2.55 billion was designated towards the fund.

Further funding needs to be approved in future budgets (Australian Government, 2017a). However, unlike the CEA, the ERF is voluntary and offers financial incentives to corporations that improve their efficiency (Schiermeier, 2014). During the budget review 2014-15, the Australian Parliament estimated AUD 2.55 billion would be spent through the ERF by the financial year 2020-21. In this scenario, 421 million tonnes of CO_2e would have been avoided or offset. The average price per ACCU in this scenario equates to AUD 5.35 per tonne of CO_2e (Parliament of Australia, 2015). It was noted during the budget session that such a purchase price per Australian carbon credit unit (ACCU) might not be sufficient to reach the proposed targets. At the time, the price per tonne of CO_2e of other schemes ranged between US$8 – 18 per tonne (Greenmarkets, 2015). The ERF is composed of three key elements. First, participants register their emission reduction projects with the regulating bodies of the CEA (the Regulator). Once approved, participants will then undertake their reduction projects and report the emission reductions to the Regulator. Once the reductions are verified, one ACCU per every CO_2e that was reduced will be credited to the account of the proponent through the Australian National Registry of Emission Units (ANREU). Secondly, the Clean Energy Regulator runs competitive reverse auctions where the ACCUs can be sold to the government or private-sector purchasers through the secondary market. Thirdly, the safeguard mechanism, which commenced on 1 July 2016, ensures that reduced,

credited emissions will not be offset elsewhere in the economy (Australian Government, 2017a).

As per February 2018, the ERF has paid out AUD 2.28 billion, equivalent to 191.7 millions tonnes of CO_2e of the intended 421 million tonnes of CO_2e as stated above. However, as per the end of the sixth auction round in December 2017, only 26.5 million tonnes of CO_2e of the accepted 191.7 million tonnes have been effectively delivered. This amount is equal to approximately fourteen percent of the total abatement portfolio (Australian Government, 2017b). With an average cost per tonne of CO_2e of AUD 11.89, the price per ACCU has been much higher than initially anticipated (MacKenzie, 2018).

Concerns have been raised with regards to the accountability and selectiveness of the projects selected under the ERF (MacKenzie, 2018). While there are safeguard and verification mechanisms in place to make sure emissions will not be emitted elsewhere in the economy, there are loopholes to be considered. A number of the won contracts stem from 'low-polluting' industries where it is unclear whether the claimed emissions would not have been abated anyway while heavy industries are underrepresented. A sizeable proportion of the contracts are related to tree-planting projects as well as reduced emissions from savannah burning (MacKenzie, 2018).

Broken solutions – Worldwide

The global issue makes everything more complex and can create arbitrage opportunities. This can be the case where some countries have implemented taxes on carbon while most others have not, incentivising firms to pursue economic runoff. However, there are various examples of past problems where the global community came together to solve them, such as cutting the rates of extreme poverty in half since 1990 (United Nations, 2015). Tackling GHG emissions via economic instruments do not represent a solution to the problem. However, it can help alleviate the current state.

To ensure a sustainable future, there is a need for proper measures and strategic actions from the public and the private sector derived from a global agreement. These measures and actions will help to ensure that the limited resources are utilised in a sustainable way and that the ecological limits of the planted are taken into consideration (Linnenluecke, Verreynne, et al., 2017). The absence of carbon markets

and legally-binding, unified global agreements makes society foot the bill for the externalised cost caused by organisations emitting GHGs without paying for the clean-up cost. While organisations reap the benefits of mining minerals, extracting oil, and deforesting land for crops and other, the bystanders bear the consequences. Furthermore, the problem of externalised costs is exacerbated by climate inequality, whereby less-polluting countries face more drastic consequences of emissions that were caused by other countries. Tol (2013) concluded that by 2050 the majority of countries around the equator as well the entire African continent will suffer the highest loss of GDP. The loss of GDP is attributed to negative impacts on poverty-related health problems as well as loss of water, outweigh the positive effects of CO_2 fertilisation on agriculture (Tol, 2013). These are some of the reasons why most economists support a price on carbon in one shape or another since economic activity is supposed to maximise social good. However, the absence of a price in the case of emissions represents a negative externality (Avent, 2011).

The paper about legal looting by Linnenluecke et al. (2017) exemplifies just one of the reasons some carbon markets are broken on a global scale. Other causes include the chronic oversupply of carbon certificates, which was the case for the EU ETS (Oroschakoff and Stefanini, 2017). This caused the EU ETS allowance price to be extremely low for the majority of its existence (see Figure 2). In November 2017, the European Union agreed to overhaul the EU ETS in an attempt to boost its price per allowance. This action was in line with the EU climate goals, which were drafted at COP21 and later confirmed at COP22 (Krukowska, 2017). The agreement helped to strengthen the price per allowance as it reached close to EUR 8 in November 2017, shortly after concluding the meeting. Overhauling the EU ETS was a step into the right direction since the price was nowhere near reflecting the true SCC, which ranges between US$33 and US$220 (See chapter: 2.2.4)

According to Sir Nicholas Stern (2007), as previously mentioned, economic actions need to be guided positively through the provision of sound market signals about the underlying cost of goods, services, and activities to overcome market failures. This can help to an efficient allocation of resources and achieve equity and climate change risk mitigation (Stern, 2007). By virtue of providing correct signals, good, services, and activities reflect the true cost that they impose on others through the damage caused. Policymakers can help operate markets more efficiently when it is

ensured that the price of fossil fuels and the subsequent release of GHG emissions reflect their true cost. Stern estimated that the price per tonne of carbon must be between US$40 – 80 by 2020 and between US$50 – 100 by 2030 to be able to achieve the goals of the Paris Agreement (Grantham Research Institute, 2017).

The Climate Change 2014 Synthesis Report notes that climate change is expected to contribute significantly to environmental and economic consequences both for the present and future generations. The subsequent net negative externalities can be in the form of altered physical (sea level effects, land loss, and alteration of hydrological systems), biological (marine and terrestrial ecosystems), and human-managed systems such as food production, health, and livelihoods (Pachauri and Meyer, 2014). Since the emission of carbon is currently too cheap or unregulated, markets fail to reflect those risks adequately, and firms are not able to price the cost of carbon into their decision-making frameworks. In order to internalise the social costs of carbon, economists argue that putting a price on emissions is one of the most effective ways to mitigate global emissions and achieve agreed-upon targets (Keohane & Olmstead, 2016).

2.2.6 Proposed solutions

In order to tackle and achieve the goals outlined in the Paris Agreement, various economic instruments have been proposed, such as carbon taxes and subsidies. In this section, a background on the most prevalent methods around the global is given, and the instruments are analysed and compared. Furthermore, alternative positions, such as non-financial solutions, are taken into consideration. The economic instruments, as well as practical approaches to absorb CO_2 emissions, are elaborated on in greater detail.

The global context: Carbon markets

Sir Nicholas Stern noted that ‘Providing a strong, stable carbon price is the single policy action that is likely to have the biggest effect in improving economic efficiency and tackling the climate crisis. Clarity on policy and prices is all the more important now with companies facing significant uncertainty because of the financial crisis: the two risks compound each other, dampening investment, making it all the more important that we take actions now that will markedly reduce uncertainties about future

carbon policies and prices.' Further, he notes that 'we know the types of economic instrument necessary; crucially this requires a price for greenhouse gases to correct the market failure of the damage caused by emissions.' (Brohé et al., 2012).

In 1990, Finland was one of the first nations to launch a carbon tax, which was applied to gasoline, diesel, light fuel and heavy fuel oil, jet fuel, aviation gasoline, coal, and natural gas. Shortly after, the Netherlands, Norway, Denmark, and Sweden followed with similar taxes (see section 2.2.4 for an excerpt of carbon taxes around the globe). While the schemes are slightly different from one another, they often exempt high-energy consuming industries or classify them under a reduced tax category. The usual reason for exempting those industries was the fear of losing their competitiveness (Lin and Li, 2011).

Carbon markets have been created to regulate, price, reduce, and cap the emissions of CO_2. Currently, two solutions are prevalent: emission trading and carbon taxes. From an economic point of view, carbon taxes are Pigouvian taxes, aiming at internalising these externalised costs (CO_2 emissions) which are currently borne by the public. Further distinction and in-depth analysis of cap-and-trade vis-a-vis carbon taxes are explored later on in this chapter.

As per the end of 2017, some 19 emission trading systems (ETS) were active and operated across the world (ICAP, 2017). ETS are the equivalent of a cap-and-trade system, whereby a set amount of emissions is allowed to be released in a given timeframe and allocated to polluters. When a polluter is short on certificates, the firm needs to purchase them on the market. This way, a market-based price mechanism is created to lower the number of allocated certificates every year. In theory, this unlocks incentives to develop carbon-efficient means of production as well as spur investments in innovative low-carbon technologies (ICAP, 2017).

As of 2017, the current systems, operating in various economies equivalent to roughly half the world gross domestic product, cover approximately fifteen percent of the global emissions (ICAP, 2017). At its inception in 2005, the European ETS (EU ETS) was one of the largest cap-and-trade systems. Since then, the EU ETS has been battling with the open-ended question on how to reconcile the price signals for the short and long-term. The EU ETS has been in operation for more than a decade to spur

investments and innovation as well as the subsequent and gradual reduction of GHG emissions in Europe within the power and industry sector. The system has been set up as a market-based mechanism public-policy instrument with the goal to achieve climate change targets such as the INDCs. The theory states that an emission cap is set to gradually reduce GHG emission by twenty percent in 2020 and by forty percent in 2030, with 2005 being the base year. In order to achieve the above goals, investments and innovations in low-carbon technologies, as well as efficiency gains, need to be realised and supported by complementary policies where necessary (ICAP, 2017). The EU ETS and other markets are discussed in more depth under section 2.2.6.

Economic Instruments

Carbon Taxes

Under carbon taxes, there is a distinction between a revenue-neutral tax and a revenue-raising tax. Each is 'a tax on the carbon dioxide emissions from burning fossil fuels' (Carbon Tax Center, 2015). The revenue-raising tax has the purpose of creating more income for the government, essentially taxing per tonne of emitted CO_2 equivalent. Both taxes aim at internalising the social cost of emissions into market transactions. Therefore, if the carbon tax is correctly applied, it would be the equivalent of a Pigouvian tax. A Pigouvian tax describes a tax that aims at correcting negative externalities such as socialised costs that are currently borne by society, and it aims at bringing the market back to be an efficient solution (Linnenluecke, Smith, et al., 2017; Tol, 2011).

The revenue-neutral tax, on the other hand, is taxing on the same base per tonne of emitted CO_2e. Instead of raising additional money at the disposal of the government, the funds are redistributed to citizens via lower-income and investment taxes. Often, there is also an incentive program involved which gives companies access to a fund in case they decide to invest in research and development (R&D) of cleaner technologies (Komanoff and Gordon, 2015).

The price per tonne of CO_2 varies from country to country (See Table 4). Most regions adopted a planned and gradually rising price to give businesses time to adapt as well as to mitigate a drain of enterprises. Further stringency can be achieved by a

‘ratcheting mechanism,’ whereby the carbon tax goes up should emission targets not be reached (Kaufman, 2016).

Table 4: Carbon taxes worldwide (excerpt)

Country / Region	Carbon tax (Per-tonne of CO_2)	Introduced	Status	Coverage
Sweden	US$140 (With industries exempt)	1991	Operational	49%
Finland	EUR 18.05	1990	Operational	51%
Canada (British Columbia)	CAD 10 (2008) + CAD 5 each year CAD 30 (2012)	2008	Operational	N/A
Ireland	EUR 15.00 (2010) EUR 20.00 (2012)	2010	Operational	51%
Australia	AUD 23.00 (2012) AUD 24.15 (2013) AUD 25.40 (2014)	2012	Abandoned in 2014	N/A
Chile	US$5.00	2017	Operational	N/A
Colombia	US$5.00	2017	Operational	24% of the countries GHG emissions
Singapore	US$2 – 10	2019	Planned	

(Carbon Tax Center, 2016; Ecofys et al., 2017; OECD, 2018)

Both types of carbon taxes are currently in place in various countries and regions across the globe. One example of a revenue-neutral tax is the Canadian province of British Columbia. British Columbia introduced its carbon tax in 2008 and set the price per metric tonne of CO_2 at a rate of CAD10. It was the first jurisdiction in North America to adopt a carbon tax on an economy-wide level. Over the following years, there was an annual tax increment of CAD5 per tonne until the current level of CAD30 per tonne of CO_2 was reached in 2012. During the CO_2 taxed period, the average annual per capita emission of British Columbia was 12.9 percent less than the before-CO_2-tax period, a drop that was 3.5 times greater than the rest of Canada which only fell by 3.7 percent. During the same timeframe, GDP in British Columbia grew with an annual average of 1.55 percent compared to 1.48 percent for the rest of the country (Komanoff and Gordon, 2015).

Tradable Allowances

Another method of putting a price on carbon is the ‘cap-and-trade’ method, providing incentives to reduce the overall greenhouse gas emissions. This artificially imposed cap is gradually reduced over time to ensure that the predicted emission target can be reached. Furthermore, it aims at spurring investments into the development of clean and energy-efficient systems in the renewable energy sector (David Suzuki, 2014). It is an alternative to the carbon tax and represents, amongst

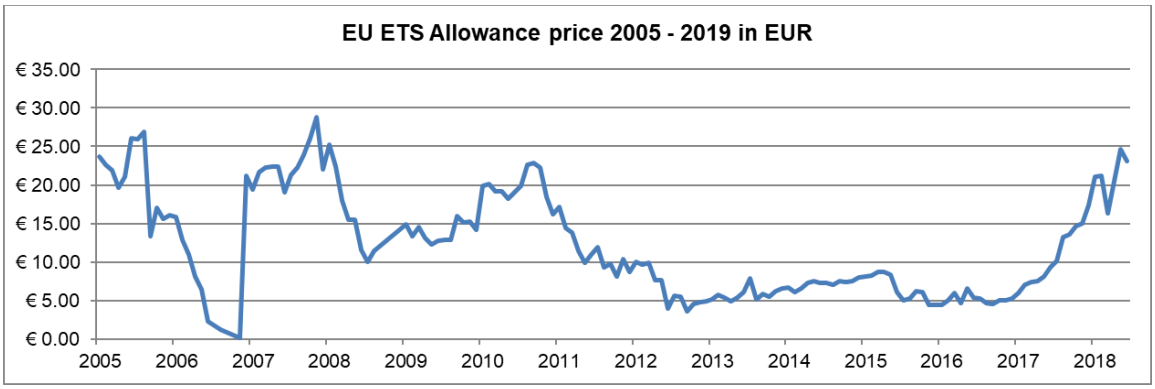
other countries and regions, the cornerstone of one of the largest schemes, the European Union's 'Emission Trading System' (See Vignette: EU ETS). First, a governmental body or other central authority determines which the trading system covers industries and facilities. Then, a 'cap,' a total emission target, is set for a given period during which the covered facilities are operating. After that, the rights to emit, which are measured in tonnes of CO_2e, are distributed by either an auction, allocated freely or a combination of both. At the end of the compliance period, each entity must submit allowance equivalents by the levels of emissions for which they were responsible. Emitters with a negative allowance will either engage in buying surplus allowances off the market or invest in low-emitting technologies to drive down emissions in the first place. By this method, the firms are given a financial incentive to control their emissions as well as the flexibility to decide by when and through what means their emissions will be reduced (Center for Climate Energy Solutions, 2011).

The ETS allowance price is supposed to signal which operation investment decisions are based on, depending on what price is anticipated to be in the short and long term is. A firm's willingness to invest in emission-reducing equipment depends on the abatement cost of carbon. So long as the abatement costs are below the carbon price signal created by the markets, there is an incentive to act upon this arbitrage opportunity. Subsequently, the 'low-hanging fruit' emissions will be reduced first while more expensive abatement options would be unlocked at a further stage, as the price per ETS allowance will rise significantly due to the continuous reduction of total allowances in a given period. In practice, however, a multitude of factors have caused the price per allowance to decrease dramatically. In the case of the EU ETS, one of the factors was the initial oversupply of allocations, having overestimated future emissions.

Furthermore, the drastic reduction of economic activity during the financial crisis leads to a further decrease in demand. This was combined with a boom in renewable energies in Europe as well as more energy-efficient technologies further driving oversupply (Corporate Europe, 2015). While the highest price achieved was around EUR 28, it first dropped to almost zero in June 2007. After having recovered, with volatility for the past four years as per January 2019, the price is currently around EUR 23 (Figure 2). With a very low average price signal, as well as high volatility and uncertainty, the policy concepts of the current EU ETS are not sufficient to spur the

necessary investments to reduce GHG emissions and reach the climate pledges. The current price per allowance does not truly reflect the climate ambitions of the European Union and therefore, provide little incentive for companies to abate CO_2 (ICAP, 2017).

Figure 2: EU ETS Allowance price



Source: (Investing, 2019)

Vignette: EU ETS: The European Union (EU) had introduced the first of three stage of its EU ETS in 2005 which ran until 2007. During this phase, the administrative and regulatory bodies were put in place for the management of the EU ETS. All installations included in the scheme were given credits equal to 100% of their emissions at the time. Afterwards, it was soon discovered that most installations had been allocated a surplus of carbon emission credits because the calculations had been based on inflated estimates. This was the main reasons that the market collapsed and the price per carbon credit was driven down to practically zero. Another reason was that the companies successfully reduced their emissions within the first two years of Phase I and there was no full need of the allocated allowance (Caney and Hepburn, 2011).

Phase II, which ran from 2008 to 2012, the carbon credits which were allocated were adjusted closer to the industries' baseline. This was done to prevent oversaturation of the markets as had happened in Phase I. However, there were other events involved, such as the global financial crisis and the subsequent fall in industrial production, which caused the price per carbon emission to fall due to a lack of demand from said industries.

Phase III was introduced in 2013 and will run through to 2020. The EU has high hopes that the demand for carbon credits will increase together with the economic recovery. Furthermore, the total allocation of carbon credits allowances is planned to be reduced by 21% by 2020, with 2005 being the baseline year. This is with the goal in mind to reduce overall carbon emissions in the EU. Additionally, the EU seeks international agreements with non-EU countries to reduce the allowances to as much as 30%. Phase IV is planned to be running from 2021 to 2030, trying to reach the reduction of up to 43% emissions by the last year versus 2005 values. The annual reduction will be around 2.2%, compared to the current reduction of 1.74%. Around 6.3 billion allowances are expected to be allocated for free during said period (European Union, 2018).

In 2019, the EU ETS covers all 28 EU countries as well as Iceland, Liechtenstein, and Norway. Furthermore, there are plans to link the Swiss ETS to the EU ETS (Ecofys et al., 2017). Approximately 45% of the total EU emissions are limited by the EU ETS, covering roughly 11,000 power stations, manufacturing plants, and most of the aviation traffic between the countries. It is the largest emission trading market and accounts for approximately three-quarters of the total worldwide emissions traded (European Commission, 2013).

China launched its ETS, named 'Chinese national carbon trading scheme,' in late 2017 after several years of regional pilot projects (Timperley, 2018). It is set to cover approximately three Gt of CO_2, which makes it by far the largest carbon market worldwide. Once it is operational, roughly a quarter of global emissions will be covered by some form of carbon-pricing systems (Timperley, 2018).

Carbon Tax vs. Cap-and-Trade

As discussed in the paragraphs above, a carbon tax is usually levied on fossil fuels as well as related products such as coal, gas, jet fuel, and natural gasses depending on their carbon content. The aim is to drive down fossil fuel consumption and the associated carbon emissions. The effects of a carbon tax are manifold. On the positive side, it usually promotes the substitution of fuel products and can change the structure of energy production and consumptions as well as encourage energy-saving and improvements in efficiency. On the other hand, it can influence investment and consumer behaviours through the recycling of the revenue collected via the tax. This can lead to the promotion of renewable energies, subsidised by the collected tax as well as expedite technological developments of energy-saving and emission reductions, thereby enforcing previous effects (Baranzini et al., 2000).

In the short run, however, the prices of related products will increase, weakening the competitiveness of energy-intensive industries and potentially pose negative impacts on economic growth. Moreover, the mitigation effects of a carbon tax are uncertain as some enterprises might shift the increased cost onto consumers (higher prices), and the tax will only lead to an increase in fiscal revenue and not in an emission reduction. If the price elasticity is high, it will be harder to shift the cost of the carbon tax onto consumers and have better overall mitigation impacts. Otherwise, the costs of the carbon tax will be shifted, which will result in lower mitigation effectiveness. Finally, if tax revenues are not injected back into the economy, the carbon tax will impose a higher cost to polluters than an emission trading system or command-and-control policies, potentially decreasing public acceptability (Baranzini et al., 2000).

Table 5: Pro and Con: Carbon tax vs. cap-and-trade

	Carbon Tax	Cap-and-Trade
Allowances	• Unlimited, 'pay-as-you-pollute'	• Limited, tradeable • In some systems, allowances are allocated for free → Achieving desired distributional outcomes
Price per CO_2e / Volatility	• Predefined and stable, 'ratcheting mechanism' • No volatility issues. Predefined and stable, 'ratcheting mechanism'	• Variability, dependent on market price (Supply and demand) • Volatility can be an issue as demand for allowances likely to be inelastic (Short-run). Can be addressed with price floor and/or ceiling
Attainability of CO_2 reduction goals	• Uncertain. However, the ratcheting mechanism ensures tax adjustment if reductions too low	• Given, limited by a cap on CO_2 emissions
Government Revenue	• In the case of revenue-raising tax • Not in case of a revenue-neutral tax	• Emission allowance auction
Emission reduction incentive (financial)	• Constant incentive so long as • marginal reduction cost < marginal tax	• Only until emission targets are met, after that no incentive for reduction
Governmental interference	• Pigouvian tax • Set price (Can increase over time)	• Since emission is set by the government, it is a heavy governmental intervention. • Price floors
Disadvantages	• Uncertainty of total CO_2 emissions	• Reliant on policy design: Most caps allow generous emissions (EU ETS), can be ineffective • Initial pollution permits might be given for free to certain industries ('Grandfathering') to ease the adaptation process
Administration & Regulation	• Less costly as applied upstream (Import/production of carbons): Far fewer points of regulation	• Costly to administer as applied downstream (Near ultimate combustion point for carbons): Millions of points of regulation

(David Suzuki, 2014; Goulder and Schein, 2013; Grantham Research Institute, 2013; Kaufman, 2016)

Subsidies

A further economic instrument that can be applied across various sectors can come in the form of subsidies. This can include but is not limited to policy design such as tax rebates, grants, or loans. However, depending on the social and economic context, reducing subsidies can equally lead to a reduction of GHG emissions (Pachauri and Meyer, 2014).

Subsidy strategies, much like a price on carbon, seek to offer an incentive for both businesses and individuals to change decisions with regards to production methods, services, and purchases and switch to less intense GHG options (Freebairn, 2014). While a price on carbon is a form of penalising emissions, it aims at internalising said cost. Subsidies, on the other hand, offer a reward for change. Freebairn (2014) found that subsidies can cause higher transaction costs compared to a price on carbon due to increased administrative and compliance costs. These high costs, in turn, may deter potential solutions not to tender for the subsidy (Freebairn, 2014).

Subsidies can most prominently be found in the energy sector, such as in the renewable power segment. In Australia, households and small businesses may be eligible to receive benefits to incentivise the installation of renewable energy sources and reduce purchase costs (Australian Government, 2019). Electric vehicles are often subsidised by governments around the globe, aiming at reducing GHG emissions and consumption of fuel as well as improving air quality. The United States provides a tax credit of up to US$7,500 for several Plug-in Electric Vehicles (PEVs), with additional state subsidies available (U.S. Department of Energy, 2019).

Alternatives views

Economic solutions are not the only way to tackle the SCC. Imposing taxes in the form of either subsidies or costs will hamper the investment of businesses (Patt and Lilliestam, 2018). Therefore, Murphy (2009) suggests considering another option: reliance on economic growth. He states that it is not a politically popular method but indicates that it might tackle the problem of climate change just as well as the other solutions, if not better. The reasoning is that, next to many uncertainties in the models advocating taxes, any tax limits economic growth, leaving humans less wealthy in the process. In turn, this inhibits people's financial abilities to adapt to the problems as

their financial freedom is cut. Murphy agrees that any ignored market externalities are Pareto inefficient. However, it does not take into account said inefficiency would be solved by the superior information which future generations can acquire due to their higher degree of economic freedom and higher material wealth (Murphy, 2009).

Economists have argued that the outcomes of a 'command-and-control' approach, which is the traditional regulatory approach, could be achieved at a lower cost to society as well as a smaller bureaucratically effort through a tax. It is also argued that taxes would provide incentives to corporations to continuously improve their environmental performance as they look into ways to minimise their costs, whereas there would be no more reason for a company to exceed the pollution abatement once expectations (cap-and-trade) are reached (Brohé et al., 2012).

Patt and Lilliestam (2018) build a case against a higher price on carbon in their paper. While they are in full agreeance with regards to the economic implications of climate change, they suggest that a higher price on carbon does not directly address the challenges necessary to undergo the transition from the current state to carbon-efficient or carbon-neutral technologies (Patt and Lilliestam, 2018). Instead of penalising old technologies (price on carbon), it is suggested to incentivise upcoming, low-carbon technology to speed up the transition. While prices on carbon did have a right to exist in the past, according to their paper, it is currently climate policies that seem to be more likely to bring about change (Patt and Lilliestam, 2018).

Furthermore, opponents of carbon pricing also argue that heavy manufacturing industries (i.e., cement) may suffer, which might lead to economic runoff of the affected industry sector into other regions or countries. In the case of British Columbia, a transitional relief mechanism was put into place whereby affected industries are paid back parts of their carbon taxes. However, the funds are earmarked and need to be invested in the development of clean technologies (Toomey, 2015).

Solutions Overview

Enclosed, an overview of some of the proposed solutions (IPCC Synthesis Report, p108 - excerpt)

Table 6: Solutions overview

	Energy	Transport	Industry
Economic Instruments: Taxes	• Carbon Tax	• Fuel taxes, vehicle taxes	• Carbon tax
Economic Instruments: Subsidies	• Fossil fuel subsidy removal	• Biofuel subsidies • Vehicle purchase subsidies (e-cars)	• Incentives for fuel-switching
Economic Instruments: Tradable allowances	• Cap-and-trade (emission trading)	•	• Cap-and-trade (emission trading)
Regulatory approach	• Environmental performance standards	• Standardised measurements of efficiency and emissions	• Standardised measurements of efficiency and emissions

(Pachauri and Meyer, 2014)

Carbon Capture and Storage (CCS)

Carbon Capture

According to the Intergovernmental Panel on Climate Change (IPCC) special report, 'Carbon dioxide (CO_2) capture and storage is a process consisting of the separation of CO_2 from industrial and energy-related sources, transport to a storage location and long-term isolation from the atmosphere. This report considers CCS as an option in the portfolio of mitigation actions for stabilisation of atmospheric greenhouse gas concentrations' (Metz et al., 2005).

The report further notes that the capture of CO_2 can be applied to any significant point source. A point source is a stationary, single localised CO_2 emitter such as fossil fuel power plants, cement production, or refineries. CO_2 is absorbed at the point source, compressed, and transported to an adequate, potential storage method where the aim is to store it safely in the long run. Alternatively, the CO_2 can be used industrially (Metz et al., 2005). Industrial CCS distinguishes three types of CO_2 capturing techniques: pre-combustion, post-combustion, and oxy-Fuel. Each of the capturing technique consists of four parts: capturing, compressing, transportation, and storage (Victoria State Government, 2018).

During the capturing process in the pre-combustion process, fuel is converted into a mix of hydrogen and carbon dioxide, which is done by methods such as

‘gasification’ or ‘reforming.’ Both the gasification and reforming processes are well established and already implemented around the world. The output of the gasification process is called ‘syngas.’ Syngas, combined with steam in a shift reactor, produces CO_2 and hydrogen. After this process, hydrogen is burnt to power turbines and creates electricity output. The carbon dioxide, on the other hand, is then compressed and dehydrated, which makes it ready for transportation and storage (Carbon Capture & Storage Association, 2015; Metz et al., 2005). Post-combustion technology can be either retrofitted on existing facilities or installed in new power plants. Burned fuel is producing steam to power turbines to generate electricity. The by-product is a flue gas consisting of nitrogen, carbon dioxide, and water. In a process called ‘chemical wash,’ the water and nitrogen are separated from the carbon dioxide (Carbon Capture & Storage Association, 2015).

Meanwhile, the captured CO_2 is being compressed, dehydrated, and made ready for transportation and storage (Carbon Capture & Storage Association, 2015). Once CO_2 is prepared for transport, a few different techniques can be applied to move it from point A to B. Although CO_2 is already transported daily in many parts of the world, substantial investments are required to enable more significant deployment of CCS. Current means of transportation include pipelines, ships, and road tankers (Global CCS Institute, 2015; Metz et al., 2005).

Pipelines have been well practised and are similar to the technique that is used to transport natural gas, oil, and other fluids. Currently, this method is the most popular amongst all the methods and is likely to continue to be. Nowadays, there are already millions of kilometres of pipeline laid out around the globe (Metz et al., 2005). The recent and future development of new, both regional and local CCS pipeline infrastructure, could lead to clusters of pipelines in areas that have a high concentration of CO_2 intensive industries. Once multiple industry sources start using the developed CCS pipeline cluster, this might prove to be the most cost-effective way to transport CO_2. In the long run, this will drive down the associated costs of transporting CO_2 and ultimately lower the overall costs for consumers (Global CCS Institute, 2015). Once the captured CO_2 is compressed into a fluid state (Supercritical CO_2), it can then be stored in various ways, some of which are discussed in the following paragraphs.

Storage: Deep Saline Aquifer

Pumped into a deep saline aquifer, CO_2 will rise to the top of the reservoir as it is more buoyant than saltwater. There, it becomes structurally trapped under the cap rock, which is forming an impermeable barrier and acts as a seal. Over time, some of the CO_2 will start to dissolve into the saline water (solution trapping) while other parts are trapped in the pore spaces (residual trapping). Mineral trapping occurs where CO_2 is reacting with the rocks of the reservoir where chemical reactions form a new mineral, effectively trapping CO_2 permanently (Carbon Capture & Storage Association, 2015; Global CCS Institute, 2015). The IPCC Special Report on Carbon Sequestration and Storage notes that evidence from oil and gas fields suggests that hydrocarbons (crude oil and natural gasses), as well as other gasses and fluids (including CO_2), can remain trapped for millions of years (Metz et al., 2005).

Storage: Enhanced oil or gas recovery

An alternative method of storage is deploying the Enhanced Oil and Gas Recovery method (EOR/EGR), which has been around since the 1970s. Reservoirs with declining oil or gas productions are suitable for this method to improve their productivity after most of the primary production of the field has already reached the surface. At this moment, CO_2 is injected and moves the remaining trapped oil or gas through the reservoir, directing it to the wells. A different method is alternating the injections of CO_2 with water, reducing process costs. Oil and gas that can be recovered via these methods, which would not have been extracted otherwise, contribute to offset some of the costs that occur with the sequestration of CO_2 (Carbon Capture & Storage Association, 2015; Metz et al., 2005).

With regards to long-term storage, The Global CCS Institute is noting that industrial-scale, as well as pilot and research-scale facilities, inject millions of tonnes of CO_2 underground every year. Furthermore, the oil and gas industry has an accumulated experience of over forty years of injecting CO_2 into reservoirs to increase yields. Therefore, the Institute is concluding that CO_2 can be stored underground without any concerns: safely, securely, and for a long time. Current CCS projects have not documented any significant safety, health, or environmental impacts (Global CCS Institute, 2015).

Storage: CarbFix

CarbFix is a geological storage process deployed in Iceland which captures CO_2 from a nearby point source (Geothermal power plant) through the dissolution in water. Afterwards, this water is injected into the subsurface, which is comprised of basaltic rocks. The carbonated water reacts with the calcium and magnesium present in the rock formation and is permanently sequestered without any harmful by-products. The project was jointly initiated in 2006 by four founding members comprised of Columbia University, Reykjavik Energy, the University of Iceland, and CNRS, Toulouse with the goal of finding a solution to limiting Iceland's GHG emissions (CarbFix, 2018; Gislason et al., 2010).

It was found that more than ninety-five percent of the injected CO_2 into the CarbFix site in Iceland was sequestered within two years. These findings present a stark contrast to the prevailing opinion regarding slow sequestration rates of geological storage of CO_2 (Matter et al., 2016). The theoretical estimates of the sequestration potential for Iceland are four hundred gigatons of CO_2, which is equivalent to approximately 11 years of global annual emissions (Levin, 2018; Orkuveita Reykjavikur, 2018).

A common problem is the sequestration cost of the CCS process. General cost estimates range from US$38 to US$143 per tonne of CO_2. A paper by Gunnarsson et al. (2018)estimates that the CCS cost within the CarbFix project could be between US$24.80 and US$48.40. The price per tonne of CO_2 is dependent on the unsubsidised cost of energy as well as of the abundance of either fresh or seawater, which can be a major drawback of the CarbFix project. Twenty-seven tonnes of freshwater is necessary to sequester one tonne of CO_2 during this process (Orkuveita Reykjavikur, 2018). The excessive use of water during the sequestration process would pose a significant inconvenience for the majority of countries across the globe considering that more than one billion people currently live in water-scarce regions, a number that may rise to 3.5 billion by 2025 (World Resources Institute, 2018).

Carbon Capture and Storage Installations

CCS installations are currently deployed in conjunction with both power plants and non-power plants. As per September 2016, the CCS Project Database lists 16

Power Plant CCS projects with an output greater than 60 Megawatt (MW), with a planned, under construction, or operational status. The combined designated sequestration rates per year are approximately 27 Megaton (Mt) of CO_2e. Furthermore, as per 7 April 2016, MIT lists twenty-four non-power plant projects, most of which are in conjunction with gas processing facilities (Massachusetts Institute of Technology, 2016). The IPCC report (Metz et al., 2005) notes that if leakage were to occur at a CCS site, fixing the leakage could involve standard well repair techniques or interception of CO_2 before it could leak into the groundwater. Since geological storage of CO_2 is associated with a long timeframe, site monitoring may be required for very long periods. The report further notes, if CCS were to be accepted as a mitigation technology, an upper limit to the amount of leakage that can take place must be applied (Metz et al., 2005).

Other Storages

Forestry and Oceans

Finding the best method to manage forests to store carbon is a much-debated topic (Valentin and Sebastiaan, 2014). While trees absorb CO_2 from the atmosphere, wood can be utilised as an alternative to fossil fuels as well as a substitute for building materials such as concrete and steel. Over the past decades, forests have taken up to thirty percent of the anthropogenic CO_2 emissions, which is similar to the absorption of the oceans (Pan et al., 2011).

The forest carbon cycle describes the life cycle of a tree. During the growing phase, a tree absorbs CO_2 which is released during decomposition or when burned as wood. Therefore, forests can act as temporary storage of CO_2 and substitute some of the fossil fuels. From 1990 to 2005, the net sequestration (carbon storage) of forests in Europe equated to approximately ten percent of the region's fossil fuel emissions (Valentin and Sebastiaan, 2014). With the quality and consistency of forest management differing significantly across the globe, projection models disagree whether the forest carbon balance in 2100 will be positive or negative. Models vary from forests becoming a carbon sink, absorbing thirty-six gigatons of CO_2 per year, to becoming a source of carbon, emitting 22 gigatons of CO_2 per year (Valentin and Sebastiaan, 2014).

It is also worth noting that approximately twenty-five to thirty percent of CO_2 released into the atmosphere every year dissolves into the ocean, contributing to the ongoing acidification (NOAA, 2016a). Small-scale experiments have investigated the potential for injecting captured CO_2 into the ocean where it could be stored for centuries at great depth, untouched by the atmosphere (Metz et al., 2005). However, no controlled, deep ocean studies have been performed. Therefore, the effects and consequences that the CO_2 might have on the marine life and the ecosystem remains unclear (Metz et al., 2005).

2.2.7 Carbon Mineralisation and Mineral Carbonation

The following section will explore the background of carbon mineralisation and mineral carbonation methods in greater depth. A summary of the literature will be given to determine its usefulness but also show its limitations. Bacterially mediate carbon mineralisation will be expanded on to evaluate what the potential utility of this method could be to overcome some of the impediments of the passive carbon mineralisation methods.

Introduction

Power et al. (2011) noted that carbon sequestration is the natural reaction of magnesium and calcium-containing minerals with CO_2. Over time, carbonates are formed, sequestering CO_2 permanently. Carbon sequestration has many unique advantages, such as the abundance of feedstock (rocks) as well as the natural occurrence of the process. Lastly, the carbonate is a stable product that needs supervision, and the re-release of CO_2 is not an issue. The overall slow reaction time and sequestration of CO_2 remains a major drawback. Therefore, the main challenge will be to identify an environmentally friendly, scalable industrial solution with favourable economics.

Much of the earth's outer layer comprises of adequate rock type for these processes (Burgess et al., 2011). The IPCC Special Report on Carbon Dioxide Capture and Storage (Metz et al., 2005) noted that there are enough magnesium and silicate deposits around the world to sequester all the CO_2 that would be produced if all known fossil fuel resources were burnt. One deposit in Oman alone would have the potential to fix all CO_2 that has been added to the atmospheric concentration since the start of

the industrial revolution (Kelemen and Matter, 2008). Over geological timescales, the chemical reaction forms a stable compound and thereby permanently absorbs the CO_2. This process has been well described in the literature, and its feasibility has been proven (Beinlich and Austrheim, 2012; Power et al., 2007; Pronost et al., 2011; Wilson et al., 2006). The problem, however, is its usefulness for the human or industrial timescale (Zevenhoven et al., 2011). The current hurdles are the slow speed at which the chemical reactions are taking place.

Due to its slow speed of absorbing CO_2, scientists have looked at ways to speed up the reaction in order to make it useful for the human timescale (Zevenhoven et al., 2011). When applying heat and pressure, the absorption can indeed be sped up. In this thesis, this process is referred to as 'accelerated carbon mineralisation' (See Table 7). However, the main drawbacks are the associated costs, which render the process financially unviable (Zevenhoven et al., 2011). Estimated prices for this process range with very high variability from USD 64 to USD 128 (Adjusted from 2016 Australian Dollars) per tonne of CO_2, (Burgess et al., 2011; Hitch and Dipple, 2012; Metz et al., 2005). Currently, there are only a few countries worldwide that have put a price on carbon (See: 2.2.6). Without a price on the emission of carbon dioxide, it is not realistic and not financially viable to have accelerated mineral carbonation in place for the absorption of carbon dioxide.

Definition of Carbon Mineralisation

Carbon mineralisation is the reaction of CO_2 with an alkaline earth metal that bears silicate and hydroxide minerals ('silicate weathering'). The reaction forms a stable and poorly soluble carbonate at near-surface temperatures (Power, Harrison, et al., 2013). Materials that can be compounded involve elements of calcium, magnesium, and iron. Magnesium silicates, such as serpentine and olivine as well as calcium silicates, draw the most attention as all of them are widely spread throughout the world. Australia, however, seems to be in a somewhat unique position as it has large deposits of low-grade magnetite which would be suited for sequestering CO_2 via the mineral carbonation process (Burgess et al., 2011). Carbon mineralisation is a naturally occurring process, albeit a prolonged one, and will therefore eventually sequester large amounts of anthropological GHG's through 'natural weathering,' a process of crustal rocks which comprises of the outer layer of the earth (Burgess et al., 2011).

Zevenhoven et al. (2011) have done an extensive and wide-ranging literature review on the subject. They confirm that mineral carbonation mimics a naturally occurring 'weathering' process. During the weathering process, calcium (Ca) or magnesium (Mg) from silicate minerals dissolve in water and binds over geologic time with CO_2, forming stable calcium and magnesium carbonates ($CaCO_3$, $MgCO_3$) which are environmentally benign. It is stable and represents the long-term storage of CO_2. Mineral carbonation, on the other hand, is described as the acceleration of the carbon mineralisation process using pressure or heat to speed up sequestration rates of CO_2. Table 7 contrasts these three methods.

Throughout this thesis, the biologically accelerated carbon mineralisation method will be referred to as '(biological) carbon mineralisation,' the natural method will be referred to as 'natural carbon mineralisation,' and the method of using heat and pressure will be referred to as 'heat/pressure mineral carbonation.'

Table 7: Carbon mineralisation vs. Mineral carbonation

	Carbon mineralisation (Passive)	Carbon mineralisation (Accelerated)	Mineral carbonation
Occurrence	Natural	Artificial induced, (Bio geochemically, bacteria)	Artificially induced (Heat & pressure)
Temperature and Pressure	Ambient, standard pressure	Ambient, standard pressure	Artificial heat and pressure
Relative sequestration speed of CO_2	Low	High	High
Relative energy economics	High	High	Low
Cost per tonne of CO_2 sequestered	Nil	Not estimated	Varies, AUD 30 - 255

(Power et al., 2014), 1) (Hitch and Dipple, 2012), 2) (Metz et al., 2005), 3) (Burgess et al., 2011)

Usefulness and application of Carbon Mineralisation

Translating carbon mineralisation into an economically viable technology, which would allow fixing large amounts of CO_2, has been extensively researched since the 1990s. Seifritz (1990) was the first to suggest utilising carbon mineralisation to harness anthropogenic CO_2 while Lackner et al. (1995) was the first to propose the utilisation of ultramafic rocks on an industrial scale.

Many suitable locations with adequate feedstock for carbon mineralisation can be found across the globe. Examples include Finland, Portugal, USA, some regions in Australia, and Oman. Detailed lists of deposits around the world can be found in the following chapters of the thesis. One deposit in Oman alone has the potential to fix all

CO_2 that was added to the atmospheric concentration since the start of the industrial revolution (Kelemen and Matter, 2008).

Recent research in the field of carbon mineralisation as favoured the following two approaches: in situ carbon mineralisation and ex-situ carbon mineralisation. The in-situ method makes use of the potential energy, which is inherent in the exposure of the earth's crust (tectonic mantle of peridotite) at the surface. Furthermore, there is little need for extensive transportation or treatment of solid reactants. It requires low energy for maintaining optimal temperature and pressure for carbon mineralisation to take place (Wilson et al., 2014). In situ carbon mineralisation is promoting subsurface carbonation via direct injection of CO_2 or via injection of dissolved CO_2 bearing solutions directly into the mafic and ultramafic formations (Cipolli, 2004; Gislason et al., 2010; Kelemen and Matter, 2008). Ex-situ carbon mineralisation at industrial sites focuses on low-temperature and low-pressure carbonation of alkaline industrial wastes such as smelter slag, fly ash, alkaline and saline brine, construction waste, and mine tailings (Wilson et al., 2014). Examples of ex-situ carbon mineralisation include the utilisation of mineral waste from mining sites and turning it into new products, such as cement, plasterboards or bricks (Mineral Carbonation International, 2018).

Limitations of Carbon Mineralisation

It is widely recognised in the literature that the sequestration of CO_2 via carbon mineralisation, passive, accelerated, or artificially induced, has the potential to absorb vast quantities of CO_2. The IPCC Special Report notes that 'there are enough magnesium and silicate deposits around the world to sequester all the CO_2 that would be produced, if all known fossil fuel resources were combusted' (Metz et al., 2005). Furthermore, carbon mineralisation is an overall exothermic process and requires no post-storage supervision as it is a stable product (Romanov et al., 2015). If all estimated carbon mineralisation feedstock in this thesis were utilised to absorb CO_2, the subsequent release of energy would warm the world oceans by a negligible $3x10^{-5}$ degrees Celsius (See Table 8).

Table 8 - Carbon Mineralisation Exothermic Energy

CO_2 sequestration via Forsterite	$Mg_2SiO_4 + 2HCO_3^- + 2H^+ <-> 2MgCO_3 + SiO_2 + 2H_2O$
Energy release per ton of CO_2 sequestered (Gibbs free energy)	511.04 Megajoule
Sequestration potential estimated in this thesis	7,254 Megatons (Equal to 7,254,000,000 tons of CO_2)
Total energy release	3,707 Petajoule (Equal to 60% of Australia's annual energy consumption)
Celsius heat units	The amount of energy required to raise the temperature of 1 lb of water by 1 degree Celsius
Total warming of the oceans through total energy release	0.00003 degrees Celsius

Sources: (Australian Government, 2018a; ConvertUnits, 2019; Power, Wilson, et al., 2013; Purdue University, 2019)

Despite all the benefits, research and development (R&D) have not yet yielded a technology that is mature enough to be applied in a large-scale project while simultaneously being economically viable. The significant drawbacks are revolving around slow chemistry flowsheets as well as the vast quantities of feedstock and other materials that are required to induce the reaction. Furthermore, there are concerns about the overall energy economics of the process (Zevenhoven et al., 2011).

Notwithstanding, carbon mineralisation undeniably has the potential to be an attractive addition to underground sequestration of carbon as it offers large quantities of feedstock as well as a permanent storage solution of carbon. However, as the International Energy Agency states, 'it is unlikely that mineralisation will offer an opportunity for sequestering large volumes of CO_2' (IEA, 2008). This is due to the unfavourable energy economics, and the accompanying high costs per tonne of CO_2 sequestered. The IPCC special report on CCS (Metz et al., 2005) estimated the costs for mineral carbonation to range from USD 64 to USD 128 (Adjusted from 2016 AUD). The Novel CO_2 capture task force report (Burgess et al., 2011) found similar numbers, indicating process costs of the order of USD 180 (Adjusted from 2011 AUD) per tonne of CO_2 (See Table 7). Dipple and Hitch (2012) assessed the economic feasibility analysis of integrating carbon mineralisation into mining operations since the required feedstock is adequately stored in-situ via mine tailings (See Figure 3). They found a vast range of USD 29 to USD 245 per tonne of CO_2 sequestered (Adjusted from 2012 AUD). This assumption is further underpinned by various other studies across the globe, attributing this to the poor energy economics of mineral carbonation (Burgess

et al., 2011; Metz et al., 2005).

Bacterially mediated Carbon Mineralisation

Mineral deposits that are hosted in mafic and ultramafic rocks and deposits have been identified in various locations around the globe. The mineral system can form nickel-copper (Ni-Cu), nickel-copper-cobalt (Ni-Cu-Co), and nickel-copper-platinum group elements (Ni-Cu-PGE) sulphide deposits, found in association with some of the main iron ores (Geoscience Australia, 2016a). Ultramafic rock typically contains a high proportion of magnesium oxide which can equal up to fifty percent of the weight (abundance of magnesia as serpentine and olivine), which is an ideal feedstock for the carbon mineralisation process (Metz et al., 2005).

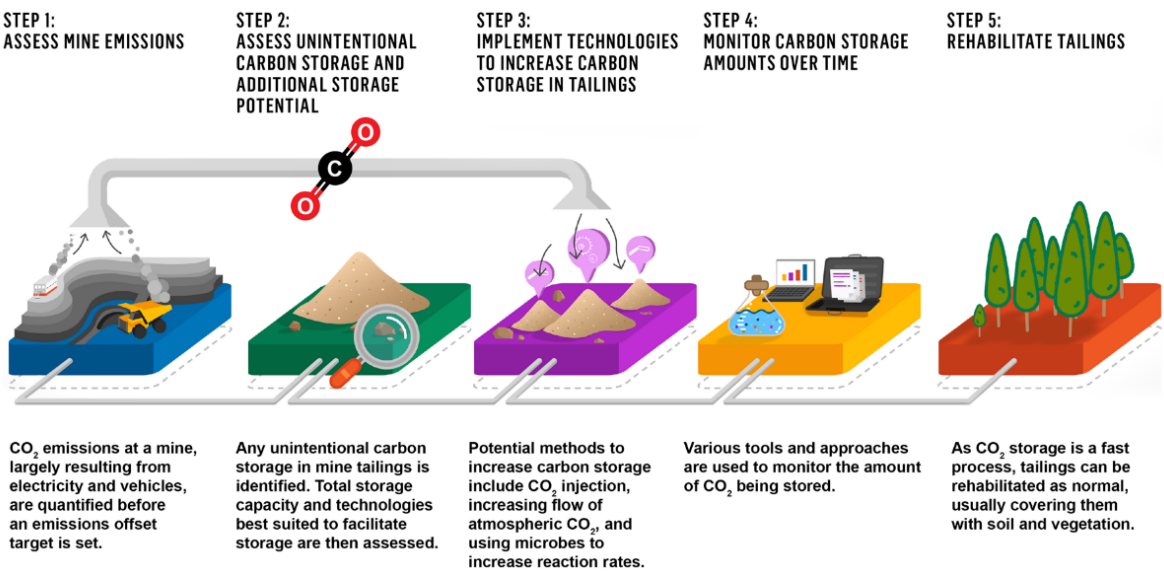
Utilising mineral waste rocks from ultramafic mine sites for carbon mineralisation has been previously documented (Beinlich and Austrheim, 2012; Pronost et al., 2011; Wilson et al., 2006). However, when estimating the carbon dioxide absorption rates, generally, small sample sets have been used. More recently, complementary laboratory experiments and reactive transport modelling have been deployed to investigate and quantify the carbonation rate in mine tailings (Wilson et al., 2014). However, a developing technology that uses naturally occurring soil bacteria (Cyanobacteria) to induce the carbon mineralisation process without the need of external energy sources overcomes many of these obstacles (Power et al., 2009). As stated, this CO_2 sequestration method will be referred to as carbon mineralisation (Table 7). Carbon mineralisation utilises the original, naturally occurring passive carbon mineralisation process, which occurs at a near-surface temperature and standard pressure. Therefore, it overcomes one of the biggest roadblocks of accelerated mineral carbonation, which requires heat and pressure to speed up the carbonation. More recently, complementary laboratory experiments and reactive transport modelling have been deployed to investigate and quantify the carbonation rate in mine tailings (Wilson et al., 2014). The utilisation of in-situ mine tailings as feedstock for CO_2 sequestration is ideal, seeing that the rocks are conveniently crushed up, increasing absorption rates. Mine tailings currently serve no further purpose after mineral extraction; therefore, their utilisation as feedstock for CO_2 sequestration can create a positive, unintended contribution.

Passive, weathering-related carbonation processes take advantage of the

thermodynamically driven natural transformation of ultramafic rocks into carbonate and are thus cost and energy effective.

A depiction of the process, as envisioned by De Beers Company, can be seen under Figure 3.

Figure 3: Mineral carbonation process at a diamond mine site



(Mervine et al., 2018)

Although these strategies have proven effective in laboratory-scale studies, Power et al. (2014) point out that pilot projects are necessary to evaluate strategies for carbon mineralisation which, if successful and cost-effective, could be incorporated into tailings storage facility design of future mine sites to sequester CO_2. The authors discuss these strategies and propose two scenarios for pilot projects, which if implemented at the mine-scale could render some mining operations carbon-neutral. They also provide estimates of the operational costs of the proposed scenarios on a dollar per tonne of CO_2 basis as well as quantification of the financial benefits to better assess the potential of carbon mineralisation strategies (Power et al., 2014).

2.2.8 Understanding the Potential of Carbon Mineralisation

Understanding the potential of carbon mineralisation as a means to absorb CO_2 is discussed in the first two chapters of this thesis. Here, the sequestration potential from both an Australian and a global perspective is assessed, based on both nickel and diamond mine sites. Nickel and diamond are primarily hosted in mafic and

ultramafic rocks, which, when ground up, are an ideal feedstock for carbon mineralisation. Businesses around the globe find themselves in an ever-changing context as discussed in the second part of the literature review. It has been understood that several forces are drivers for change. Society continues to demand goods and services of higher quality. However, there is an increasing focus on environmental aspects. At the same time, policymakers try to establish unifying frameworks and regulatory approaches with a global impact in mind, reducing opportunities for freeloading, economic runoff, and arbitrage (Linnenluecke, Smith, et al., 2017). Firms, on the other hand, need to continually prepare themselves for future changes in the legislative and competitive landscape (Linnenluecke et al., 2015). Current trends seem to indicate that a price on carbon, in one form or another, is inevitable for the majority of countries around the globe (CPLC, 2017; Gallé, 2017; World Bank and Ecofys, 2018). Therefore, it is of the utmost importance for the firm to investigate avenues that could contribute to the decarbonisation of economic activity early on to gain a competitive advantage as carbon prices continue to gain traction (World Bank and Ecofys, 2018).

Carbon mineralisation could offer a unique perspective for selected countries, regions, and firms to reduce their externalised costs and carbon footprint. The mining industry is designated to have a profound interest in this solution, as it could help render some of the sites carbon-neutral or even become a carbon-sink (Wilson et al., 2014).

At a time where only a few countries and regions enforce a price on carbon, the justification of the business case for carbon mineralisation is difficult to establish. Traditionally, governments enforce change by applying a valuation and pricing structuring mechanism to evoke the desired outcome. However, it becomes clear that putting the ‘right’ price on carbon is a highly complex topic, resulting in different prices and utilised models around the world. As suggested by Pezzy (2019), governments could tackle the problem via marginal abatement costs instead of trying to put a value on the social cost of carbon. Modelling low-cost approaches through marginal abatement costs could present a pathway to reach climate targets. Nevertheless, pioneers in the industry are leading the way and have paved the way to change in the past, adopting unconventional methods and ideas early on. The second part of the literature review aims at understanding how the business case for sustainability can

be justified and how carbon mineralisation has the potential to fit into that framework.

Global Motivation

World Bank President Jim Yong Kim stated the following in 2017 at the One Planet Summit:

'To meet the objective of the Paris Agreement, we need to get to ... scale. None of the critical investments will be possible unless we get the policies right. That means creating incentives for change—removing fossil fuels subsidies, introducing carbon pricing, increasing energy efficiency standards, and implementing auctions for lowest-cost renewable energy' (The World Bank, 2017b).

To tackle the problem of GHG emissions on a global level, one needs to recognise that there is an inherent circular equation problem present. While governments are committed to address the problem and decarbonise their economies, the impression arises that it has been challenging to find common ground across nations. Depending on the countries' industries, geographical location, economic status, and development, different 'best-practice' scenarios emerge. This, in turn, leads firms to be unaware of how to move forward and in what way they will be part of the solution. The often-absent price on carbon makes it difficult to price it into the corporate financial decision-making framework. Hence, the firms have no incentive to stop emissions from rising.

This circular problem needs to be addressed on a global level with a unified framework that works across borders. In doing so, countries will lack the incentive to abstain from their responsibility. Furthermore, it will de-incentivise firms from pursuing economic run-off, where they relocate to a less regulated country or region. Once the global problem is addressed, solutions need to be found on a local level to tackle the emissions. All countries can have an array of different methods and need to develop tailor-made solutions fitted to their potential. Seeing that today's most industrialised nations are responsible for the majority of the past emissions, least developed countries (LDCs) will strongly oppose having the same restrictions being applied to them, seeing it as their turn to pollute. This could be resolved by offering financial incentives for LDCs to leapfrog certain technologies such as coal-fired power plants and instead directly opt for renewable energy solutions (LDC Climate Change, 2016).

Industry Motivation

Having a legally enforced price on carbon would have substantial implications across all industries, particularly energy-intense industries such as the mining sector. In 2018, the optimisation of energy consumption was amongst the top ten business risks faced by the mining industry (Ernst & Young, 2017b). The report by Ernst & Young noted that increased government incentives and policies drive the industry to increasingly support renewable energy to reduce GHG emissions (Ernst & Young, 2017b).

In order to understand how to incorporate corporate financial decision-making frameworks that include a price on carbon, industry leaders are already changing the way of doing business. Microsoft has been a front-runner with regards to charging an internal price on carbon to all their offices, fostering creative, sustainable solutions, and optimising energy efficiency by holding them accountable for their emissions (DiCaprio, 2013; Microsoft, 2018)

It is estimated that the development of cleantech patents has the potential to contribute in the order of US$10 to US$15 trillion by 2050 (Linnenluecke, Han, et al., 2017; OECD/IEA and IRENA, 2017). The corporate financial decision-making framework would be affected, creating the necessity of incorporating the price of carbon into any investment decision in order to make smart choices. It is for these reasons that many industry leaders start to think about ways of adjusting their decision-making frameworks at an early stage to be ahead of the competition once a price on carbon is legislated globally.

Governmental Motivation

From a governmental perspective, it is crucial to pick and apply the right policies and incentives to support countries, regions, and industries with the achievement of the emission targets and the decarbonisation of their activities. Governance and legal developments in the implementation and definition of emerging carbon pricing initiatives must also foresee the potential for such technology innovations and allow for systems that are dynamic to reach new sectors and achieve scale (World Bank and Ecofys, 2018). While many carbon markets around the globe had a rough start, especially cap-and-trade due to their market-based mechanisms, prices and coverage

have picked up recently (Investing, 2019). Nevertheless, due to the lack of a globally unifying agreement, the majority of the emissions are either uncovered by a price on carbon or far below anything that is considered a 'fair' social cost (see 2.2.4).

Australia, with other developed and developing countries, has proposed various pathways to address its emission reduction targets. The Deep Decarbonization Pathways Project (DDPP) is a collaborative global research initiative which develops individual pathways for its member countries to transition to a low-carbon economy from a technological, socio-economic, and policy perspective. To achieve the decarbonisation of the energy systems, a three-pillar model has been developed: energy efficiency and conservation, decarbonising electricity and fuels, and switching to energy end-uses to lower-carbon ones with the goal to eventually switch to zero-carbon energy carriers, such as renewable energy, in combination with CCS (Deep Decarbonization Pathways Project (2015), 2015).

Under the 'Paris Agreement,' Australia plans to tackle their pledged reduction of emissions via a portfolio of policies. Amongst others, it plans to decarbonise its energy production by promoting the deployment of renewable energy as well as the overall improvement of energy efficiency. Part of the solution is the National Energy Productivity Plan, which aims to improve productivity by forty percent between 2015 and 2030 (Australian Government, 2015b). This thesis aims at identifying what impact carbon mineralisation could have on the proposed pathways, in Australia, as well as from a global perspective.

Academic Motivation

From an academic point of view, the lack of research that investigates the economic potential mineral carbonation could have is acknowledged. Little research has been undertaken to investigate what the country-specific and aggregated potential is to support the decarbonisation of economies via this method. Furthermore, there is a clear absence of a business case built around carbon mineralisation, which in part acts as a roadblock for industry participants to invest in said technology.

Picot et al. (2011) have assessed the worldwide potential for ex-situ mineral carbonation and identified eight major mine sites that are within a 300-kilometre radius of a large CO_2 point source (>1 megaton of CO_2 per year). However, the self-imposed

restrictions of having to be within a sizeable CO_2 point source narrows potential mine sites tremendously. Furthermore, the carbonation methods discussed by Picot et al. (2011) use heat and pressure, which vastly differs economically from the biologically induced method presented in this thesis (see 2.2.7). Bodéan et al. (2014) describe how mineral waste could be used to sequester large amounts of CO_2. However, their paper also assumes the utilisation of heat and pressure to facilitate the chemical reaction, which is financially a non-viable option given current prices on carbon.

This thesis presents a different approach, assessing both nickel and diamond sites for adequate feedstock on a global level. In doing so, the results might give insights to the assessed countries and promote pathways that leverage mine tailings to sequester large amounts of CO_2 with the mission of decarbonising both industries and economies.

2.3 Part 2: The Potential of Carbon Mineralisation

The first part of the literature review investigates the usefulness of carbon mineralisation and its potential role as a means to attain country-specific goals outlined under the Paris Agreement. Building on these findings, the second part of the thesis investigates decision-making within the firm. Executives often adopt a short-term perspective, which seems to relate to compensation and general decision-making criteria that are primarily tied to annual and quarterly reporting. The research aims at analysing the current state, identifying roadblocks preventing firms from investing in methods such as carbon mineralisation, and offering a redefined decision-making framework. Having a framework that incorporates a long-term outlook of the firm and embeds sustainability would enable the maximisation of the long-term creation of shareholder value.

2.3.1 Short-Termism

The first part of the literature review has highlighted the theoretical potential for mineral carbonation as a means for the mining industry to decarbonise their economic activities. Chapter 3 and chapter 4 will be dedicated to assessing the amount of CO_2 that could be absorbed from nickel mines, both from an Australian and global perspective. This second part of the literature review aims to understand why firms do not support the idea of reducing their carbon footprint via mineral carbonation, a technology which requires a modest investment. The hypothesis is that flawed and inadequate managerial decision-making tools, agency problems, executive compensation, investor pressure, and other problems can lead to short-termism, preventing firms from looking at methods that internalise social costs through such means as mineral carbonation.

The institutional level, the firm level, and the individual level are explored. The literature aims to understand where the three realms intersect and what the repercussions are of the friction caused by said intersections. The tension between sustainability, triple-bottom-line, and shareholder value maximisation is also explored. It is further recognised that more recent developments in the firm's landscape provide a changing context. Customers along the value chain, governments, and executives at the firm drive new ideas, changing the institutional sphere and leading firms to implement corporate social responsibility, sustainability, and social engagement. This

proves to be a different view from the traditional 'shareholder approach,' leaning towards a 'stakeholder approach'[2].

Short-Termism is 'the focus on short time horizons by both corporate managers and financial markets, prioritizing near-term shareholder interests over the long-term growth of the firm' (Mason, 2015).

An organisation is supposed to balance the short-term resources without compromising the long-term survival to be sustainable (Bansal and DesJardine, 2015; Laverty, 1996). Undervaluing, overlooking, or intentionally ignoring the value of the long-term outlook can create an imbalance and poses the potentially biggest threat to a company's sustainability.

Short-termism can generally be used interchangeably with 'myopia,' or more precisely, 'temporal myopia.' Both terms describe a temporal orientation that focuses on the short over the long-term and are defined as a cognitive limitation that can affect decision-making (Miller, 2002). The idea of short-termism is not limited to the executives of the firm but can equally be attributed to other stakeholders, such as shareholders. Samuel (2000) described shareholder myopia as the tendency to focus on the short-term behaviour of stock prices over long-run.

Investments in research and development (R&D), as well as other intangible expenses, require a long-term view, as the potential pay-off usually materialises at a much later point in time. The costs, on the other hand, must be borne in the present. This is a classic example of an intertemporal trade-off and carries the inherent risk of executives of the firm being tempted to forgo long-term returns for short-term results because of short-termism and the subsequent pressure from investors (Terry, 2015).

As Meadows and Wright (2008) state, one of the challenges of short-termism is the fact it does not have adverse effects on all parties involved. A single investor or executive of a firm can reap benefits and derive personal gain from transferring the burden onto the next in line. Therefore, the need to address short-termism does not solely stem from an individual level, as it can be beneficial, but from a societal or

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[2] For a comprehensive critique of stakeholder theory, see Donaldson and Preston (1995); Key (1999); Phillips et al. (2003)

collective point of view, seeing that it can have a net-negative effect (Meadows and Wright, 2008; Rieg, 2015).

The following section examines current literature with regards to what the main structural determinant drivers of short-termism are. It identifies three main realms, which are the institutional, the firm, and the individual level. Here, it is explored where the realms intersect and what the subsequent effect is. It is essential to point out that the identified determinants of short-termism are not a conclusive but an illustrative list.

2.3.2 The Institutional, Firm and Individual Realm

Institutionalism

In strategic management, three main views have emerged. Initially, the industry-based view (Porter, 2008), followed by the resource-based view (Barney, 1991), and more recently, the institution-based view (Peng, 2002, 2003). In recent decades, as part of a broader intellectual movement, various strategic management researches evaluated that institutionalism is more than purely background conditions. On the contrary, institutionalism shapes and determines what arrows firms have at their disposal in their proverbial quiver (Dimaggio and Powell, 1983; Peng et al., 2008).

Institutions were defined by North (1990) as human-made constraints that structure human interaction. This is in contrast to Scott (2013), who sees it as a means to provide social behaviour with meaning and stability through regulative, normative, and cognitive structures. While institutions can be comprised of various actors depending on the definition, North's (1990) scheme loosely identified formal and informal components. The formal component is mostly composed of governmental rules, regulations, and policies (North, 1990). This shows that the government can directly influence the institutional realm through the introduction of new legislation and policy. The informal component is created and influenced by all actors. It entails norms, ethics, and cultures which are based on normative and cognitive pillars which develop and change over time (North, 1990). Institutions can emerge after the fact, that is, when a firm has made a significant contribution in an emerging field and subsequently becomes institutional in the first instance before being influenced by the government and emerging competitors, setting the 'rules of the game' (Peng et al., 2009). Peng et al. (2009) further argued that while both formal and informal institutions govern the

behaviour of the firm, the informal role becomes more significant and helps to reduce uncertainty and provide legitimacy in times where formal constraints are either unclear or fail to deliver support. However, it is often observed that as firms mature, the decisions start to become more rational, whereby the institutional realm is influenced, and a constrained environment is created that leaves little room for change later on. Large and established organisations can reach a point whereby the institutional environment is virtually defined and dominated by them, making new entrants follow suit instead of changing it (Dimaggio and Powell, 1983).

Dimaggio and Powell (1983) argued that organisations are becoming more alike over time, something described as 'Institutional Isomorphic Change.' Three main mechanisms are identified, all of which contribute to firms copying each other and becoming less different: coercive isomorphism is derived from political influence, such as the firm versus other competitors. This leads firms to start adapting to each other and becoming more similar. Mimetic isomorphism is defined as the imitation of legitimacy. New entrants face a high uncertainty in the environment and start copying norms and values of established firms. The last mechanism is normative isomorphism (Dimaggio and Powell, 1983).

For this thesis, we define the institutional realm as the environment in which the mining industry is situated. This encompasses virtually all stakeholders surrounding firms of that sector. Furthermore, it includes competitors and investors (institutional and private), the natural environment, employees, management, the government with its local, regional, and national legislation, but also global policies such as the Paris Agreement.

While the Paris Agreement is an extraordinary achievement on a global scale, it remains a voluntary commitment and is legally non-binding (UNFCCC, 2015b). The agreement does provide accountability to some degree. However, it remains to be seen whether it can achieve its goals by 2030 and 2050. This thesis does not provide insights into how regulatory and policy approaches can lead to the decarbonisation of economies worldwide. Having a global agreement can provide a shared vision, but it will not alleviate the problem. One way to approach this issue is the rise of other stakeholders in the absence of strong formal institutions so that radical change can occur on a national and local level, driven by firms and individuals through means of

being influential industry leaders. This circular problem has already been acknowledged in part one of the literature review.

The stakeholders mentioned above shape and influence the institutional realm and are at the same time influenced by it. An example of the institutional realm of the mining industry can be found in the Social License to Operate (SLO) (Thomson and Boutilier, 2011). In Australia, the past decades have seen the mining industry come under increasing pressure with regards to the way that their business is conducted, as well as the change of societal values and attitudes toward the environment as well as the industries that have negative impacts on it (Thomson and Joyce, 2006). It has become clear that it is no longer satisfactory to follow the formal legislative conditions but that it is also necessary to hold an SLO (Lacey et al., 2012). The SLO needs to be earned by the company through their stakeholders and requires constant management of the needs and expectation of local communities, employees, and the government (Australian Government, 2013; Winston, 2018b). It is a privilege to be earned and a vital pillar of any mining company and was subsequently named amongst the top business risks faced by the industry in 2018 (Ernst & Young, 2017b). Tahoe Resources Inc. mining company had failed to consult with the local population at the Escobal silver mine in Guatemala. This failure to earn its SLO lead to the suspension of mining activities and a subsequent drop in Tahoe's share price of approximately forty percent (Scheyder, 2018).

In the following paragraphs, various intersections of the institutional, the firm, and the individual realms, all of which have the potential to lead to short-term behaviour, are investigated.

The Firm

A firm can be defined as a nexus of contracts (Jensen and Meckling, 1976). An organisation is a social unit, an entity comprising of a multitude of people, founded to either meet a need or pursue collective goals. Organisations have a management structure with assigned roles that determine the relationships between different activities of its members. Coase (1937) analysed why organisations exist in the first place and what the reasons for their existence are under certain conditions. A firm is one form of legal creation which serves the purpose of a nexus for contracting relationships. Coase (1937) found that due to the numerous transaction costs, such as

the search for information, bargaining, enforcement, and trade secret costs, contracting might become too costly. Focusing on the cost of using markets to effect contracts, Coase argued that it only makes sense to do so if the cost of using said markets is higher than the costs of using direct authority (make vs. buy). Therefore, to avoid those costs, firms arise and produce what is needed internally instead of outsourcing it, whereby the number of contracts and subsequently the transaction costs are significantly reduced (Coase, 1937, 1960). Furthermore, the firm is characterised by shares, which represent a divisible residual claim on the assets and cash flow of the respective organisation. These shares can, in general, be sold without consulting or needing the permission of other shareholders (Jensen and Meckling, 1976).

Under the premise of the management principle, known as value-based management, it is within the duty of the executives to first and foremost serve the needs of the shareholders (Hillman and Keim, 2001). Therefore, it is commonly accepted that the primary objective of the executives is to maximise the value of the firm for its shareholder (Boatright, 2017; Moyer et al., 2017). Pigou (1920) stated that economic theory suggests that the firm should not concern itself with any negative externalities by internalising them unless it strictly relates to shareholding stakeholders. Therefore, according to Pigou, the firm should focus on its core business and not address societal issues with regards to communities, employees, or the environment. A clear distinction between profits and shareholder value, maximising short-term profits versus the creation of long-term shareholder value, needs to be made. However, consensus can still be found between the two statements (Barton and Wiseman, 2015). The famous article by Nobel Laureate Milton Friedman (1979) put it more directly, as he stated that the sole social responsibility of a business is to increase its profits and executives only motivation should be to increase the long-term shareholder value. This was coined as the shareholder approach as opposed to the later-developed stakeholder approach, which sought to broaden the concept and push it beyond traditional economics origins (Freeman and McVea, 2001). Friedman authored this article during a time where the notion of corporations having to act responsibly started to gain traction. While he did argue for firms to focus on shareholder value creation, he was not opposed to firms engaging in social welfare activities at all. However, his rationale was that focusing on core activities will itself increase social welfare in free-

market capitalism (Dunn and Burton, 2006).

In the context of this thesis, the ‘firm’ is defined as a participant of the mining sector. The mining industry is subject to both formal and informal influences in its institutional realm. From a formal perspective, the mining sector is tightly regulated, which is also due to its heavy involvement with the natural environment and the potential consequences that derive thereof. On the other hand, various informal aspects need to be considered. The mining industry faces a lot of public exposure, scrutiny by environmental advocates, and increased demand for accountability by end consumers. The combination of this pressure is increasingly shaping the institutional realm and exerts a lot of pressure on mining companies to rethink their practices and become more innovative with environmentally friendly solutions to extract minerals to reduce their carbon footprint.

Due to the nature of mining activity, firms in this industry traditionally assume a long-term vision for the projects that they undertake. An average nickel mine site has an extraction period of approximately twenty years, not including lead time, while copper mines can be mined for up to seventy years (Statista, 2019). Despite this long commitment, mining companies often seem to lack a holistic, long-term outlook. Short-termism is prevailing even in the most significant companies as two recent ecological disasters in Brazil have shown. Both events seem to have stemmed from reluctance to comply with work-safety standards, which lead to the death of hundreds of people, irreversible ecological damage, the destruction of dozens of billions of shareholder value, and billions of dollars in legal fees and compensation claims (BHP Billiton, 2018; Lannin, 2017; Macalister, 2016; Phillips, 2018).

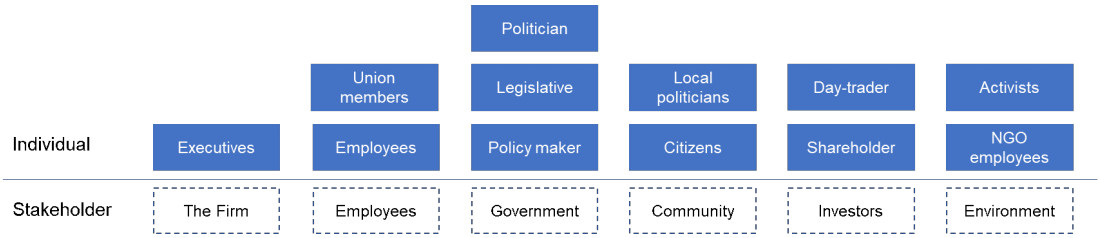
Another example can be found in the Alberta oil sand industry in Canada, which contain the third-largest reserves of oil, behind Saudi Arabia and Venezuela. The energy-intense process of separating the oil from the sand is very energy-intensive, accounting for roughly 10% of Canada’s GHG emissions in 2013 (Liggio et al., 2019; Stocker et al., 2014). The operation companies face an intertemporal decisions, as to whether they chose a long-term strategy and actively invest into technologies upfront to mitigate the effects of climate change or wait for the government to implement more stringent regulations that will legally force them to do so (Slawinski and Bansal, 2015). While most companies chose to focus on short-term profits and delay the investment

of large sums into technologies, some industry players have decided to forgo short-term profits in anticipation of future changes in legislation and regulation, to stay ahead of the competition (Slawinski and Bansal, 2015). The following paragraphs identify some of the reasons that might lead to short-termism as it can be found in existing literature and how the firm realm intersects with the individual and the institutional realm.

The Individual

The focus of any conversations about proposals on how to decarbonise economies traditionally revolves around global policies such as the Paris Agreement (UNFCCC, 2015b). Furthermore, there is a focus on individual economies and countries, providing an individual pathway to achieve their goals such as the Australian pledge to reduce GHG emissions twenty-six to twenty-eight percent by 2030 (Australian Government, 2015b; Meinshausen and Alexander, 2017; UNFCCC, 2015a). However, it is crucial to recognise the individual as an integral part of the process. People are at the foundation of any organisation and institution in the stakeholder realm and are therefore part of the problem and solution. Acemoglu and Johnson (2005) noted that it is the individual (also through the firm) that often finds ways to alter the terms of both formal and informal contracts in the presence of weak contracting institutions. It is also the individual that is capable of driving change, be it advocates of the natural environment, the broader community, the government, or the firms. For example, in the context of relevance regarding climate change and GHG emissions, Busch and Hoffmann (2007) and Kolk and Pinske (2007) identified investors, customers, and competitors as some of the most essential stakeholders. All are composed of various individual whose actions contribute in some way to the ever-changing landscape and discourse (Carroll, 1991). Figure 4 depicts an excerpt of the landscape of individuals that make up the stakeholders of an organisation such as a mining company.

Figure 4: Stakeholders (own creation – based on Carroll (1991))



While most of the individuals of these stakeholders can have an impact on both the firm and the institutional realm, it is essential to note that there are differences in influence. An executive of the firm has an overall higher potential to make a significant impact on the firm and the institution compared to an activist.

The examination and impact of all relevant individuals amongst stakeholders provide an interesting context for further research. In the context of discussing the intersection of the individual realm with the institutional and the firm, the focus will be on the executive of the firm, without touching on other stakeholder individuals, since the individual at the firm level has the highest potential of driving substantial change. While policymakers hold significant power and could bring about regulatory changes (coercive isomorphism) leading to the overturn of the inherently assumed short-term perspective of many firms, no overarching, unifying, and binding agreements have been reached. Therefore, the absence of such formal institutional context gives rise to the informal institutional context, enabling the individual to influence this realm. Larry Fink, CEO of Blackrock, wrote in his 2019 letter to CEOs that the absence of government had created a vacuum that needs to be filled with leadership. He stated the following:

> ‘Stakeholders are pushing companies to wade into sensitive social and political issues – especially as they see governments failing to do so effectively.’
> (Fink, 2019).

The change brought about by executives of the firm can have a significant impact. To produce industry-leading firms that can drive substantial change, it is essential to have individuals at the foundation that create and drive such a vision. In accordance with Dimaggio’s paper (1983), institutional isomorphism (mimetic and normative) has the potential to work both ways, driving positive or negative change. Industry leader individuals can pave the way with best-practice approaches and positively influence the informal institutional realm in the absence of the coercive, formal pillar. This, in turn, can influence competitors to align with their visions and spread their ideas over time.

However, the individuals at the firm-level, such as executives, find themselves in a situation where a balancing act between personal goals and firm goals needs to be struck (Jensen and Meckling, 1976). Agency theory discusses this mismatch in detail

and subsequently brought about management compensations systems, which try and curb selfish behaviour and align the goals of the individual with the company's goals (Eisenhardt, 1989; Jensen, 1983). It becomes problematic when the design of these compensation systems is flawed in their ways to measure the individual's success, which are often based on metrics such as quarterly company results, fuelling individual, self-serving actions (Barney and Ouchi, 1990). It incentivises the executive to take a short-term strategy and make investment decisions that produce the desired quarterly results. The results of such actions can subsequently lead to the destruction of shareholder value and compromise the long-term strategy of the firm (Murphy, 1999, 2013).

Paul Polman, the long-time CEO of Unilever, is a strong advocate for abandoning quarterly reporting. He introduced this measure on his first day at his new job in 2009 (Boynton, 2015). Since then, notable figures of the industry, such as Warren Buffet (Berkshire Hathaway) and Jamie Dimon (JP Morgan Chase), have reinforced Polman's view and urged publicly listed companies to move away from quarterly reporting to reduce the pressure for short-term profits (Davis and Chiglinsky, 2018). The issue of quarterly reporting is further discussed in section 2.3.3.

2.3.3 Drivers of short-termism

With the institutional, the firm, and the individual realms defined above, the following paragraphs identify where they intersect. These intersections are researched for findings in the literature as to what degree the caused friction has the potential to drive short-termism.

The literature investigating short-termism has identified four main pillars that can serve as an explanation (Rieg, 2015). First, the rules, structure, and actors of the capital markets. This relates to the frequency of reporting, which can cause short-termism. It also refers to the actors in capital markets, such as investors under pressure who in turn pass on that pressure to executives of the firm (Bhojraj et al., 2009; Demirag, 1995; Ernstberger et al., 2019).

The second pillar revolves around the type of ownership and structure of the firm. It has been established that privately-owned firms have a different time horizon compared to publicly traded firms. While private firms often adopt a long-term vision

due to the absence of short-term pressure, public firms tend to take a shorter strategy (Zellweger, 2007). In this thesis, the focus will be on solely on public firms.

The third pillar highlights the importance of proper corporate governance, which can incentivise or disincentivise particular behaviour. Evidence has been found that executives will act in a short-term manner when offered incentives that reward such behaviour and vice versa (Demirag, 1995; Marginson and McAulay, 2008; Marginson et al., 2010). Laverty (2004) takes the position that executives operate within the given framework and, in the absence of a clear structure, the systems are to blame, not the individual.

The fourth pillar surrounds the personal traits of the individual, who can have a disposition towards short-term behaviour. This is discussed in parts with regards to management compensation (Jensen and Meckling, 1976; Laverty, 1996).

It is noted that the identified and described intersections are by no means a definitive list of what has been discussed in the existing literature. The following paragraphs represent an excerpt of what has been deemed useful with regards to how the institutional, firm, and individual realms have been outlined as per the preceding sections. A focus is put on the individual at a firm-level as has been defined in the prior paragraph. The reason for this is because it is seen to have the highest potential to be a strong driver for change. The following subchapters, however, provide a literature review that serves as a foundation for chapter 5 of this thesis.

This thesis focuses on exploring the potential for a novel CO_2 sequestration method, as well as cause and effect of short-termism as means to give reasons why such an approach is mostly unsupported by the mineral industry. However, a behavioural finance or psychology focus may offer more fruitful lenses and will not be part of this thesis.

Quarterly reporting

The institutional realm and the firm level intersect in various ways, such as quarterly reporting. Quarterly reporting is a well-established tool that informs investors on the state of the publicly listed company. It is mandatory in various stock markets and was required in the United States since 1930. The United Kingdom made it

mandatory in 2007. However, they returned to half-yearly reporting in 2014, followed by most European countries (Zaring, 2018).

Accounting and finance research literature finds that the majority of managers sacrifice long-term investments due to pressure from financial markets. A large-scale quantitative study by Graham et al. (2005), which interviewed 400 financial executives, found that as much as seventy-eight percent of the subjects chose to smooth earnings over the long-term value creation, risking potential negative long-term consequences. Some of the results indicated that most executives chose earnings over cash flows as the most important figure, as earnings are considered to be the key metric for investors. According to the interviewees, the most important benchmarks are quarterly earnings and the consensus estimate done by analysts. Managers noted that they are facing a decision where they need to choose between short-term delivery and the long-term objective of making shareholder value maximisation investments (Graham et al., 2005). Stein (1989) showed in his paper how managers are pressured by capital markets to borrow at unfavourable rates. This is done to boost the current market price, and it comes at the cost of potentially destroying shareholder value in the long run.

Ewert and Wagenhofer (2005) demonstrated that increased pressure on price leads to less efficient management decisions through the tightening of accounting standards, which subsequently increased the incentive to manage real earnings. In another study done by Brav et al. (2005), some of the findings concluded that the pressure by capital markets leads managers to avoid cutting dividends at all costs. Since dividends have a negative impact on available cash for investments, some positive NPV investments are left out or are postponed. While dividends appease stockholders in the short-run, positive NPV investments have a more significant impact on shareholder value creation in the long-run. Similar findings by Bushee (1998), Dechowe & Sloan (1991), Bartov (1993), and Penman & Zhang (2002) show evidence that is consistent with the observed behaviour of managers selling assets or reduce spending on R&D to meet quarterly earnings targets. Barton and Wiseman (2015) concluded in their article that executives are affected by the fear of delivering a negative income statement over the coming quarters and the subsequent wrath of the investor, leading them to polish short-term goals instead of focusing on long-term value. This results in buying back shares with excess cash instead of actively investing. In his paper about the macro impact of short-termism, Terry (2015) concluded that the

pressure to deliver short-term results every quarter cuts U.S. growth by about 0.1 percentage points per annum. Conversely, privately held companies invest at approximately 2.5 times the rate of publicly traded companies because they are free to focus on a long-term strategy. The continuously lower investment rates of public companies, namely the 350 most significant listed companies in the US, may reduce U.S. growth by an additional 0.2 percentage points per annum (Terry, 2015).

Drucker (2011) noted, 'Everyone who has worked with American management can testify that the need to satisfy the pension fund manager's quest for higher earnings next quarter, together with the panicky fear of the raider, constantly pushes the top executives toward decisions they know to be costly, if not suicidal, mistakes,.' The tyranny of expecting great quarterly results has been identified as the main culprit for short-term behaviour and is believed to be the principal reason for the perceived decline of the Western economy. This view has been shared by both academic and experts of the fields (Dertouzos et al., 1989; Hayes and Abernathy, 1983; Jacobs, 1991; Laverty, 1996; Porter, 1992).

There is disagreement from other experts. Robert Pozen (2016) noted that investors would try to fill in the blanks when not receiving quarterly reports of non-US companies by relying on price-relevant information of other companies' quarterly reports of the same industry. This can create a problem since the price reactions during the missing quarters might be overreacting to the information given by U.S. company reports. This can cause substantial cost to the investors with regards to inaccurate pricing during the missing period and potentially lead to insider trading (Pozen, 2016). Instead of omitting quarterly reports, Pozen suggests stretching the assessment period for management incentive systems, which currently usually comprise of one year, to three to five years to reduce short-termism.

Another approach involves steering clear of quarterly reporting for listed companies, which forces said organisations to focus on the short term instead of the long term. Paul Polman, CEO of Unilever, decided to stop producing quarterly reports on the first day he started his position in 2009 (Boynton, 2015; Winston, 2015). He reasoned that:

‘Many companies are driven by the short-termism of the markets. [They] make short-term decisions that often go against the long-term viability of the company. Before I came, we were making a lot of short-term decisions to make the quarterly numbers, [and these decisions were] driving the company, over time, downwards (Boynton, 2015)’

By refusing to publish quarterly results, Unilever is allowing itself to take on a longer view, shunning shareholders that don’t buy into the long-term, value-creation model which offers equitability, sustainability, and shared values (Boynton, 2015). In their paper about the publishing frequency, Gigler et al. (2014) noted it is also a question of governmental policy choice, which can help curb some of the managerial short-termism. Furthermore, it was noted that the layman’s notion of corporate myopia, which is said to be purely fuelled by traders who seek to maximise their short-term gains and ask for managerial action from the firm, is not sufficient to explain this complex problem. While it is true that current, impatient shareholders seek to maximise their payout, they need to care about what the next buyer will pay and so forth. Therefore, this makes the chain of impatient shareholders indefinitely long, caring for the subsequent buyer even though at each stage, one is only concerned with their maximisation of the stock (Gigler et al., 2014).

Nallareddy et al. (2017) studied the effect in the UK, after the introduction of mandatory quarterly reporting in 2007 and after mandatory quarterly reporting was stopped in 2014. It was found that the effect lies somewhere in the middle of two extreme views. The initial introduction of quarterly reporting leads to greater transparency, while the change in the rate of investment was unaffected. After the abandonment, firms that chose to stop quarterly reporting lost the coverage by analysts. While corporate short-termism did not cease to exist, investors were not left entirely in the dark, which is a commonly voiced concern (Nallareddy et al., 2017). The paper found that contrary to the opinion expressed by Warren Buffet and Jamie Dimon (2018) and Larry Fink (2018), earning guidance does not categorically destroy value. Rajgopal (2018) concluded that it is paramount for the firm to balance the short-term needs without having the long-term focus compromised by quarterly reporting. Having voluntary quarterly reporting would allow each firm to individually decide whether it provides a net-benefit and then make a justified decision.

Finance Reaction

The reaction of the financial markets, which can include institutional and private stockholders, analysts, or portfolio managers, is a critical intersection where the institutional realm meets the realm of the firm. Financial markets provide essential signals to firms and the public with regards to their corporate governance, earnings outlook, and the general pricing of the firm. However, short-term corporate behaviour has been identified as a severe problem, with many firms prioritising quarterly earnings over long-term investment. This topic has been explored under 'Quarterly Reporting.' The following subchapter presents findings in the existing literature regarding the role of the interplay of earnings management, analysts, and short-term investors, who are often framed as being part of the problem (Edmans, 2017).

A popularly held view is that institutional investors and analysts assume a short-term view when giving advice or actively making investment decisions (Marston and Craven, 1998). The overall contribution of this, particularly in the U.S. and the UK, is seen as detrimental to the long-term corporate development of shareholder value. Dallas (2011) noted that it is of further importance to distinguish between various categories of institutional shareholders. Shareholders that are classified as transient, with regards to their stability of the portfolio as well as the size of the stakes taken, seem to have a short-term focus time-horizon. This type of shareholder is classified as having a high portfolio turnover and a highly diversified portfolio as well as having a high use of momentum trading (Dallas, 2011). Institutional ownership by transient shareholders can affect the executive decision-making and influence the spending on R&D as an earnings management tool to meet the short-term targets (Matsumoto, 2002). This form of earnings management can affect the reporting quality since these firms are more likely to build accruals that cannot be mapped into cash flow realisation. In turn, this can lead to more frequent misreporting compared to long-term oriented shareholders and may have a negative impact on the firm's access to capital on the markets (Burns et al., 2006).

Pressure from capital markets has often been cited as one of the leading causes of short-termism (Jacobs, 1991). Controls on institutional investors have been introduced to counter this pressure and make hostile takeovers more complicated and encouraging firms to focus on the long-term (Laverty, 2004). However, there is

disagreement on whether pressure from capital markets and its institutional investors is the leading cause, seeing that R&D spending increased for companies held by this type of investors, while it was found to be decreasing after anti-takeover measurements had been implemented, essentially having a negative effect on shareholder value rather than reducing short-termism (Meulbroek et al., 1990). On the other hand, Brav et al. (2017) examined the post-hedge fund intervention effect on R&D, both from a quantitative (total expenditure) and qualitative (patent quality and quantity) point of view. It was found that while the spending tends to fall significantly after a hedge fund intervention, there appears to be no reduction in output quality. This led the authors to the conclusion that, on average, the innovation output of the targeted firm improves its efficiency (Brav, 2017). However, Rieg (2015) hypothesised that the problem of short-termism could stem in the first place from firms' goals of maximising shareholder value as well as the practice of value-based management with its appropriate incentives and decisions structure. This leads both investors and executives to behave in a myopic manner (Rieg, 2015).

Earnings management, as touched on in the preceding sub-chapter on quarterly reporting, can further exacerbate the situation. The significance of earnings in the corporate reporting landscape has been demonstrated by Graham et al. (2006). A sample of 401 executives ranked the three most important measures that are reported to outsiders. Earnings reports were the most commonly named measure by over fifty percent of respondents, with revenues coming second (twenty-two percent of participants).

Analysts who provide high expectations force executives to potentially sacrifice their long-term strategy to meet the demand of the stock markets and keep up the earnings of the firm (Graham and Harvey, 2006; Graham et al., 2005). However, there is evidence pointing to the opposite. Bartov et al. (2002) found in their research that firms who manage their earnings appropriately and meet or beat expectations tend to perform better on the long-run compared to firms who missed their earnings. There are still questions as to what role the analysts play, how precise their estimates are, and what the take-aways should be for forecasting the next quarter. This was highlighted in the case of Microsoft, where the analysts' quarterly estimates were beaten forty-one times in a row by the firm (Bartov et al., 2002).

Short-term selling stockholders do not have to be causally linked to short-term behaviour of executives. It can serve as a means to discipline the firm in its practice through a mechanism that is called 'governance through exit' (Edmans, 2017). Here, firms are incentivised not to overestimate and inflate earnings to meet targets and instead carefully plan long-term investments. Evidence suggests that short-term investors will identify such earning manipulation before being publicly revealed and sell their stakes, subsequently diluting shareholder value in the process (Fang et al., 2016). Edmans concluded that 'patient,' long-term capital seems to be very desirable. However, it needs to provide the right kind and not patience and loyalty at any cost. Locking in shareholders to adopt a long-term investment strategy through such incentives as 'loyalty dividends' (Kubota, 2015), higher capital gain taxes for short-term investors, or extra voting rights after a specific holding period might enable longer-term holding periods but does not necessarily provide stewardship; it simply entrenches the acting executives of the firm and encourages the hoarding of control (Edmans, 2017).

Management compensation

The relationship between stockholders and executives of a corporation can be defined as a pure 'agency relationship,' and therefore all prevalent issues associated with 'separation of ownership and control' subsequently arise (Jensen and Meckling, 1976). The foundation of agency theory discusses arising problems when cooperating parties engage in risk-sharing while having different attitudes towards said risk. Jensen (1976) attributes the theory of agency relationships and the subsequential costs associated with said relationship as one of the reasons why the goal of the firm can be compromised or inadequately served. An agency relationship is defined as a contract under which one or more agents engage another person, the agent, to perform services on their behalf; either some or all decision-making authority is delegated to the acting agent. Agency problems arise when labour is divided, and responsibilities between cooperating parties with different goals are shared. The most common association with this principal-agency relationship is when the owner of the firm (shareholder) outsources the task of running the business to a third party, who takes on the role of executive (Eisenhardt, 1989; Jensen and Meckling, 1976).

Agency theory reconfirms the importance of incentives and self-interest within an organisation. It serves as a reminder that within the life of an organisation, most actions

are based on self-interest (Barney and Ouchi, 1990). Adam Smith (1776) wrote that 'the directors of such [joint-stock] companies, however, being the managers rather of other people's money than of their own, it cannot well be expected, that they should watch over it with the same anxious vigilance with which the partners in a private copartnery frequently watch over their own. Like the stewards of a rich man, they are apt to consider attention to small matters as not for their master's honour and very easily give themselves a dispensation from having it. Negligence and profusion, therefore, must always prevail, more or less, in the management of the affairs of such a company'.

The appearance of a goal conflict between agent and principal arise when different people engage in a cooperative effort bound together by a contract. The subsequently resulting costs associated with agency problems are called agency costs (Jensen and Meckling, 1976). Agency costs arise when the principal limits the agents' divergence from his outlined interests by establishing monitoring tools as well as incentives to restrict the deviant activities. It is viewed as impossible to have zero agency costs while having the goals of the agent and the principal aligned at the same time (Jensen and Meckling, 1976). The total reduction in welfare for the principal as a subsequent result of the divergence from the goals by the agent is also considered as a cost of the agency relationship, namely defined as 'residual loss.' Therefore, the total agency costs are defined as the sum of monitoring expenditures, bonding expenditures plus the residual loss(Jensen and Meckling, 1976). Two significant contributions can be drawn from agency theory, attributing them to organisational thinking: the first concerns the treatment of information. In agency theory, information is treated as a commodity which can be purchased at a certain cost. Knowing this, formal and informal information systems are being given an important role. Furthermore, it implies that organisations should invest in information systems to curb the appetite for agent opportunism (Eisenhardt, 1989).

The early 1900s were accompanied with the emergence of 'professional executives' which were non-owners hired to manage a firm's assets on behalf of the shareholders, displacing traditional owner-managed and family-founded firms (Murphy, 2013). Agency problems subsequently arose between the parties, as explored early on by Berle and Means (1932) and Jensen and Meckling (1976). While there is a recognition that many boards do have compensation, systems linked to the

performance of the executives, they often do not serve the interest of the shareholders. Furthermore, there is ample research expressing surprise at the fact there is a lack of appropriate performance-driven compensation packages for executives (Pearce et al., 1985; Ungson and Steers, 1984).

While it is assumed that the negotiation of executive compensation packages is supposed to be arms-length bargaining between managers and board members, it seems as if the reality has strayed far from the said model. Bebchuck and Fried (2004) argue that it is the pervasive role of managerial power which has flawed and distorted the current compensation landscape, hand-in-hand with corporate governance processes.

The managerial power that executives have over board members is dependent on various features of the respective corporate governance of each firm (Bebchuk et al., 2002). This suggests that the more managerial power an executive has over the board, the higher the compensation and the lower the performance-based components. The managerial power approach contains one crucial building block named 'outrage cost' (Bebchuk et al., 2002). These costs reflect the extent how the said agreement is perceived by outsiders, whose views matter to the executive and the board. The more outrage is expected by a compensation package, the less willingness from the executive to demand it since it is likely that the board will be reluctant to approve it. Executives and boards might expect this reaction and resort to another pillar of the managerial power approach: camouflaging. Here, the compensation package will try to conceal the actual level of performance-sensitivity (or insensitivity), thus allowing executives to reap benefits without having to fear public outrage (Bebchuk and Fried, 2004).

Bebchuck (2012) hypothesises that executive compensation arrangements did provide incentives for excessive risk-taking in the lead-up of the financial crisis. Often, the design of pre-financial crisis management compensation leads executives to be fully exposed to the upside of risks taken. However, they were shielded substantially from the downside. This shield incentivised executives to take risks beyond optimal levels for the firm and shareholders (Bebchuk, 2012). One of the main reasons for excessive risk-taking lies partially in the design of the compensation package with a focus on short-term results, decoupling from the long-term creation of shareholder

value. Therefore, executives were able to cash in their equity-based bonuses based on short-term rises of stock prices (Bebchuk and Fried, 2009). Several studies further confirmed the findings of Bebchuk, supporting the hypothesis that the design of pay structure can contribute significantly to risk-taking behaviour by executives of the firm (Chesney et al., 2019; DeYoung et al., 2013; Gande and Kalpathy, 2017).

Executives argue that the systems their companies operate in, such as the financial market pressures and overreactions, encourage decisions that at times sacrifice long-term value to meet earnings targets. This logic echoes the evidence in the survey by Brav et al. (2005) on corporate payout policy. They find that strong stock market reactions drive executives to avoid cutting dividends at all costs, even if this means bypassing positive Net Present Value (NPV) investments which in theory prove that said investments contribute positively to the creation of shareholder wealth (Brav et al., 2005). The influence of decision-making tools as a means to contribute to short-termism is reviewed under 2.3.1.

Much of the literature is in agreement that an executive compensation package that is adequately designed can serve as a critical piece to good corporate governance. It does so by aligning the goals of the executive with the goals of the shareholders concerning decision-making and long-term strategy. Aside from a base salary, most compensation packages include a bonus, stock options, a severance package, and performance-based incentives (Faulkender et al., 2010).

Kirkpatrick (2009) analysed the post-financial crisis lessons learnt from a corporate governance point of view. This was not limited to compensation but also included risk management systems. It was concluded that the financial crisis could in part be attributed to the significant weaknesses in the corporate governance arrangements, which in turn lead to failures as they did not protect the goal of the firms and encouraged excessive risk-taking. Furthermore, it was concluded that in several cases, the remuneration systems were not aligned with the strategy and the risk appetite of the firm as well as the long-term interests (Kirkpatrick, 2009).

Marginson et al. (2010) concluded in their explorative study on the relationship between performance measurement systems and short-termism that the results do not support the idea that financial systems in general lead to short-termism, which was

also confirmed by other literature (Erel et al., 2013; Fahlenbrach and Stulz, 2011). Furthermore, their study also does not support the hypothesis that using non-financial measurements can discourage such behaviour. They concluded that it is crucial which way either type of system is utilised, seeing that non-financial measure can lead to short-termism when used purely in a diagnostically manner and financial measures (Marginson et al., 2010). However, Fahlenbrach and Stulz (2011) investigated whether the incentives related to chief executive officers (CEOs) of banks were associated with poor performance during the credit crisis. Their findings showed that compensations systems that are well aligned with the interests of the shareholders did not produce better results than non-aligned systems. One of the explanations given is that CEOs took excessive risks to maximise shareholder wealth under the aligned management compensation systems, which lead to unexpected outcomes (Fahlenbrach and Stulz, 2011).

Mehran et al. (2011) proposed tying parts of the compensation of executives to a measure of the default riskiness of the firm, to align the shareholders' preferences. Other research, such as done by Bebchuck and Spamann (2009) as well as Edmans and Liu (2010), does suggest to link the compensation scheme of executives directly to debt. Compensating executives with 'inside debt' (debt held by managers within the firm, such as pension fund benefits) is claimed to be of superior efficiency compared to equity-based incentives, such as stocks and options, in their effort to curb agency costs (Edmans and Liu, 2010).

Decision-making models and tools

In the previous subchapters, the possible effect of financial markets, quarterly reporting, and management compensation as a cause for short-termism were explored, highlighting some of the problems that can arise during such a relationship as well as the potential impact on shareholder value. In this section, the decision-making models and tools that executives of the firm utilise are being investigated.

Building on the previously identified definition of short-termism (Section 2.3.1), Laverty (1996) defined short-termism as 'decisions and outcomes that pursue a course of action that is best for the short term but suboptimal over the long run.' Laverty describes the possible decision that executives face between two mutually exclusive project options: 'A' and 'B.' 'A' yields an immediate net return, which initially is higher

than the one of ‘B’ up to a certain point in the future, while ‘B’ initially offers a negative net return before eventually surpassing ‘A.’ This simple model highlights the need for decision-making models with a long-term view and highlights the ‘optimal’ trade-off between the long- and the short-run (Laverty, 1996).

Schumpeter (1942) had already highlighted that appraising a choice of investments that is out of sight (ex visu) at a given point in time makes no sense, for the reason being that this decision is dealing with a process whose elements may only come into full effect in the distant future. Loewenstein and Thaler (1989) described such intertemporal choices as making a decision ‘in which the timing of cost and benefits are spread out over time.’

Decision-making models are at the core of any intertemporal choice since their outcome can have a significant influence on the objective of shareholder value maximisation. Therefore, they inherently possess the potential to either compromise short-term profits or ensure long-term sustainability for the firm. The complexity is that such an investment decision can take several years before its actual value-added is revealed as noted by Laverty (1996) and Henderson (2015). Since the initial cost of such investments is borne in the present, executives might be tempted to forgo long-term returns for short-term results, fuelled by short-term thinking and investor pressure (Terry, 2015). Therefore, the timing of dealing with these trade-offs as well as the tools utilised to make said decisions become apparent and are central to the notion of a sustainable, long-term outlook (Laverty, 1996).

Laverty (2004) further hypothesised that while executives are well educated on the notion of valuing long-term investments with tools such as NPV, it is possible that the decisions are not all made on a rational basis. This hypothesis is based on the observations of Frederick et al. (2002), who concluded that decision-makers stray far from utilising the NPV discounting model in a normative manner in a wide range of situations.

Kurz (1987) defines rules that ignore all intertemporal substitution possibilities which may arise from unevenly distributed resources as myopic decision rules. This is in contrast to nonmyopic decision rules, whereby the decision-maker simultaneously considers all limitations over the entire period and makes optimal intertemporal choices

based on the constraints given. This leads to the generalisation that myopic behaviour, or short-term decision-making, can be defined as compromising the long-term goals for the short-term concerns (Kurz, 1987).

Winston (2017, 2018a) argues that some of the problems surrounding short-termism in firms derive from widely-used decision-making criteria. Return on investment (ROI), as an example, is not consistent with the creation of long-term shareholder value, seeing that the return component often fails to adequately reflect off-balance-sheet intangibles such as brand value and reputation, which can make up to eighty percent of the value of a firm (Ocean Tomo, 2017; Winston, 2017).

The concept of the time value of money is crucial for the understanding and effectiveness of financial management as it is essential for the decision-making process for executives of the firm. Money can be thought of having a time value in a way that money received today is more valuable than receiving the same amount of money in one years' time. The primary reason for a dollar today (present value) having more value than a dollar tomorrow (future value) is the opportunity to invest it and earn a rate of return (interest). Interest is the return that is paid to an investor who forgoes the opportunity to utilise today's money to either consume or invest alternatively. The invested money at present value will end up being worth more in the future, under the condition that the interest rate is not negative (Moyer et al., 2017).

Baucells (2018) showed that the average applied discount rate on the intertemporal choice between receiving money today versus receiving money half a year, one year, two years or four years in the future was very high, averaging at sixty-five percent for MBA students and three-hundred percent discount rate for non-MBA students. Also, the further away the payout was from today, the lower the chosen discount rate was. Baucells determined this displays a pattern of decreasing impatience, effectively being a change of mind without changes of any other parameters. It was further concluded that people tend to pay attention when consequences are large but are lenient when smaller consequences are involved, something called the 'Magnitude Effect' (Baucells, 2018). As previously demonstrated (Frederick et al., 2002; Johnson and Bickel, 2002; Read, 2004), the magnitude effect highlights the poor understanding of time value of money as well as the interlinked discount rate.

Investment decisions over the short or long-term are often based on the use of the Discounted Cash Flow (DCF) method, such as it is common in the mineral industry (Bhappu and Guzman, 1995). Here, the net expected future cash flows are identified and discounted at the cost of capital (rate of return). After having discounted the anticipated cash flows, the net initial investment is subtracted from the sum, whereby one is left with the Net Present Value (NPV). The decision rule under the NPV method states that an investment should be accepted if the net present value is equal to or greater than zero, which is in accordance with the creation of shareholder value. If the NPV is less than zero, the investment should be dismissed, as its execution would result in a reduction of shareholder value (Moyer et al., 2017).

While discounted cash flow models and the subsequent NPV analysis are prevalent throughout the corporate landscape, they are not without flaws. NPV does consider the time-factor to the extent that it values money now higher than money later, which has been described in the previous section. However, it assumes perfect certainty of the expected project cash flows (Miller and Park, 2002) and furthermore omits the underlying volatility of options and the potential influence on the investment decision, such a situation where $NPV_{now} < NPV_{later}$ (Moel and Tufano, 2002). Therefore, the NPV model treats the investment as assuming a passive position. That is, once the decision has been made to either go forward with a project or walk away (positive or negative NPV), nothing else is considered. In reality, most investment projects take place in a highly flexible environment where deferring, expanding, or contracting an investment can be seen as viable alternatives, especially in a market with high uncertainty. Dixit and Pindyck (1994) showed that the static NPV model ignores the flexibility which is inherent in most projects and therefore forgoes the flexibility which can be acquired with real options (Moel and Tufano, 2002). The uncertainty factor, represented as volatility, can drive the value of a deferred investment past a simple NPV assessment. For such a decision, real options might be the preferred valuation method for investments (Moel and Tufano, 2002; Robinson and Kyng, 2003; Trigeorgis and Reuer, 2017). See Table 9 for the four options.

Table 9: Real Options

Investment Timing Option	Abandonment Option	Shutdown Option	Growth Option
Delaying an investment for a certain period can allow a firm to gather additional information with regards to inputs, outputs, market conditions, or changes in policy. Investing today versus waiting for one year to invest in the same is an example of mutually exclusive projects. 'Waiting-to-invest' is a standard option that characterises real options.	The abandonment option essentially walks away from the running investment. This is a real option and an important decision within capital budgeting. A choice can be made between salvaging the equipment on the secondary market or switching to an alternative product while utilising as much of the equipment of the existing project as possible. This real option can be used to limit the potential downside risk of an investment.	A firm might have to consider to temporarily shutting down a project that displays current negative cash flows. An example can be found within the mining industry where a mine site of a particular type of mineral can be shut down due to low market prices. Once the prices have recovered, operations can continue and become financially viable again.	When an opportunity presents itself to a firm to invest into a new venture or research area, it may choose to build a small facility, make a strategic acquisition, or run a pilot project to serve the new potential new market. While the initial net cash flows are usually negative, and therefore, the project will also yield a negative net present value, such investments can be seen as a potential growth option for the firm. If this option is exercised in the future, it may eventually lead to a more substantial, positive net present value investment.

(Moyer et al., 2017)

The valuation of a novel approach to CO_2 sequestration, such as carbon mineralisation, with traditional methods, such as the NPV method, prove to be financially unviable due to the mostly absent reasonable price on carbon (See 2.2.4). Therefore, such an investment decision would be deemed economically unviable, returning a negative NPV and thus creating no incentive for a firm to invest in such a venture. As mentioned previously, the NPV model assumes that a project is held passively once the decision to invest has been made and assumes perfect knowledge of expected cash flows (Miller and Park, 2002). In reality, this does not hold true as there are various dynamic decisions to be made during the lifetime of a project such as expanding, contracting, or abandoning a project (Power et al., 2014). Dixit and Pindyck (1994) illustrate that the NPV process ignores the real option's flexibility, whereby the executives of a firm obtain the right but not the obligation to take a different strategic approach at some point in the future. One of the main implications of applying real options is to deal with the underlying uncertainty that firms face when deciding about investing in such projects as carbon mineralisation. It helps the firms to capitalise and better understand the uncertainty (Chung et al., 2013). Overlooking real options and implementing them as a fixed part of capital budgeting can result in missed opportunities thanks to poor judgement and decision-making. While real options have been known for several decades, most executives avoid them due to a lack of knowledge and expertise (Baker et al., 2011).

The growth option showcases the potential of real options with its underlying volatility. Its relevance for this thesis can be illustrated with the following example: a mining company in Australia does not pay for CO_2 emissions since the price of carbon was revoked in 2014. Given the accomplishments of the last Conference of the Parties in Paris, Marrakech, and Bonn (2015 – 2017) and the subsequent pledge by the Australian government to significantly reduce its GHGs over the following decades, it is likely that the mining sector will have to contribute in one form or another to said goal (Australian Government, 2015b; Deep Decarbonization Pathways Project (2015), 2015; UNFCCC, 2015a). Utilising the conventional discounted cash flow approach is overall useful and should be considered. It can result in a downward-biased estimate of the real value of a project's net present value and contribution to shareholder value. Real options, on the other hand, offer a more dynamic pricing approach and help to reflect the inherent value of managerial flexibility to adapt on future in highly volatile markets

(Moyer et al., 2017; Power et al., 2014).

Investing in carbon mineralisation as a mining company could potentially be justified from an ethical, sustainable, or responsible point of view. While strictly applying the NPV model to such an undertaking does not yield a positive value at current prices on carbon in most countries, utilising real options as a valuation method highlights that an early, modest investment into the development of this carbon-capturing method today might be beneficial. Using real options model for opening, delaying or shutting down decision has been identified as a useful descriptor in the mining industry (Moel and Tufano, 2002). With today's low carbon price, rendering the project currently financially unviable, a potential investor, such as a mining company, could essentially create an option but not an obligation to expand the investment. In doing so, the modest investment would give the company the option to quickly capture the unlimited upside potential once the market has corrected the carbon price in the future and gain a competitive edge thanks to an early investment and the subsequently acquired expertise. The inherent value of the real option can then be captured by mining companies invested in the technology when the price of carbon moves closer to the true SCC (Power et al., 2014). It needs to be noted, however, that the real options model could also reveal that the most viable outcome is to delay the investment decision until a different price might justify the option to invest (Wait-and-see approach).

2.3.4 A changing context

The preceding chapters investigate the findings in the literature with regards to the potentially pervasive short-termism in the realms of the firm. This following section provides an insight into the changing context and the rise of the importance of how firms are becoming increasingly sustainable (Bansal and DesJardine, 2014). Paul Polman, the former CEO of Unilever, abandoned quarterly reporting to focus on sustainability not as an act of kindness but as the creation of long-term business value (Polman, 2013). This section of the literature also highlights the differences between sustainability and corporate social responsibility (CSR). While these terms are often misused interchangeably, the key differences are compared and contrasted. At the same time, there is a concern that some firms practice 'green-washing,' creating a perception around brands of an ethical and sustainable correct strategy (Aybaly et al., 2017). This section of the literature review will serve as a segue for the main chapters

of the thesis, investigating how the method of carbon mineralisation could serve as a means for mining companies to reappraise their mine sites and become both socially responsible and sustainable at the same time.

Sustainability and Corporate Social Responsibility

The term 'sustainability' has become increasingly popular and fashionable in recent years, associated with the right and wrong-doing of firms (World Commission on Environment and Development, 1987) while the exact meaning of the term is often neither clearly defined nor understood. While it is mostly associated with environmental issues, it is often used interchangeably with corporate social responsibility (Bansal and DesJardine, 2014). Sustainability gained much attention in the late 1980s, when social issues, including life quality and human rights issues, particularly in less-developed countries, became more apparent (Sharma and Aragón-Correa, 2005). With the increased focus on said societal issues, the public pressure continuously increased and new approaches to deal with the existing problems needed to be found. The goal was to find approaches regarding the integration of environmental protection and development and ultimately alleviate poverty. Subsequently, the World Commission on Environment and Development (WCED), an entity of the United Nations, defined sustainable development in 1987 as follows: 'Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (World Commission on Environment and Development, 1987, p. 41). This definition implies that sustainability has the goal to secure equity for generations to come. From an organisational perspective, it created the challenge of improving human and social welfare while simultaneously reducing the environmental impact of business activities and making sure that corporate objectives are achieved (Sharma, 2002). Variations of the definition by the WCED followed concerning organisations, referred to as corporate sustainability. Some of the definitions were either of ecological concern or related to a broader concept of corporate sustainability, namely to integrate corporate economic activities while also focussing on social and natural stakeholders (Dunphy et al., 2003). The term sustainability has since become used more frequently, and its use in literature has since been exponential (Google Inc., 2018). These observations are in line with the findings of the research paper by Linnenluecke & Griffith (2013): business research activity in corporate sustainability has grown, with numbers of publications having

grown from 50 each year in the 1990s to over 500 per year in 2010 (Linnenluecke and Griffiths, 2013). However, instead of treating corporate sustainability as an inseparable part of the organisation, the focus has been revolving around stakeholder management as well as discussions about what the impact on the financial performance is when implementing sustainable practices. Furthermore, the paper notes that the corporate sustainability field of research is mostly disconnected from such issues as climate change or finite resources (Linnenluecke and Griffiths, 2013).

For firms to survive, they must invest in a way that caters to both short-term and long-term revenue streams (Bansal and DesJardine, 2015; Laverty, 1996; Samuel, 2000). On a micro-level, a firm runs the risk of underinvesting into research and development (R&D), which will erode the long-term income streams. Firms that manage the balancing act of short versus long-term investments will enhance their chance of survival (Bansal and DesJardine, 2014). The central point of sustainability is that it requires a trade-off. Bansal and DesJardine call it an 'intertemporal trade-off,' leaving a firm with the decision of either investing more for higher profits later or less for smaller profits sooner (Laverty, 1996). This goes hand-in-hand with the trade-off between exploration and exploitation. A firm has a finite amount of resources which it can choose to distribute between marketing to sell more products (short-term) and research and development (long-term) to secure a steady pipeline of new products.

Business or corporate sustainability is defined by Bansal and DesJardine (2014) as the ability of a company to respond to short-term needs without compromising their (or others') future needs. This definition fits as an antidote to the definition of short-termism as defined in 2.3.1. It can also be seen as a resource-based view, focusing on managing the 'triple bottom line' (TBL), an accounting framework term first coined by John Elkington (1998). Instead of purely focusing on traditional measurements such as shareholder value, TBL included the environmental and societal dimension. It has been seen as a pivotal support instrument of making an investment decision that 'captures the essence of sustainability by measuring the impact of an organisation's activities on the world…including both its profitability and shareholder values and its social, human and environmental capital' (Savitz, 2013). While scholars have found a consensus on the definition of TBL, one of the main problems is how to measure it, seeing that the interrelated dimensions of profit, people, and planet do not share a common unit of measure (Slaper and Hall, 2011). Lozano and Huisingh (2011)

suggested that while an integrated reporting framework can help provide a holistic view on both the financial and non-financial performance of a firm, interlinkages between the two will further help the creation of better performance analysis.

Carroll (1979) defined the corporate social performance of the firm more in-depth and found it to contain four components: economic responsibility to investors and clients, legal responsibility to abide the law, ethical responsibility to society, and discretionary responsibility to the community. The advent of globalisation has increased calls for firms to utilise their resources and address a wide range of social problems. Examples can be found within the pharmaceutical industry, where companies are asked to donate free vaccines to nations and patients that cannot afford the necessary treatment. However, it has also been questioned (Hillman and Keim, 2001) whether this is an adequate role for firms within society: can successful firms address such societal issues and be economically viable at the same time? Hillman and Keim (2001) further analysed how the firm's shareholders respond to such increased responsibilities in current competitive capital markets. In their paper, it was suggested to divide the responsibilities into two categories: stakeholder management and social issue participation. Stakeholder management is only concerned with serving the primary stakeholder that has a direct relationship with the company, such as employees, customers, or governments. Social issue participation relates to the utilisation of the firm's resources to participate in social issues which do not have a direct link to the relationship with primary stakeholders. Abstaining from such issues can include, but is not limited to, refraining from doing business in countries accused of human rights violation, refusing to sell to the military, or engaging in tobacco, alcohol, and gambling (Hillman and Keim, 2001).

Hillman and Keim (2001) went on to test their hypothesis, which implied that the investment in stakeholder management might be complementary to the creation of shareholder value and provide a competitive advantage for the firm. The argument is that this investment creates a closer relationship with the primary stakeholder and presents a resource advantage that cannot be easily copied by competitors. It is also noted that in this case, not only shareholder value is being created, stakeholders' likewise profit. The participation in social issues, on the other hand, proved to have a negatively correlated relationship and is not seen as a means to create shareholder value. It is crucial to note that these conclusions are strictly applicable to the creation

of shareholder value. It needs to be taken into consideration that some firms may have multifaceted performance goals to attend, which can include social issues activism (Hillman and Keim, 2001).

Campbell (2007) investigated the reasons firms do or do not act in a socially responsible manner, building on earlier work by Rowley & Berman (2000) as well as Ullmann (1985). Given that the goal of the firm is to maximise shareholder value (Boatright, 2017; Moyer et al., 2017), Campbell researches incentives that lead firms to act socially responsible. His findings show that a weak economy, as well as weak corporate performance on a firm-level, can negatively affect the probability that firms will act in a manner that is deemed socially responsible. The reason found for this is that financially sounds firms have disposable funds while firms performing weak do not; this is referred to as the 'slack resource theory' (Waddock and Graves, 1997). Competition, on the other hand, was found to have a more complex effect. High and low competition evokes lower levels of corporate social responsibility, while moderate competition produces the highest levels of social responsibility (Campbell, 2007). There is an argument to be made for the institutional sphere, described in chapter 2.3.2, showing that firms operating in an environment that is regulated, collectively self-regulated, or is monitored by various independent organisations encourage higher socially responsible behaviour. In an increasingly globalised economy, Bartely (2003) showed that governments started to partially off-load regulatory responsibility to the private sector, which leads to the emergence of institutionalised dialogues between firms, NGOs, governments, and other stakeholders to ensure against corporate unsocially behaviour (Campbell, 2007). The idea that the treatment of the stakeholders by the firm is dependent on the institutions within which they operate was also found by other researchers, such as Fligstein and Freeland (1995) and Hall and Soskice (2001). On the other hand, evidence in economic performance literature suggests that there is no coercive need for institutional facilitation of corporate social behaviour in a globalised environment. When firms treat their employees fairly or engage in other forms of social contributions, national development and economic growth improve (Kapstein, 1999; Putnam, 2004; Zak and Knack, 2001).

Linnenluecke and Griffiths (2010) examine the concept of corporate sustainability and its link to culture in organisations, the possibility for organisations to display a unified sustainability-oriented culture, and whether corporate culture can drive

sustainability in organisations. Their findings concluded that in a given organisation, various subgroups exist amongst employees, each emphasising a different aspect in the pursuit of sustainability. The aspects can range from environmental protection, stakeholder management, resource efficiency, or staff development. These findings help explain the 'differentiation perspective,' which states that there is not only one dominant culture with consensus and shared values and beliefs amongst employees prevalent in any given organisation (integration perspective) but an array of subcultures. These subcultures can hold different views and perspectives towards a particular subject, which might even be contradictory to the other subcultures (Martin, 2001; Zammuto, 2005). Linnenluecke and Griffiths (2010) concluded that the subcultures above provide certain barriers for driving a comprehensive sustainability-related change of culture. Nonetheless, changes on the surface level of an organisation can provide a conducive context for changes in employees' values, beliefs, and core assumptions. Change can be driven through such means as publishing corporate sustainability reports or integrating critical measures of sustainability into employee performance evaluation in order to challenge the inherent values and beliefs of an organisation (Dunphy et al., 2003; Linnenluecke and Griffiths, 2010).

These recent findings seem at odds with Friedman's statement in the late 1970s, telling companies to focus on stakeholder-related activities only. Moran and Ghoshal (1997) challenged Friedman's statement and advocated a change of business strategy, one which should reflect that 'what is good for society does not necessarily have to be bad for the firm and what is good for the firm does not necessarily have to come at a cost to society.' It seems that the tide has turned indeed as the Ernest & Young report on environmental, social, and governance (ESG) practices (Ernst & Young, 2017b) exemplifies. Investors, especially institutional investor, have incrementally expressed their support for ESG-related themes. The movement further gained traction when Larry Fink, the CEO of the largest hedge fund in the world, Blackrock, sent a memo in 2018 and 2019 to all S&P 500 firms as well as all the largest corporations in Europe (Fink, 2018, 2019). He stated that firms should stop focusing on quarterly results and dividend payouts and instead concentrate on long-term investments. Moreover, he requested firms to be transparent about future growth plans and focus on environmental, social, and governance factors since they carry real and quantifiable financial impacts. Blackrock manages US$4.6 trillion in assets as of 2017, of which

US$200 billion are in sustainable investment strategies. Fink makes a point of arguing that well-performing companies who track their ESG, in many cases, also signal excellence in operations (Ernst & Young, 2017a). One of the most significant conversation starters was the Conference of the Parties in Paris, 2015 (COP21) as well as the subsequent conferences (UNFCCC, 2015b). Besides raising awareness for climate issues around the globe, the COP21 also stimulated conversation about whether changes will come or not and changed it to talks about what needs to be done to implement the changes towards zero emissions technologies (Ernst & Young, 2017a). It should be noted, however, that the above-quoted findings could be seen as anecdotal evidence, requiring further research to underpin that a truly long-term change in strategy is underway.

CSR differs from sustainability in a way that it does not necessarily require a trade-off decision (Bansal and DesJardine, 2014). By being more responsible today, a company does not prevent itself from being as much or more responsible in the future. Siegel and McWilliams (2001) argue that CSR comprises of various organisational activities that are good for both the company and society at the same time. Since it is not a trade-off, CSR can be seen as a very effective method for improving business (McWilliams and Siegel, 2001). The missing trade-off can be seen as a significant difference between sustainability and responsibility. CSR is a win-win situation which creates value for both the company as well as the society (Porter and Kramer, 2006). It takes the needs and wants of various stakeholders into consideration and balances them by choosing actions that seem most acceptable, regardless of whether they align with the company's overarching strategy or not.

Bansal and DesJardine (2015), on the other hand, conclude that CSR aims to create 'shared value' amongst current stakeholders, whose interests might be diverging, therefore potentially omitting intertemporal trade-offs. CSR aims at fixing a problem in the present while borrowing from the future without compensation. Most business and governmental bodies run charitable, socially responsible departments which tries to counterbalance injustice and inequality (Bansal and DesJardine, 2014). While many mining companies try to create shared values through the strengthening of the local community via the construction of schools and hospitals, the original reason (mining) might compromise the future of the said community by destroying the surrounding environment while additionally disrupting traditional lifestyles. While

decisions are often concluded with community leaders, the future needs might be obscured (Bansal and DesJardine, 2015). According to Bansal and DesJardine (2015), organisations need to step up and minimise the confusion of sustainability and responsibility. Their paper highlights that the only moral imperative, the main principle that should compel any organisation to act, should be to secure short-term resources without compromising long-term survival. This will secure long-lasting relationships, innovation, and the survival of an organisation (Bansal and DesJardine, 2015).

Sustainability, conversely, is not necessarily dictated by moral and sentimental impediments as it focuses on the systems the organisation is operating in. These systems are not morally judged on whether they are right or wrong, but solely on whether they can be sustained over time or not (Bansal and DesJardine, 2014). The time component of sustainability becomes central as it is supposed to balance the resources usage and supply over time adequately. When the resources consumed are not matched by the planet's capacity to regenerate them adequately, one borrows from the future. This statement is true for any extraction or consumption of resources, whether it is mining for minerals, oil drilling, gas fields or logging. Over time, this will lead to the inability of future generations to meet society's needs (Bansal and DesJardine, 2015).

Unsustainable Business Model

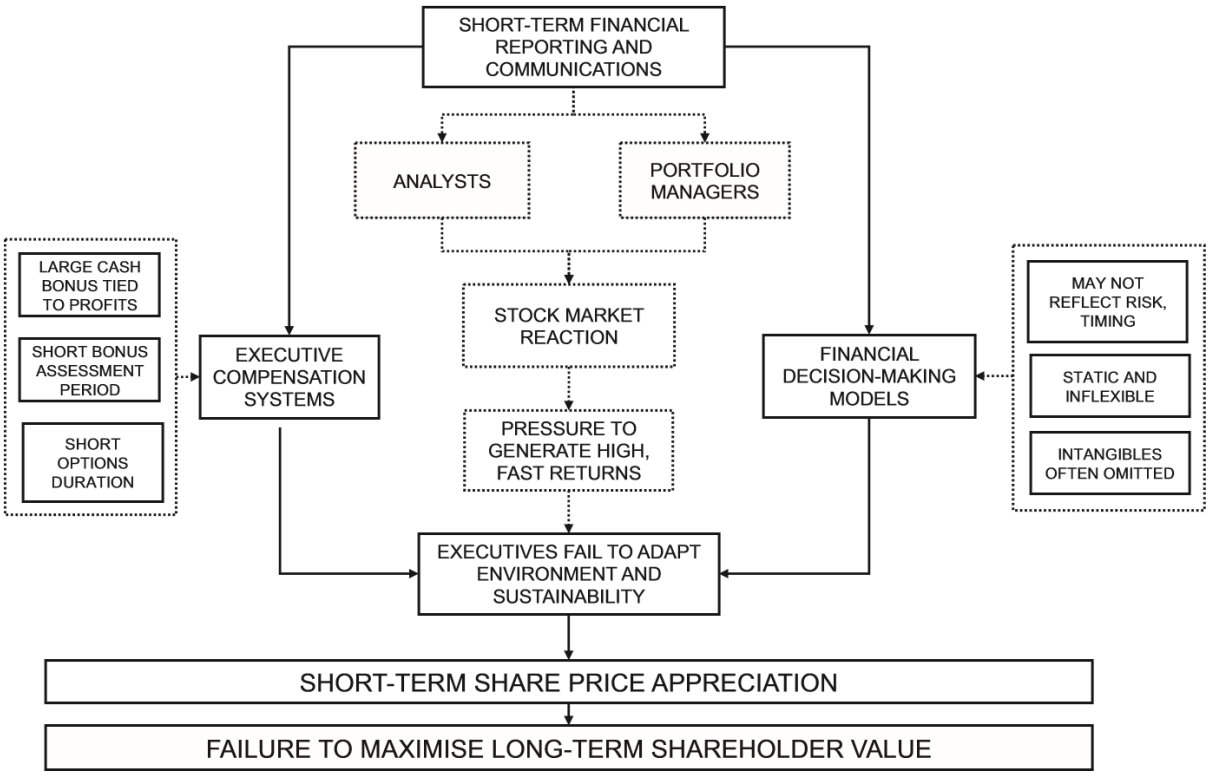
Figure 5 depicts the synthesized 'unsustainable business model'. It incorporates various shortcoming identified throughout the literature review and attempts to demonstrate the mechanisms by which the short-term perspective leads to the erosion of long-term shareholder value. Chapter 5 of this thesis will expand on both the reasoning and potential solutions to overcome the following three major pillars that have been identified to be the major drivers of short-termism (Zellweger, 2007):

(i) executive compensation systems (Brav et al., 2005; Bushee, 1998; Graham et al., 2005; Jensen and Meckling, 1976; Laverty, 1996);

(ii) stock price reactions resulting in investor pressure for fast and high returns (Bhojraj et al., 2009; Demirag, 1995; Ernstberger et al., 2019); and

(iii) financial decision-making models (Winston, 2017).

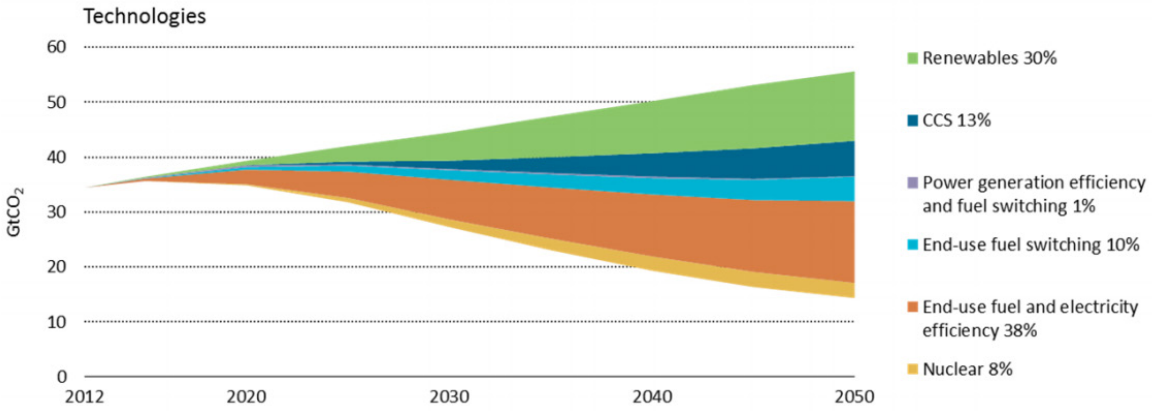
Figure 5: Unsustainable Business Model (own creation)



2.4 Conclusion

While the Australian Novel CO_2 Capture Taskforce acknowledges that carbon geosequestration (carbon mineralisation) technology may 'genuinely and permanently sequester the necessary quantities of CO_2 for centuries' (Burgess et al., 2011), it dismisses it as a viable alternative for sequestering large amounts of CO_2. The energy required to accelerate the carbonation reactions from geological to industrial timescales present an economic obstacle (Zevenhoven et al., 2011). It is mainly because of these obstacles that the carbon mineralisation technology proposed in this thesis has been somewhat unobserved by both the public eye and research. Pumping CO_2 underground (CCS), as well as afforestation, have all drawn significant attention when it comes to CO_2 mitigation technologies (Newell and Stavins, 2000) and have been in focus for the predicted thirteen percent that CCS contributes to the CO_2 reductions in 2050, as seen in Figure 6 (IEA, 2015).

Figure 6: CO_2 reductions by technologies and sectors



(IEA, 2015)

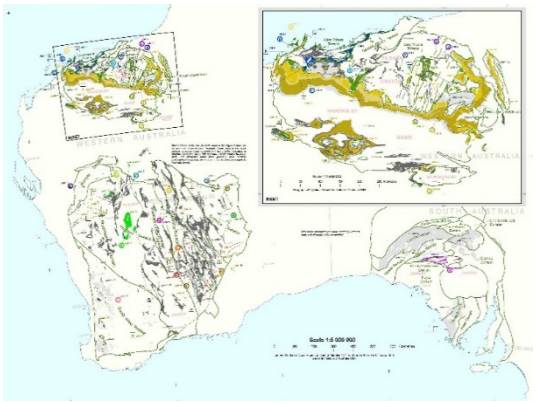
However, this thesis proposes leveraging a developing technology which uses naturally occurring soil bacteria to overcome the obstacles above (Power et al., 2009). While lab results have shown promising results, there is a gap regarding the quantity of this carbon mineralisation method and its potential contribution to the decarbonisation of economies. Carbon mineralisation has potential, not only in Australia but also on a global level. However, a proper estimate of the CO_2 sequestration potential, as well as the potential financial value, would represent a practical pathway as a contributing method to an array of solutions to tackle the pledges made within the Paris Agreement.

The first part of the literature review provides a rationale for having a price on carbon dioxide as it presents an externalised cost that is currently borne by society. Furthermore, it was found that various countries have tackled emissions in the past, with varying degrees of success. A wide range of both economical and practical methods are currently being deployed in order to help economies reach their goals committed through the Paris Agreement. Carbon mineralisation, although dismissed as a method for CO_2 absorption, could prove its usefulness due to newly emerging techniques such as bacterially mediated carbon mineralisation.

The third chapter will assess the potential of this method with nickel mine sites from an Australian perspective. In order to do so, suitable feedstock (e.g., mafic and ultramafic rock) from past and future mining activities will be identified, and the sequestration potential thereof is quantified. Geoscience Australia's Archean events map (Figure 7) highlight the continental scale of carbon mineralisation that could be

realised from events producing rock units that cover 100's of km^2. For example, a single rock unit 20 km^2 by 50 m depth would hold in excess of 10^{10} tonnes of ultramafic rock that could sequester ca. 1 Gt of carbon (Power et al., 2014).

Figure 7: Mafic-Ultramafic map of Australia



(Hoatson et al., 2009)

However, it needs to be noted that this thesis has a focus on abandoned, active, and future mine sites. The reason lies in the readily available feedstock from their operations. As minerals get extracted, the rocks are conveniently ground up, supporting the speed of the carbonation process (Power et al., 2014).

The fourth chapter goes a step further and identifies adequate feedstock from nickel and kimberlite (diamond) mine sites worldwide. After that, the total CO_2 sequestration potential is quantified. Moreover, it offers insights into the economic potential of this method by estimating a rough net present value under the assumption of hypothetical price on carbon, set at US$20.

The literature shows that short-termism is deeply embedded in corporations, manifested through the three realms, namely the individual, the firm, and the institution. However, the changing global context could provide a way forward into a more holistic, inclusive, and sustainable manner. The second part of this literature review has provided some insights into where short-termism is prevalent, historical developments, and what some of the obstacles are that prevent firms from moving towards a more sustainable business model. Addressing the broken corporate financial decision-making framework manifests as one of the significant potential ways forward, seeing that the utilised tools have not been updated in decades. In doing so, the creation of long-term shareholder value could be fostered while simultaneously benefitting all stakeholders involved. It also highlights the need for industry leadership through

individual actions instead of waiting on regulatory approaches, seeing that formal institutions have largely failed to provide guidelines. This literature has identified that part of the problem of short-termism is inherent in the structuring mechanism. Based on the currently existing valuation processes (such as financial decision-making models), the implementation of a price on carbon is made very difficult if not rendered impossible. Chapter 5 of this thesis will explore how sustainability can overcome these obstacles and be embedded in the corporate financial decision-making framework of the firm. The author of this thesis recognises that the suggestions in chapter 5, such as adapting the compensation systems, is a difficult undertaking, facing a multitude of stakeholders with vested interests. Seeing that the systems which seemingly cause short-termism govern the structures within which the firms operate, further increases complexity. However, the identification of the potential root of the unsustainable business model is deemed the first step into the right direction to remedy the current situation with the long-term goal of embedding sustainability into the corporate financial decision-making framework.

Chapter 3: Australian Carbon Mineralisation Potential

3.1 Abstract

Carbon mineralisation has the potential to sequester and safely store large amounts of carbon dioxide (CO_2). However, this technology has not seen the same level of development as geological storage in sedimentary reservoirs. This is primarily because early work on carbonation of minerals focused on high temperature and pressure process routes, which are cost-prohibitive to accelerate the reaction from geological to industrial time scales. Bacteria-mediated carbon mineralisation of mine tailings (Power et al., 2014) overcomes this impediment because it occurs at ambient temperature and standard pressure and the rock is already crushed. With abundant mafic and ultramafic rock, a highly developed mining sector, and a warm climate that promotes fast carbonation reactions, Australia presents an optimal region to develop this technology. This chapter assesses the mineralisation potential of Australia's existing and future nickel mine tailings and estimates that this carbon sink could sequester up to 2,171 Megatons (Mt) of CO_2.

3.2 Introduction

Over the last several decades, there has been growing concern that the increased concentration of CO_2 in the atmosphere may have detrimental effects on the environment and the economy (Linnenluecke et al., 2016; Winn and Kirchgeorg, 2005). In 1958, geochemist Charles David Keeling began to record measurements of the CO_2 concentration at the Mauna Loa Observatory, Hawaii. Yearly average concentration levels on the 'Keeling curve' have since risen sharply from 315 parts per million (ppm) in 1958 to averaging 402.24 ppm in August 2016 (Scripps Institution of Oceanography, 2016). The level of 400 ppm has been considered a critical barrier for taking action to mitigate anthropogenic climate change. In 2015, the 21st yearly session of the Conference of the Parties (COP21) in Paris produced an agreement to reduce greenhouse gas emissions and keep the global average increase in surface temperature from climbing over 2°C, relative to pre-industrial levels. This agreement was ratified by more than 190 countries (UNFCCC, 2017a).

Before COP21, participating countries were invited to initiate or intensify the domestic preparation of their respective Intended Nationally Determined Contributions (INDC). The INDCs entail each country's specific emission reduction goals, describing

how those will contribute to achieving the objectives of the then-upcoming COP21 meeting in Paris (UNFCCC, 2015b). The Australian Government submitted their INDCs in August 2015 with targets covering all facets of the economy and committed to reducing greenhouse gases (GHGs) by twenty-six to twenty-eight percent by 2030, relative to 2005 levels (Australian Government, 2015b). Australia faces an exceptionally challenging undertaking because the emissions reductions must not impede the expected growth in the economy of more than two percent per annum as outlined in the 'Pathways to Deep Decarbonisation in 2050' report (Denis et al., 2014a).

This report is part of the global Deep Decarbonization Pathways Project (DDDP), which outlines how countries can decarbonise their economies. Amongst the proposed pathways for Australia, one of the key technologies identified is carbon capture and storage (CCS). In the said report, CCS is foremost described as the process of capturing CO_2 at point sources (e.g., power plants), transporting it, and injecting it into an appropriate rock formation that is suitable for the long-term geological (stratigraphic) storage of CO_2 (Denis et al., 2014b). The Novel CO_2 Capture Task Force Report (Burgess et al., 2011) provides details on how CO_2 in Australia could be temporarily and permanently absorbed and stored to meet the nation's decarbonisation goals. In addition to the 'traditional' CCS methods, this report also mentions a role for mineral carbonation.

The Australian Novel CO_2 Capture Taskforce states that passive or accelerated carbon mineralisation technology (carbon geosequestration) may 'genuinely and permanently sequester the necessary quantities of CO_2 for centuries' (Burgess et al., 2011). Carbon mineralisation involves a naturally occurring reaction of CO_2 with magnesium and calcium-containing rocks (mafic and ultramafic rocks) to form carbonate minerals (similar to chalk) which are composed of calcium carbonate, thereby storing CO_2 in a stable and benign form (Burgess et al., 2011). The energy economics to accelerate the slow rate of passive carbonation reactions present a severe obstacle (Zevenhoven et al., 2011), resulting in the methods being unequivocally dismissed in various reports (Burgess et al., 2011; Denis et al., 2014b) as a viable means to contribute to the decarbonisation of the Australian economy. However, a developing technology that uses naturally occurring soil bacteria (Cyanobacteria) to induce the carbon mineralisation process without the need of external energy sources overcomes many of these obstacles (Power et al., 2009).

Utilising mineral waste from ultramafic mine sites for carbon mineralisation has been previously documented (Beinlich and Austrheim, 2012; Power et al., 2007; Pronost et al., 2011; Wilson et al., 2006). However, when estimating the CO_2 mineralisation rates, generally, small sample sets have been used. More recently, complementary laboratory experiments and reactive transport modelling have been deployed to investigate and quantify the carbonation rate in mine tailings (Wilson et al., 2014). Although these strategies have proven effective in laboratory-scale studies (Power et al., 2014), pilot projects are necessary to evaluate strategies for accelerating carbon mineralisation which, if successful and cost-effective, could be incorporated into tailings storage facility design with the purpose of sequestering CO_2.

Power et al. (2014) discuss these strategies and propose two scenarios for pilot projects which, if implemented at the mine-scale, could render some mining operations carbon-neutral. They also provide estimates of the operational costs of the proposed scenarios on a dollar per tonne of CO_2 basis to assess the economic feasibility of carbon mineralisation strategies (Power et al., 2014).

In this chapter, the potential of the geo-biological carbon mineralisation process described by Power et al. (2014) to sequester CO_2 across Australia is assessed. The area of focus is on a subsample of Australian nickel mines, which present optimal geological preconditions as a mineral feedstock (mafic and ultramafic host rock). First, the total sequestration potential of a subset of mines based on their past production is estimated. Next, these results are extrapolated to the entire population of Australian nickel mines. After adjusting for differences in carbon mineralisation rates by ultramafic/mafic rock source, this chapter estimates the Australia-wide carbonation potential based on existing nickel mines while platinum group metals, chrysotile asbestos, diamond, chromite, and talc mines can also enhance carbon mineralisation. Finally, the potential CO_2 sequestration is estimated based on past production and known Australian reserves. The key questions that are dealt with in this chapter are the following:

- What is the total available mafic and ultramafic mineral feedstock from both past and future mine production?
- What is the potential of bacterially mediated carbon mineralisation to sequester CO_2 across ultra-mafic/mafic nickel mines in Australia?

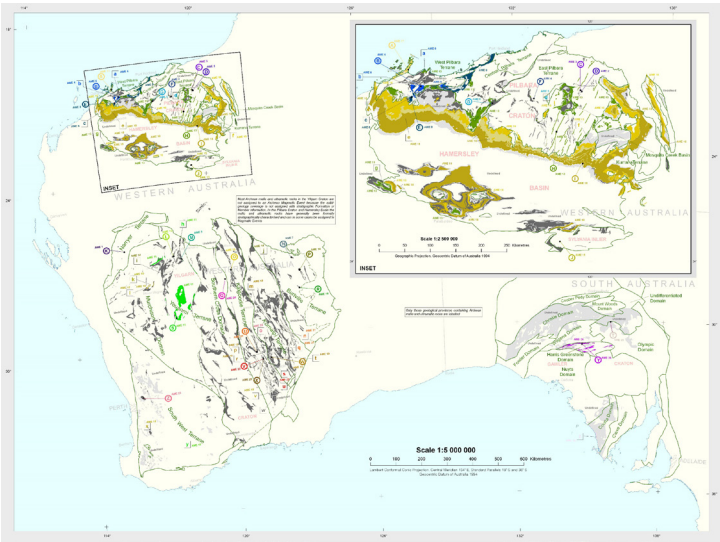
- What is the yearly uptake potential of carbon dioxide through bacterially mediated carbon mineralisation?

3.3 Methods

3.3.1 Study area: mafic and ultramafic nickel mine sites

Using Geoscience Australia's Archean, i.e., mafic and ultramafic magmatic, events map (Figure 8) the continental scale of carbon mineralisation that could be realised from events producing rock units that cover 100's of km^2 can be appreciated (Hoatson et al., 2009). For example, a single rock unit 20 km^2 by 50 m in depth would hold in excess of 10^{10} metric tonnes of ultramafic rock that could sequester 1 Gt of carbon (Table 10, Reactions 1 - 5).

Figure 8: Mafic-Ultramafic map of Australia



(Hoatson et al., 2009)

Ultramafic rock typically contains a high percentage (up to fifty percent, by weight) of magnesium oxide. Ophiolite belts, which are comprised of an abundance of magnesium as serpentine [$Mg_3Si_2O_5(OH)_4$], olivine (Mg_2SiO_4), and brucite [$Mg(OH)_2$], represent the best feedstock for carbon mineralisation (Metz et al., 2005). Mafic and ultramafic mine sites are a valuable feedstock for carbon mineralisation, and there is potential to be used to offset CO_2 emissions that are generated by the mining industry. It has been documented that passive carbonation is already occurring at various mine sites (for example, Mount Keith, Australia, Clinton Creek, Canada and Diavik, Canada); however, the potential remains largely untapped (Power et al., 2014).

Exact figures on how much mine tailings are generated annually from the production of nickel, platinum group elements, chrysotile asbestos, diamond, chromite, and talc are currently unknown. Power et al. (2014) estimated a global, annual output of 416 Mt. However, there is data available for individual ore deposits. As an example, the nickel mine at Mount Keith, Western Australia produces approximately 11 Mt of tailings each year. The complete carbonation of the tailings could sequester approximately 4 Mt of CO_2 every year [see chemical reactions: Table 10, reproduced from (McCutcheon et al., 2016)], which represents ten times the annual emissions of Mount Keith (Power et al., 2014). Although passive carbonation is ongoing at the Mount Keith mine site and accounts for roughly eleven percent of total GHG emissions per annum, the core potential remains untapped (WMC Resources Ltd., 2005).

Table 10: Chemical reactions

Silicate weathering: $Mg_3Si_2O_5(OH)_4 + 3\ H_2SO_4 \rightarrow 3\ Mg^{2+} + 2\ Si(OH)_4 + H_2O + 3\ SO_4^{2-}$	(1)
Carbon Mineralisation: $5\ Mg^{2+} + 4\ CO_3^{2-} + 2\ OH^- + 5\ H_2O \rightarrow Mg_5(CO_3)_4(OH)_2{\cdot}5H_2O$	(2)
Photosynthesis: $HCO_3^- + H_2O \rightarrow CH_2O + O_2 + OH^-$	(3)
Carbon dioxide equilibrium with water: $CO_2 + H_2O \rightleftharpoons HCO_3^- + H^+$	(4)
Carbonate ion formation: $HCO_3^- + OH^- \rightarrow CO_3^{2-} + H_2O$	(5)

(McCutcheon et al., 2016)

3.3.2 Focus: Nickel mine sites

Nickel mines are the area of focus in this paper as they present optimal feedstock (mafic and ultramafic rocks), and both active and abandoned sites can be found in large numbers across Australia. As of September 2016, the Australian Mine Atlas lists 129 mines (historical, operational, and planned) as well as 207 deposits containing nickel (Geoscience Australia, 2016b). Australia is one of the largest nickel producers in the world with a production of 246 Kt and holds approximately one-quarter of the world's estimated economic nickel resources, which equated to 81 Mt in 2014 (Geoscience Australia, 2014).

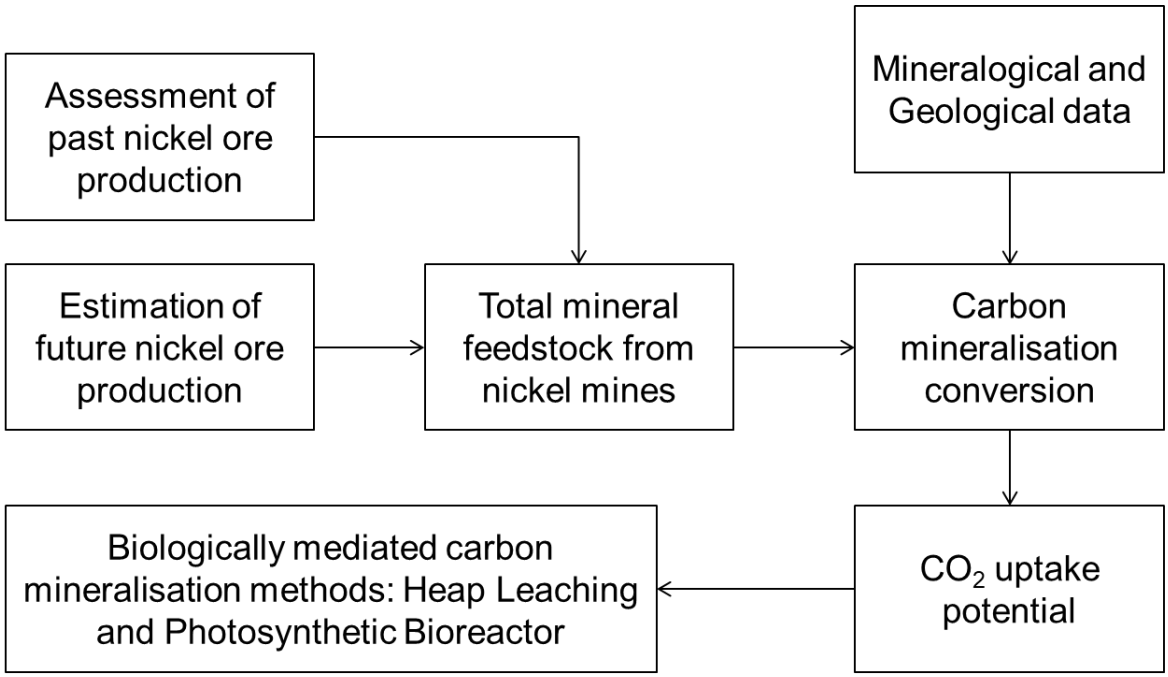
Nickel can commonly be found in two main ore types: sulphide and laterite ores. Sulfide often includes copper and cobalt and sometimes precious metals such as gold, platinum, or palladium (PGMs). Laterite ores are formed near Earth's surface after extensive weathering and occur near the equator or in arid regions such as southern

Africa or Western Australia (Mudd, 2009a). In the past, most nickel production was derived from sulfide ores, due to lower cost and less complex processing requirements compared to laterite ores. In terms of resources, however, approximately sixty percent of Ni reserves are found in laterites whereas forty percent is contained in sulfide-bearing ore (Mudd, 2009a).

3.3.3 Approach

The approach for estimating sequestration potential starts with an assessment of past nickel ore production across some of the largest mine sites in Australia (Figure 9).

Figure 9: Outline of the sequestration potential approach



This list has been composed with the aid of the detailed research report on the sustainability of mining in Australia (Mudd, 2009a). The mineralogical and geological data have been assessed in detail on a mine-by-mine basis in order to determine the potential for biologically mediated carbon mineralisation. Total mineral feedstock values from the sample dataset were extended to include the remainder of Australia's nickel production. It includes estimates of future production of nickel ores; both for the selected mine sites and the remainder of Australia's nickel production. Since estimates of future potential are based on less precise estimates of mineralogy and geology, the more conservative estimates are selected to avoid overstating the carbon mineralisation potential.

The carbon mineralisation conversion table below (Power, Harrison, et al., 2013) translates the mineral feedstock into sequestration potential of carbon dioxide within various magnesium carbonate minerals (Table 11). It lists various mafic and ultramafic minerals that yield differing feedstock-to-product ratios. For example, brucite, which is a highly reactive mineral, can sequester one tonne of CO_2 for every 1.33 tonne of mineral feedstock if the mineral product has a CO_2:MgO ratio of 1:1. Contrastingly, production of artinite and pokrovskite, which have lower CO_2:MgO ratios, would require carbonation of 2.65 tonnes of brucite to sequester one tonne of CO_2.

Table 11: Carbon mineralisation conversion table

Mineral/ Formula	CO_2:MgO Ratio	Serpentine $Mg_3Si_2O_5(OH)_4$	Brucite $Mg(OH)_2$	Forsterite Mg_2SiO_4	Diopside $CaMgSi_2O_6$	Enstatite $Mg_2Si_2O_6$
Magnesite, $MgCO_3$	1:1	2.10	1.33	1.60	2.46	2.28
Hydromagnesite, ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$	4:5	2.62	1.66	2.00	2.73	2.85
Dypingite, $Mg_5(CO_3)_4(OH)_2 \cdot \sim 5H_2O$	4:5	2.62	1.66	2.00	2.73	2.85
Pokrovskite, $Mg_2(CO_3)(OH)_2$	1:2	4.20	2.65	3.20	3.28	4.56
Artinite, $Mg_2(CO_3)(OH)_2 \cdot 3H_2O$	1:2	4.20	2.65	3.20	3.28	4.56
Nesquehonite, $MgCO_3 \cdot 3H_2O$	1:1	2.10	1.33	1.60	2.46	2.28
Lansfordite, $MgCO_3 \cdot 5H_2O$	1:1	2.10	1.33	1.60	2.46	2.28

(Power, Harrison, et al., 2013)

Combining the conversion table with the previously identified mineral feedstock for both past and future production will then give a range of the amount of CO_2 that could potentially be sequestered across Australia's nickel mine sites. The last step will look into methods for absorbing the estimated amounts of CO_2 utilising heap-leaching and a photosynthetic bioreactor to accelerate carbon mineralisation.

3.3.4 Ultramafic feedstock from nickel mines: estimations

The first element for determining the CO_2 sequestration potential is the past production of nickel at various mine sites across the country. Based on data from Mudd (2009a) with regards to nickel mines in Australia, key mine sites have been selected. The data from these selected mine sites have been enriched with publicly available information from the peer-reviewed literature as well as company announcements[3]. In

[3] (Mincor Resources NL, 2016), (Mindat, 2016), (Keays and Jowitt, 2013), (Barnes, 2007), (Mason et al., 2003), (Hoaston and Blake, 2000), (Poseidon Nickel Ltd, 2015), (Standing, 2012), (Frick et al., 2001), (Hoatson, 1992), (T. N. G. Ltd, 2008), (CleanTeQ Holdings Ltd., 2016), (Elias et al., 1981), (Fiorentini et al., 2012), (Clayton et al., 2005), (Australian Government, 2014b)

a second step, the remainder ore from Australian nickel production (past and future) was estimated.

Table 12 lists nickel sulfide mines and nickel laterite mines separately. While nickel production from sulfide mines has made up the vast majority of past production, laterite mines have approximately double the reserves compared to sulfide mines. Therefore, the calculations predict that nickel from lateritic mines will make up the majority of future Australian nickel production (Mudd, 2009b).

The selected sulfide and laterite nickel mines comprise of a total of 23 mine sites, most of which are found in Western Australia. This list represents some of the largest and most crucial nickel mines in Australia that have adequate mineralogical and geological data available to estimate sequestration potentials. These mine sites have produced 3,812 kt of nickel and approximately 372 Mt of ore. The estimated reserves of the selected mine sites equate to 23,316 kt of nickel, which translates into 3,202 Mt of nickel ore.

The lower half of Table 12 lists past nickel production for the remainder of Australian mine sites, which totals 3,347 kt of nickel (as per 2015) and an estimated ore production of 438 Mt. Furthermore, Geoscience Australia has estimated the Economic Demonstrated Reserves (EDR) of nickel to be 19,000 kt, whereas the Subeconomic Demonstrated Reserves (SDR) are estimated to be 4,000 kt (Australian Bureau of Statistics, 2012). These are Economic Demonstrated Resources (EDR) measures that are established and either analytically demonstrated or can be assumed with reasonable certainty that extraction would be profitable under predefined investment assumptions. Subeconomic Demonstrated Resources (SDR) is comparable to EDR regarding the certainty of occurrence. However, the financial viability of SDR might only be evident in the future (Australian Bureau of Statistics, 2012). Since the ‘Selected nickel mines’ section covers the main nickel projects in Australia, the EDR and SDR are considered to be included therein and will not be additionally listed as mining and sequestration potential. Only the Inferred Resources (IR) are listed separately, as they present resources for which quantitative estimates are based on a broad knowledge of the geological character of the deposit. Therefore, there are either none or only a few samples or measurements (Australian Government, 2015c). It is assumed for the purpose of this paper that the nickel concentration for the

inferred resources is 0.5 percent, which is lower than past production as concentration is declining over time (Mudd, 2009b).

Table 12: Production and reserves from nickel mines

	Past nickel production (kt nickel)	Ø Nickel concentration (%)	Past ore production (Mt ore)	Total Reserves (kt nickel)	Ø Nickel concentration (%)	Total Reserves (Mt ore)
Selected nickel mines						
Nickel sulphide mines	3,434	1.02	336	8,271	0.67	1,210
Nickel laterite mines	378	1.06	36	15,189	0.76	1,992
Total selected mines	**3,812**	**1.02**	**372**	**23,316**	**0.73**	**3,202**
Remainder of Australia						
1967 – 2007 (Mudd)	1,857	0.76*	243			
2008 – 2015 (OCE)	1,490	0.76*	195			
Economic Demonstrated Resources (Included in 'Selected nickel mines')				*19,000*		
Subeconomic Demonstrated Resources (Included in 'Selected nickel mines')				*4,000*		
Inferred Resources				17,800	0.50*	3,560
Total remainder of Australia	**3,347**		**438**	**17,800**	**0.50**	**3,560**
Total Australia	**7,159**		**810**	**41,116**		**6,762**

** assumed concentration*

Sources: (Mincor Resources NL, 2016), (Mindat, 2016), (Keays and Jowitt, 2013), (Barnes, 2007), (Mason et al., 2003), (Hoaston and Blake, 2000), (Poseidon Nickel Ltd, 2015), (Standing, 2012), (Frick et al., 2001), (Hoatson, 1992), (T. N. G. Ltd, 2008), (CleanTeQ Holdings Ltd., 2016), (Elias et al., 1981), (Fiorentini et al., 2012), (Clayton et al., 2005), (Australian Government, 2014b)

3.3.5 Carbon sequestration potential

The geologic setting, production rates, reserves, and mineralogy of key Australian sulfidic and laterite-hosted nickel mines (23 locations across Australia) are well defined. Therefore, the sequestration potential for past production as well as the reserves for these sites could be estimated using publicly available data. When mineralogical data was not available, the information for a 'typical' mine type (based on the existing sulfide and laterite mine data) was applied.

The estimated mafic and ultramafic feedstock established in Table 12 will serve as a base for the calculations of carbon sequestration potential. The uptake potential is dependent on the subtype of feedstock (Table 11). In order to estimate the carbon sequestration potential from nickel mining, the mafic and ultramafic feedstock established in Table 12 were used to calculate the carbonation yields using the conversion factors provided by Power et al., (2013), which range from 1.66 tonnes (for brucite) to 2.85 tonnes (for enstatite) to fix one tonne of CO_2 as dypingite or hydromagnesite, which commonly form in Australian mine tailings, noted by Wilson et

al. (2014) This project focuses on dypingite and hydromagnesite as target carbonates because they are more stable than lansfordite or nesquehonite and their formation can be bacterially mediated (Power et al., 2011; Pronost et al., 2011; Zevenhoven et al., 2011).

For the remainder of Australia, both past production and reserves, the mineralogical setting has yet to be defined. Therefore, a mix of the profiles above (sulfide and laterite) was assumed. The ratios applied for the *'Remainder of Australia'* section are 0.9 sulfide to 0.1 laterite (for past production) and 0.3 sulfide to 0.7 laterite (for estimated reserves of the inferred resources). This was adjusted for the fact that future production of nickel will likely stem predominantly from laterite mine sites, as there is a greater abundance of these resources to be exploited (Mudd, 2009b). The CO_2 sequestration capacity assumes complete carbonation of the mineral feedstock.

A total of 2,171 Mt of CO_2 could be sequestered considering past production and future production of both the selected mine sites as well as the inferred resources. Nickel sulfide mine sites make up the largest portion of the sequestration potential from the past production of the selected mine sites, with approximately 111 Mt of CO_2 while lateritic mine sites hold a potential of 12 Mt of CO_2. An additional 148 Mt of CO_2 could be sequestered from the past production of the remainder of Australia's nickel mines, totalling 271 Mt of CO_2. The past to future production sequestration ratio is 1:7, with 271 to 1,900 Mt of CO_2.

Table 13: CO_2 sequestration potential from nickel mines feedstock

	Past ore production	Total Reserves	Sequestration from past production	Sequestration from future production
	(Mt ore)	(Mt ore)	(Mt CO_2)	(Mt CO_2)
Selected sulfide and laterite nickel mines				
Nickel sulfide mines	336	1,210	111	421
Nickel laterite mines	36	1,992	12	492
Total selected mines	**372**	**3,202**	**123**	**913**
Remainder of Australia				
1967 – 2007 (Mudd)	243		82	
2008 – 2015 (OCE)	195		66	
Inferred Resources (IR)		3,560		
Total remainder of Australia	**438**	**3,560**	**148**	**987**
Sequestration (Mt CO_2)			**271**	**1,900**
Total sequestration (Mt CO_2)				**2,171**

3.3.6 Annual CO_2 uptake estimations

A direct biotechnological approach to carbon mineralisation could be devised at mine sites by combining heap leaching, which has been used for centuries to extract metals from sulfidic low-grade ore and a photosynthetic bioreactor (Power et al., 2010; Power et al., 2014). This could be done by briefly placing the ore on a liner and inoculating with acid-generating bacteria and nutrients. Sulfidic material provides ideal conditions for acid-generating microbes, such as Acidithiobacillus spp., that accelerate the generation of sulfuric acid for mineral dissolution and metal leaching (Power et al., 2010; Power et al., 2014). For example, leaching 7500 tonnes of ultramafic mine tailings could release enough magnesium to sequester approximately 2,800 tonnes of CO_2 per year, in a 0.12 km^2 photosynthetic bioreactor.

3.4 Results

Leading up to the COP21 in Paris as of November 2015, the Australian government had pledged to reduce its overall GHGs by twenty-six to twenty-eight percent in 2030 compared to 2005 levels (Australian Government, 2015b). As of 2014, Australia emitted a total of approximately 523 Mt of CO_2 equivalent gases (CO_2e) whereas 2005 emissions amounted to 519 Mt of CO_2e (Australian Government, 2017c). Therefore, in order to reach its pledge, the annual CO_2e would have to be reduced to 376 CO_2e, which represents a reduction of approximately 150 Mt (or twenty-eight percent) of CO_2e by 2030. Assuming linearity, an average additional reduction of approximately 11 Mt of CO_2e per annum would have to occur over the following fourteen years in order to reach the goals stated at the COP21. In other words, a total amount of roughly 1,115 Mt of CO_2 would need to be reduced in total from 2016 to 2030.

While the Australian government will be working on a suite of solutions in order to achieve the pledged goals, bacterially mediated carbon mineralisation could be a substantial contributor. Based on the current data for Australia, there is potential for sequestering more than 2,000 Mt of CO_2 utilising past and future feedstock. If bioreactors were used to accelerate this bacteria-mediated mineralisation process to full potential by 2030, this would result in more than 10x the required reductions.

3.5 Discussion

Carbon mineralisation has been identified by the Australian Novel CO_2 Capture Task Force Report as being one of the few technologies that have the potential to sequester and safely store large amounts of CO_2 for centuries. Australia is an optimal region for further developing this technology due to the abundance of mafic/ultramafic rock and mineral waste that is rich in magnesium (Burgess et al., 2011).

Using mine waste as a feedstock possesses several additional benefits. First, as the rocks are crushed and ground, their high reactive surface area presents an optimal material for carbon mineralisation reactions. Furthermore, they provide an incentive for mining companies for marketing their reduced carbon footprint.

To accelerate the rate of naturally occurring carbon mineralisation, most processes rely on very high pressure and temperature, and the process costs associated with these increased reaction kinetics have rendered these processes economically unviable. Bacteria-mediated carbon mineralisation overcomes the need for much of the energy required to generate the high pressures and temperatures required to mediate the reaction.

Although this study demonstrates how bacterially-mediated carbon mineralisation of nickel mine tailings has the potential to overcome the previous energy economics objections, this study has not demonstrated its economical viability, especially given the current price of carbon. Economists concur that carbon is currently undervalued (Pindyck, 2013); while the 'social cost of carbon' is estimated at up to US$220 according to Pindyck (2013), there are dozens of different market prices in the form of national carbon floors or cap and trade systems with a proliferation of announcements in 2016 from both emerging and developed countries. Ernst and Young (2013) predict that beginning in 2020, companies are likely to be 'carbon constrained in all the major emitting and emerging countries' and expect a global carbon market to appear. A global carbon market will remove much of the uncertainty in the benefits of the process. Future and ongoing work strive to integrate the costs associated with these processes.

Chapter 4: Worldwide Carbon Mineralisation Potential

4.1 Abstract

Carbon dioxide capture and storage (CCS) is considered a crucial strategy to reduce the concentration of atmospheric carbon dioxide (CO_2) and mitigate global warming. Worldwide efforts have focused on capturing gas emitted in large concentrations (e.g., at power plants). However, carbon mineralisation is a naturally occurring geochemical process which has the potential to permanently and safely sequester substantial amounts of CO_2. This process has been widely dismissed because of the cost-prohibitive methods required to accelerate the chemical reaction from geological to industrial time scales. Bacteria-mediated carbon mineralisation, an emerging technology, could overcome this impediment because it occurs at standard pressure and ambient temperature and uses waste rock in mine tailings. The required feedstock for this process is mafic and ultramafic rock, which is abundant in mines worldwide. This study assesses the global mineralisation potential of existing (and future) nickel mine tailings. Furthermore, the potential of kimberlite diamond mines is assessed, as these mines host an ideal feedstock for the mineral carbonation process. The models show that the assessed mines have the potential to sequester up to 7,254 Megatons (Mt) of CO_2. A key hurdle to carbon mineralisation deployment includes the absence of a clear business case for mining companies to invest in this technology. However, the simple financial model estimates used in this chapter show that at a carbon price of US$20 per tonne of CO_2, the net present value of the processes is estimated to be US$13.3 billion. It is also noted that there is a role for public policy, owing to the absence of economic incentives to support the additional capital and operating costs of setting up the carbon mineralisation processes.

4.2 Introduction

Over the last decades, growing concern arose that the increasing concentration of CO_2 has adverse environmental and economic effects (Linnenluecke et al., 2016; Winn and Kirchgeorg, 2005). Levels of the concentration of CO_2 at the Mauna Loa Observatory in Hawaii rose to 407.07 parts per million (ppm) in July 2017. The levels of 400 ppm are considered a ‘critical barrier’ with regards to taking actions to mitigate climate change caused by humankind (NOAA, 2017). Therefore, the Conference of the Parties (COP) agreed during its 21st session in Paris in 2015 that decisive action is required to reduce global emissions of greenhouse gasses (GHG) and limit global

average increases in surface temperature of 2°C, relative to pre-industrial levels (UNFCCC, 2015b). The so-called ‘Paris Agreement’ entered into force on 4 November 2016, and as per May 2018, 176 of 197 parties have ratified the agreement (UNFCCC, 2017a). While the United States of America has formally announced their withdrawal from the Paris Agreement, the remaining countries have reinforced their intentions of sticking to their pledges (UNFCCC, 2017b).

Action plans to curb greenhouse gas emissions are manifold. Before the conference of the parties, the fifteen countries that account more than seventy percent of global GHG emissions have formed the Deep Decarbonization Pathways Program (DDPP). Its goal is to outline pathways for decarbonising economies by 2050 (Deep Decarbonization Pathways Project (2015), 2015). The envisioned targets will allow for a tripling of the worldwide GDP while simultaneously reducing GHG emissions massively, increasing the efficiency for every dollar of GDP. The proposed decarbonisation pathways are country-specific. In Australia's example, the assessment of the contribution of bacterially mediated carbon mineralisation towards sequestering CO_2 would represent a practical pathway from a uniquely Australian perspective (Denis et al., 2014b).

Before the start of the conference in Paris (COP21), countries handed in their ‘Intended Nationally Determined Contributions' (INDCs) on an individual basis. The INDCs are country-specific emission reduction goals and briefly describe how these reductions will contribute to achieving the objectives of the Paris Agreement (UNFCCC, 2015a). INDCs are individual, national post-2020 climate action commitments each country intends to achieve (World Resources Institute, 2015). For example, Australia handed in its INDCs in August 2015. It states that the country aims to implement ‘an economy-wide target to reduce greenhouse gas emissions by twenty-six to twenty-eight percent below 2005 levels by 2030’ (Australian Government, 2015b). When taking population growth into account, this represents a rough cut of fifty percent in emissions per capita and a sixty-five percent reduction per unit of GDP by 2030 (Australian Government, 2015b). Globally, with the current policies in place, the global mean temperature would increase by +3.4˚C (+/- 0.9˚C) whereas, with the pledged INDCs, the increase is projected to be +3.2˚C (+/- 0.9˚C); both scenarios are well above the agreed +2.0˚C (Climate Action Tracker, 2017).

The Paris Agreement has established a framework for climate action and spurred the development of future cooperation of carbon pricing amongst countries. With more carbon markets emerging internationally, the full emission reduction potential of the Paris Agreement could be released. Cross-country interaction can facilitate the implementation of INDCs and embolden countries to go beyond their pledges once countries have access to a larger pool of carbon abatement methods. For example, Mexico has pledged to reduce its GHG emissions more than initially promised should they have access to an international carbon market (Swartz, 2016). With the ratification by 170 parties, with the United States of America being the only exception, the Paris Agreement came into effect and subsequently the INDCs became Nationally Determined Contributions (NDCs). There is a total of 170 NDCs covering 195 parties, most of which have remained the same compared to the initial INDC proposals (Meinshausen and Alexander, 2017).

Notable achievements of the COP22 included a global financing roadmap which outlines the raising of US$100 billion annually. This roadmap was supported by most developed countries (UNFCCC, 2016) and lead to the creation of the establishment of the Paris Committee on Capacity-building, which explores the NDC capacity-building activities in 2017. Furthermore, the 'Marrakech Action Proclamation statement,' a high-level political statement, was released, reaffirming what governments had previously committed to regarding climate actions as well as means to encourage their businesses and civil society to act in the same way (UNFCCC, 2016). CCS was considered within the program named 'Clean Development Mechanism,' which runs until the year 2020. Carbon mineralisation was not explicitly discussed at the COP22, as the method had previously been dismissed for economic reasons (Bonner, 2016). During COP24, the Paris Agreement 'rulebook' was agreed upon, which acts as a manual on how countries plan to curb their emissions once the agreement enters into force in 2020 (Evans and Timperley, 2018).

Several countries across the globe have started to make polluters pay for the CO_2 emissions through either carbon taxes or an emission trading system (ETS). The money generated through this system was estimated at US$26 billion in 2015, which is more than sixty percent compared to the previous year (Tuck, 2016). While the transformation is still underway in developed countries, middle-income countries have taken on responsibilities as well. China currently has seven regional pilot ETS schemes,

covering eighteen percent of the country's population, and its national carbon trading scheme is set to be implemented by 2017. Once active and running at full coverage, it will collect CO_2 emissions revenues of up to US$50 billion annually (Tuck, 2016). Table 14 depicts several cap and trade systems around the globe as well as their collected revenue und type of spending. The numbers are mostly based on the years 2013 or 2014 (Carl and Fedor, 2016).

Table 14: Global cap-and-trade system revenue

Cap and trade systems	**Annual revenue (millions)**	**Per capita revenues**	**Share of GDP**	**Green spending**	**General funds**	**Revenue recycling**
European Union ETS Phase III	$4,640	$9	0.03%	80%	20%	0%
California AB 32 Cap and Trade	$1,034	$27	0.05%	45%	4%	55%
Regional Greenhouse Gas Initiative (US)	$447	$8	0.01%	49%	32%	12%
Chinese Provincial ETS	$250	$2	0.02%	10%	90%	0%
Quebec Cap and Trade	$100	$13	0.03%	100%	0%	0%
Alberta Greenhouse Gas Reduction Program	$92	$22	0.03%	90%	10%	0%
Switzerland ETS	$9	$1	0.00%	0%	100%	0%
Combined globally:	**$6,572**	**$8**	**0.02%**	**70%**	**21%**	**9%**

Carbon mineralisation is the natural reaction of CO_2 with magnesium and calcium-containing rocks (mafic and ultramafic rocks), which eventually form carbonate minerals composed of calcium carbonate. Through the chemical reaction, CO_2 is absorbed and is stored in a stable and benign form (Burgess et al., 2011). The energy economics to accelerate the slow rate of passive carbonation reactions present a severe obstacle (Zevenhoven et al., 2011). Therefore, said methods are being unequivocally dismissed as a viable means to contribute to the decarbonisation of the Australian economy in various reports (Burgess et al., 2011; Denis et al., 2014a). However, an emerging technology that uses naturally occurring soil bacteria (Cyanobacteria) to induce the carbon mineralisation process without the need of external energy sources overcomes many of these obstacles (Power et al., 2007). Using mineral waste as a substrate for the carbon mineralisation process has been documented (Beinlich and Austrheim, 2012; Power et al., 2007; Pronost et al., 2011; Wilson et al., 2006). More recently, complementary laboratory experiments and reactive transport modelling have been deployed to investigate and quantify the

carbonation rate in mine tailing (Wilson et al., 2014). While the effectiveness of these strategies has been proven in laboratory-scale studies, (Power et al., 2014) pilot projects are necessary to evaluate strategies for accelerating carbon mineralisation which, if successful and cost-effective, could be incorporated into tailings storage facility design to sequester CO_2 in the future. Power et al. (2014) propose two scenarios for pilot projects, which could be implemented at mine-scale and have the potential to render mining operations carbon-neutral. They also provide estimates of the operational costs of the proposed scenarios on a dollar per tonne of CO_2 basis to assess the economic feasibility of carbon mineralisation strategies (Power et al., 2014).

One of the tools companies use to make decisions about a project's financial viability is the Net Present Value (NPV) technique. NPV takes the timing of cash flow streams into consideration (year 1, year 2, year x) and discounts their future value at an appropriate required rate of return to the present value. A future dollar is less valuable than a present dollar due to inflation, opportunity cost, and risk. Applying this 'time value of money,' all PVs are then summed up, and the initial investment is subtracted to get the NPV. The decision rule of the NPV model states that any project with a positive NPV is worth considering for investment whereas projects with negative values must be dismissed (Gallo, 2014).

The utilisation of an NPV model as a means to analyse costs and benefits from the sequestration of CO_2 has been widely discussed in various scenarios and research papers (De Jong et al., 2000; Hitch and Dipple, 2012; Jahangiri and Zhang, 2012; King et al., 2013). Hitch and Dipple (2012) analysed the Turnagain nickel mine located in British Columbia, Canada. This mine contains an abundant amount of magnesium-bearing, ultramafic host rock. In their model, Hitch and Dipple suggest utilising the waste rock of this mine to facilitate mineral carbonation and generate an additional income stream through the sale of carbon credits. Their financial model returns an NPV of US$131.50 million at a discount rate of eight percent, noting that the positive NPV suggests that the Turnagain mine may be a viable development from an economic point of view. It needs to be noted; however, that said model is based on a price of US$100 per tonne of CO_2, which is not viable given the current market situation (Hitch and Dipple, 2012).

Preliminary evidence for Australian nickel mine sites has established the potential

for sequestering CO_2 at approximately two gigatons (Gt). The two Gt includes both past production of Nickel ore as well as future production based on estimated reserves (Siegrist et al., 2017). The first element that will be dealt with in the current paper is the assessment of the worldwide feedstock for the biological carbon mineralisation process described by Power et al. (2014) to sequester CO_2. The focus will remain on nickel mine sites as well as diamond mine sites hosted in Kimberlite, both of which comprise of mafic and ultramafic host rock. Estimates of the total sequestration potential will be made about the available, detailed, mineralogy, or magnesium content for a significant subset of mines based on their past production and estimated reserves.

Second, these findings are extrapolated to the remaining mines of the respective country where mineralogical data was not available. The findings will indicate an estimate of how much CO_2 could be sequestered based on the data gathered from nickel mines. It should be noted that platinum group metals, chrysotile asbestos, chromite, and talc mines can also possess the properties to enhance carbon mineralisation.

Thirdly, the financial viability of sequestering CO_2 via biologically mediated carbon mineralisation utilising a simplified NPV model is assessed.

4.3 Methods

4.3.1 Study Area: mafic and ultramafic mine sites

Ultramafic rock is usually composed of a high percentage of magnesium oxide (up to fifty percent, by weight). The best feedstock for carbon mineralisation is ophiolite belts, which are comprised of an abundance of magnesium as serpentine ($Mg_3Si_2O_5(OH)_4$), olivine (Mg_2SiO_4), and brucite ($Mg(OH)_2$) (Metz et al., 2005). Mafic and ultramafic rocks are abundant across the globe. A single rock unit of 20 km^2 by 50 m in depth would hold in excess of 10^{10} metric tonnes of ultramafic rock that could sequester 1 Gt of carbon dioxide, equivalent to two years of Australia's GHG exhaust (Hoatson et al., 2009; The World Bank, 2014). Mafic and ultramafic mine sites are a valuable feedstock for carbon mineralisation and hold the potential to be utilised to offset CO_2 emissions, such as those that are generated by the mining industry. Passive carbonation, which happens naturally and is already occurring at various mine sites such as Mount Keith, Australia, Clinton Creek, Canada, and Diavik, Canada (Power et

al., 2014); however, the potential remains largely untapped.

It is currently unknown how much mine tailings are generated annually from the production of nickel, platinum group elements, chrysotile asbestos, diamond, chromite, and talc. Power et al. (2014) estimated a global, annual output of 416 Mt. However, there is data available for individual ore deposits. For instance, the nickel mine at Mount Keith, Western Australia produces approximately 11 Mt of tailings each year. The complete carbonation of the tailings could sequester about 4 Mt of CO_2 every year [see chemical reactions: Table 15 (McCutcheon et al., 2014)], which represents approximately ten times the total annual emissions of Mount Keith (Power et al., 2014). In other words, utilising the carbon mineralisation process would render the Mount Keith mine not only carbon-neutral but make it a carbon sink, absorbing more carbon than it produces. This becomes especially interesting when a carbon tax is introduced, where carbon sinks would receive credits. Currently, passive carbonation is ongoing at the Mount Keith mine site, which accounts for roughly eleven percent of total GHG emissions per annum. The core potential, however, remains untapped (WMC Resources Ltd., 2005).

Table 15: Chemical reactions

Silicate weathering: $Mg_3Si_2O_5(OH)_4 + 3\ H_2SO_4 \rightarrow 3\ Mg^{2+} + 2\ Si(OH)_4 + H_2O + 3\ SO_4^{2-}$	(1)
Carbon Mineralisation: $5\ Mg^{2+} + 4\ CO_3^{2-} + 2\ OH^- + 5\ H_2O \rightarrow Mg_5(CO_3)_4(OH)_2 \cdot 5H_2O$	(2)
Photosynthesis: $HCO_3^- + H_2O \rightarrow CH_2O + O_2 + OH^-$	(3)
Carbon dioxide equilibrium with water: $CO_2 + H_2O \rightleftharpoons HCO_3^- + H^+$	(4)
Carbonate ion formation: $HCO_3^- + OH^- \rightarrow CO_3^{2-} + H_2O$	(5)

4.3.2 Mine sites worldwide

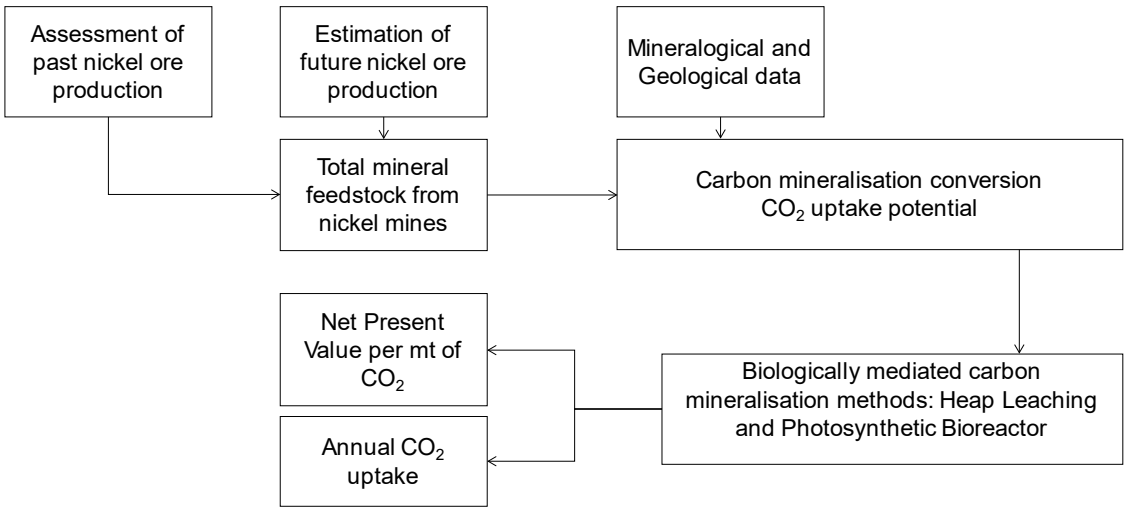
Corresponding to the previous paper (Siegrist et al., 2017), the area of focus is nickel mine sites (both abandoned and active sites) containing mafic and ultramafic host rock. Furthermore, this chapter adds diamond mine sites that are hosted in Kimberlite, which are comprised of mafic and ultramafic rock. Nickel is one of the most frequently mined metal with an annual production of approximately 2.25 million tonnes in 2016 worldwide (Schnebele, 2017).

Nickel can commonly be found in two main ore types: sulfide and laterite ores. Sulfide often includes copper and cobalt and sometimes also precious metals such as gold, platinum, or palladium (PGMs). Laterite ores are formed near the Earth's surface after extensive weathering and occur near the equator or in arid regions such as southern Africa or Western Australia (Mudd, 2009b). In the past, most nickel production was derived from sulfide ores, due to lower cost and less complex processing requirements compared to laterite ores. Regarding resources, however, approximately sixty percent of Ni reserves are found in laterites, whereas forty percent is contained in sulfide-bearing ore (Mudd, 2009b). The focus will be on a list of seventeen countries which account for approximately eighty percent of the total known reserves (Mudd and Jowitt, 2014).

4.3.3 Approach

The figure below (Figure 10) depicts the approach for estimating sequestration potential across worldwide nickel mines. It starts with the assessment of past and future nickel ore productions of the leading producing countries.

Figure 10: Outline of the sequestration potential approach



The gathered list of the most significant nickel mines worldwide is based on the work done by Mudd and Jowitt (2014), which is a detailed assessment of global nickel resources. The original resources comprised of types of nickel ore (sulfide and laterite) as well as estimated reserves of both ore and nickel. The mineralogical and geological data of the respective mine sites have been assessed in as much detail as possible. Where no or inconclusive data was available, the country average of mineralogical

data was extrapolated to the remainder to determine the total potential for biologically mediated carbon mineralisation.

For the calculation of the CO_2 uptake potential, the carbon mineralisation conversion table is used (Table 16), reproduced from Power et al. (2013). It comprises of various mafic and ultramafic minerals that yield differing feedstock-to-product ratios. Brucite, a highly reactive mineral, can sequester one tonne of CO_2 for every 1.33 tonne of mineral feedstock while artinite and pokrovskite, which have lower CO_2:MgO ratios, would require carbonation of 2.65 tonnes of brucite to sequester one tonne of CO_2.

Table 16: Carbon mineralisation conversion table

Mineral/ Formula	CO_2:MgO Ratio	Serpentine $Mg_3Si_2O_5(OH)_4$	Brucite $Mg(OH)_2$	Forsterite Mg_2SiO_4	Diopside $CaMgSi_2O_6$	Enstatite $Mg_2Si_2O_6$
Magnesite, $MgCO_3$	1:1	2.10	1.33	1.60	2.46	2.28
Hydromagnesite, $(Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$	4:5	2.62	1.66	2.00	2.73	2.85
Dypingite, $Mg_5(CO_3)_4(OH)_2 \cdot \sim 5H_2O$	4:5	2.62	1.66	2.00	2.73	2.85
Pokrovskite, $Mg_2(CO_3)(OH)_2$	1:2	4.20	2.65	3.20	3.28	4.56
Artinite, $Mg_2(CO_3)(OH)_2 \cdot 3H_2O$	1:2	4.20	2.65	3.20	3.28	4.56
Nesquehonite, $MgCO_3 \cdot 3H_2O$	1:1	2.10	1.33	1.60	2.46	2.28
Lansfordite, $MgCO_3 \cdot 5H_2O$	1:1	2.10	1.33	1.60	2.46	2.28

Where no detailed mineralogical data was available, the sequestration of CO_2 was calculated via the magnesium content and the production of hydromagnesite, absorbing 1.447 mt of CO_2 for every 1 mt of magnesium.

Cross-referencing the conversion table with the identified mineral feedstock from worldwide nickel mines, both past production and reserves, give an idea of the amount of CO_2 that could potentially be sequestered. The last step will consider methods for absorbing the estimated amounts of CO_2 utilising heap-leaching and a photosynthetic bioreactor to accelerate carbon mineralisation.

4.3.4 Ultramafic feedstock

Determining the CO_2 sequestration potential of worldwide nickel mines requires the past production as well as the reserves held by the respective mines. The basis for these calculations is the paper by Mudd and Jowitt (2014), who have assessed worldwide mine sites. The data used from this report has been greatly enriched with publicly available information from the peer-reviewed literature as well as company announcements (See sources Table 17). Where data was missing or insufficient, extrapolation has been used, based on country averages.

4.4 Results

As on can see under Table 17, the global nickel reserves are listed separately, as sulfide and laterite mines. While past production has mostly stemmed from sulfide mines, the reserves of laterite mines exceed sulfide reserves due to a higher nickel concentration in the ore. Therefore, most of the future nickel production on a global scale will stem from laterite mines. Historically, most of the production was from sulfide mines, since the extraction was more straightforward in comparison with laterite mines (Mudd and Jowitt, 2014).

The assessed sulfide and laterite nickel mines comprise a total of 139 nickel mine sites with an additional six diamond mines containing kimberlite feedstock. Within each country, the most significant mines were selected and assessed if data was accessible. Therefore, this list represents some of the largest and most important nickel mines worldwide that have adequate mineralogical and geological data available to estimate sequestration potentials. The total past production of these selected mines is approximately 4,172 Mt of ore. With a calculated average nickel concentration of 0.5%, these mines had a previous production of around 19,770 kt of nickel. The estimated reserves of the selected mine sites equate to 245,000 kt of nickel, which results from 49,113 Mt of nickel ore (Table 17).

Table 17: Worldwide production and reserves from nickel mines

	Sulfide reserves (kt nickel)	Ø Nickel concentr. (%)	Assessed mines (count)	Laterite reserves (kt nickel)	Ø Nickel concentr. (%)	Assessed mines (count)	Total Reserves (Mt ore)	Total past production (Mt ore)
Country								
Australia	2,314	1.02	17	4,009	1.06	6	6,323	810
Botswana	415	0.31	6	-	-	-	415	143
Brazil	302	0.51	2	433	1.38	7	735	103
Cameroon	-	-	-	323	0.61	2	323	-
Canada	5,752	0.34	13	-	-	-	5,752	869
Kimberlite	-	-	-	-	-	3	26	42
China	432	1.38	1	-	-	-	432	74
Colombia	-	-	-	331	0.97	1	331	108
Cuba	-	-	-	377	1.21	2	377	82
Finland	1,987	0.23	3	-	-	-	1,987	95
Indonesia	-	-	-	1,270	1.61	4	1,270	245
New Caledonia	-	-	-	674	1.86	3	674	66
Philippines	-	-	-	99	1.15	3	99	140
PNG	-	-	-	1,869	1.00	3	1,869	-
Russia	3,987	0.46	8	413	0.96	5	4,400	797
South Africa	18,100	0.18	37	-	-	-	18,100	369
Kimberlite	-	-	-	-	-	3	147	118
United States	3,016	0.14	6	-	-	-	3,016	18
Zimbabwe	2,119	0.16	6	-	-	-	2,119	94
Other	-	-	-	719	0.95	4	719	-
Subtotals	**38,423**	**0.31**	**99**	**10,517**	**1.15**	**46**	**49,113**	**4,172**
Total nickel (Mt)								**53,285**
Total nickel (kt) Reserves / Past production							*245,000*	*19,770*

Sources
Australia - (Siegrist et al., 2017), Botswana - (Maier et al., 2008), Brazil - (Haldar, 2016; Horizonte Minerals, 2016; Mansur and Ferreira Filho, 2016; Melfi et al., 1988), Cameroon - (Bair, 2009), Canada - (Haldar, 2016; Li and Hitch, 2016; Ronacher et al., 2012; Schulz et al., 2014), China - (Haldar, 2016), Colombia - (Gleeson et al., 2004), Cuba – (Porter Geoconsultancy, 2000), Finland - (Maier, Lahtinen, et al., 2015; Mutanen, 1997; Puritch et al., 2007), Indonesia - (Idrus et al., 2011; Landers et al., 2009), New Caledonia - (Landers et al., 2009; Yang et al., 2013), Philippines - (Willis and Gifford, 2010; Zhou et al., 2000), PNG - (Highlands Pacific, 2016; RMC, 2016; WinTech Group Ltd., 2011), Russia - (Barnes et al., 2001; Gertner et al., 2009; Haldar, 2016; Krivolutskaya et al., 2012; Lygin, 2010; Medvedev and Sannikova, 2012; Naldrett, 2004; Sharkov and Chistyakov, 2014; Sluzhenikin and Mokhov, 2015; Talovina et al., 2008), South Africa - (Marketwired, 2012; Schouwstra et al., 2000; Schulz et al., 2014), United States - (Miller and Ripley, 1996), Zimbabwe - (Maier, Määttää, et al., 2015), Other - (Blackdown Resources Ltd., 2013; Daigle et al., 2014; Haldar, 2016; Tavchandjian and Golightly, 2010), Kimberlite - (Mervine et al., 2018)

4.4.1 Carbon sequestration potential

The geologic setting, production rates, reserves, and mineralogy of key worldwide sulfidic and laterite-hosted nickel mines have been assessed from past ore production as well as from future production. The calculations presented in Table 17 serve as the underlying data for the sequestration potential displayed in Table 18. The CO_2 sequestration potential is dependent on the subtype of feedstock (Table 16) as described in the methods. Summing up past production and reserves, a total of 7,254 Mt of CO_2 could be sequestered from the selected countries and mine sites.

Table 18: Worldwide CO_2 sequestration potential from nickel mines

	Ore past production (Mt ore)	Ore reserves (Mt ore)	Sequestration from past production (Mt CO_2)	Sequestration from reserves (Mt CO_2)
Country				
Australia	810	6,323	271	1,897
Botswana	143	415	10	29
Brazil	103	735	15	106
Cameroon	-	323	-	39
Canada	869	5,752	148	980
Kimberlite	42	26	16	11
China	74	432	19	112
Colombia	108	331	9	27
Cuba	82	377	4	18
Finland	95	1,987	3	72
Indonesia	245	1,270	26	136
New Caledonia	66	674	5	49
Philippines	140	99	37	26
PNG	-	1,869	-	157
Russia	797	4,400	82	455
South Africa	369	18,100	37	1,815
Kimberlite	118	147	40	47
United States	18	3,016	1	137
Zimbabwe	94	2,119	15	346
Various countries	-	719	0	55
Subtotals	**4,172**	**49,113**	**739**	**6,516**
Total sequestration (Mt CO_2)				**7,254**

4.4.2 CO_2 uptake method

A direct biotechnological approach to carbon mineralisation could be devised at mine sites by combining heap leaching, which has been used for centuries to extract metals from sulfidic low-grade ore, and a photosynthetic bioreactor (Power et al., 2010; Power et al., 2014). In short, this could be done by placing the ore on a liner and inoculating with acid-generating bacteria and nutrients. The sulfidic material provides ideal conditions for acid-generating microbes, such as Acidithiobacillus spp., that accelerates the generation of sulfuric acid for mineral dissolution and metal leaching bioreactor (Power et al., 2010; Power et al., 2014). For example, leaching 7500 tonnes of ultramafic mine tailings could release enough magnesium to sequester approximately 2,800 tonnes of CO_2 per year in a 0.12 km^2 photosynthetic bioreactor.

4.4.3 Carbon pricing model

The carbon pricing model helps to make an investment decision. Here, future cash flows are discounted to the present value to provide an estimate of the net present value (NPV). The NPV model is dependent on the input factors listed in Table 20. The

weighted average cost of capital (WACC) is the average for the mineral and metal industry (Damodaran, 2019), while the chosen tax rate is an average global corporate rate according to the Tax Foundation (Bunn, 2018). The main element in the NPV model is the price of carbon (per tonne of CO_2), which is set to an initial US$20.

Furthermore, the sequestration cost per tonne of CO_2 is based off an average direct operation cost with a value of US$7.70 for the year 2020. In the following model, the currency is in million US$, and the amounts of CO_2 are in million tonnes. The idea is to utilise existing mine site tailings, which has the advantage of eliminating substantial costs and licensing necessary at a greenfield site. This includes such expenses as feasibility studies, permissions, mining, and rock-crushing equipment as well as general infrastructure costs. The initial CAPEX of US$521 million is comprised of various setup costs, engineering solutions, and equipment costs required to establish the heap leach operations (See Table 19).

Table 19: CAPEX

CAPEX breakdown (All dollar values are in millions of US$)	
Working Capital	79.2
Process pumps, plant, solution distribution piping	72.6
Leach pads/ponds	66.0
Agglomeration/stacking system	66.0
EPCM (engineering, procurement, construction management)	59.0
Import duties	52.8
Owner's preproduction cost	46.2
Equipment / materials transport	39.6
Laboratory	19.8
Initial operating supplies	19.8
Total CAPEX	**521.00**

The NPV model, which is shown in Table 21, is based on a number of the input factors in Table 20.

Table 20: NPV Model input factors

NPV model input factors (All dollar values are in millions of US$)

Total mt CO_2	7,254	WACC =	9.31%
Time horizon (years)	100	Initial CAPEX (mil US$)	$521
Sequestration Per Years (mt)	72.5	Sequestration Cost (US$ / t CO_2)	$7.70
Expected GDP Growth =	2.0%	Price (US$ / t CO_2)	$20.0
Inflation =	2.0%	Tax Rate =	23.0%

This NPV model runs for eight years, whereafter the terminal value of the time horizon of the remaining 92 years is determined. The dollar values are in millions of US$. The carbon revenues are derived from the annual CO_2 sequestration (72.5 mt) multiplied by the price, which starts at US$20. A carbon price of that magnitude fits well into the EU ETS price which has hovered around EUR 18 and EUR 27 from January to May 2019, equivalent to US$20 to US$30 (Investing, 2019). The revenue increases at two percent per annum according to the determined GDP growth in the table above. The same is true for the annual costs, which are a multiplication of annual sequestration times sequestration cost. The Future Cash Flows (FCF) near the bottom of the table are discounted at the Weighted Average Cost of Capital (WACC), which is set out to be 9.31 percent in the model. This equals to the Present Value (PV), which is summed up across the years including the Terminal Value at the end of year 8. The total Present Value equals US$13.289 billion. According to the Net Present Value decision rule, any investment project that yields a positive value presents a viable investment opportunity from a financial point of view as it contributes positively to the shareholder value creation.

Table 21: NPV Model

Simple Bio-Reactor (All dollar values in million)										
Year	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**Terminal Value**
Time	0	1	2	3	4	5	6	7	8	8
Carbon Revenues		1,451	1,509	1,569	1,632	1,697	1,765	1,836	1,909	
Annual Costs		-555	-566	-577	-589	-601	-613	-625	-638	
EBIT		896	943	992	1,043	1,096	1,152	1,211	1,272	
Tax		-206	-217	-228	-240	-253	-265	-279	-293	
Initial CAPEX		-521								
Depreciation (offset by annual CAPEX)										
FCF		168	726	763	803	844	887	932	979	19,038
Present Value (PV)		154	607	584	562	541	520	500	480	9,340

Present Value of Project	**$13,289**

4.5 Discussion

As one can see from the simple NPV model created in Table 21, a positive present value equals to US$13.289 billion results. However, the above model is based on the assumption of a carbon price of US$20 per tonne of CO_2. Additionally, to this carbon price, the model calculates the break-even cost of carbon required that make CO_2 sequestration via carbon mineralisation worthwhile. Setting the NPV to zero and running an iterative calculation on the price (US$ / t CO_2), as stated under Table 20, the break-even cost of carbon equates *to US$ 7.311* per ton of CO_2.

Having a break-even cost of carbon at US$ 7.311 is much more promising than the non-biological carbon mineralisation process estimates from Dipple & Hitch (2012), which required a price of US$200 per tonne of CO_2 to reach financial viability. Pindilli et al. (2018) have estimated the net societal benefits of managing the CO_2 sequestration of forested peatland in North Carolina, USA. It was found that actively managing the peatland would sequester between 9.9 and 16.5 million tonnes of CO_2 over a period of fifty years. This would result in an NPV of US$31.75 to US$32.9 (Pindilli et al., 2018). Academic literature suggests that the social price of carbon ranges somewhere between US$33 and US$220 (Moore and Diaz, 2015; Nordhaus, 1993; Tol, 2011, 2013). The Interagency Working Group (IWG) was established by the U.S. government, and its SCC analyses have been widely used in regulatory impact analyses (National Academies of Sciences, 2017). The first estimate of the SCC by the IWG was done in 2010 with revisions in 2013 and 2016 (IWG, 2010). The last global estimate was at US$47 per tonne of CO_2 (Pindilli et al., 2018). Weitzman (2009) argues that the fat tail associated with low-probability, high-impact events, and

uncertainty may render median and average estimates of the SCC meaningless. Nonetheless, policy decisions that impact emissions are frequently being made, therefore estimating the monetary value of the SCC may support more informed decision-making.

4.5.1 Limitations of the study

According to the findings in this chapter, approximately 7 Gt of CO_2 could be sequestered through past and future feedstock from nickel mines. While this is a relatively small figure, it should be noted that only nickel and some diamond mines have been considered while many other mined minerals have been omitted. Platinum group metals, chrysotile asbestos, chromite, and talc mines can also produce mafic and ultramafic tailings which can be utilised for the carbon mineralisation process (Azadi et al., 2019; McCutcheon et al., 2016). It is estimated that nickel mine sites produce roughly fifty percent of the annual mafic and ultramafic feedstock, which equates to 419 Mt (Power et al., 2014).

In order to fulfil the worldwide pledges made at the COP21, an array of solutions and countermeasures will be necessary. One of the most crucial steps will be the global implementation of adequately functioning carbon markets, comprising of either a carbon tax or a trading scheme. Currently, approximately thirteen percent of worldwide greenhouse gas emissions are covered (The World Bank, 2017a). While it is essential for leading countries to step up and induce the implementation of said markets, it is equally crucial to have carbon markets worldwide to avoid economic run-off which results in carbon-tax evasion, where corporations resettle in regions where CO_2 emissions are not regulated. One of the reasons carbon markets do not function properly is that some industries (usually high energy-consuming industries) are exempt, which is effectively a way of receiving tax exemptions. This way, the envisioned reductions in emissions will not be met while at the same time, the stimulation of technological development of carbon-reduction measures is diluted (Lin and Li, 2011; Murphy, 2009).

A properly functioning carbon market would act as an incentive, spurring technological development and general efficiency improvements. Furthermore, it would enable carbon sequestration models, such as the one described in this paper,

to be genuinely considered for implementation. Mining corporations will have the option to opt not only for carbon-neutral mine sites but even create potential carbon sinks (Power et al., 2014).

Chapter 5: Embedding Sustainability into Corporate Financial Decision-making

5.1 Abstract

The business case for sustainability can be built upon: (i) cost reduction from efficient resource utilisation, (ii) revenue enhancement, (iii) risk management, and (iv) intangible assets. However, executives often adopt a short-term perspective owing to executive compensation, investor pressure, and decision-making criteria tied to fixed financial reporting systems. We propose an integrated conceptual framework, which highlights how firms could embed environment and sustainability into their long-term financial decision-making framework. To give this goal structure, the firm could adopt: (i) longer-term executive compensation plans, (ii) longer-term financial reporting, and (iii) flexible financial decision-making models which embed intangibles.

5.2 Introduction

During the late 1980s, when social issues increasingly came into focus, the concept of sustainability gained much attention, and the subsequent public pressure led to the exploration of new ways to deal with existing environmental and social problems (Sharma and Aragón-Correa, 2005). Unsustainable business practices can lead to externalised costs, which are borne by the public while excess returns are privatised (Chomsky, 2006). Although governments should protect the interests of their citizens, elected officials resist implementing unpopular policies which may translate to lost votes in future elections (Barbour and Wright, 2019). From an organisational perspective, the challenge of sustainability is that social welfare improvements and reduction of environmental impacts must be incorporated into businesses in a way that will not impede economic development (Sharma, 2002).

From an agency perspective, the firm revolves around the creation of a perpetual legal entity with the overarching goal to maximise shareholder value. In theory, this should require firms to take a long-term view to deliver the required results, but in practice, most firms adopt a short-term perspective (Barton and Wiseman, 2014; Terry, 2015; Winston, 2010). There is extensive academic literature demonstrating how executives will act in a short-term manner when offered incentives that reward such behaviour (Demirag, 1995; Marginson and McAulay, 2008; Marginson et al., 2010). Misaligned compensation systems lead executives to make decisions that are not in line with creating long-term shareholder value (Brav et al., 2005; Bushee, 1998;

Graham et al., 2005; Jensen and Meckling, 1976; Laverty, 1996). There is also a body of academic findings on investor pressure to generate fast, high returns (Bhojraj et al., 2009; Demirag, 1995; Ernstberger et al., 2019), contributing to the short-term time horizon of public firms (Zellweger, 2007).

From the practitioner viewpoint, Winston (2017) argues widely-used financial decision-making criteria are not consistent with the creation of long-term shareholder value because the return component often fails to fully reflect off-balance-sheet intangibles such as brand value, reputation, a social license to operate (SLO), and customer and employee loyalty. Esty and Winston (2009) build their business case for sustainability on four key value drivers: revenues, intangibles, costs, and risks, while our current models focus on costs and benefits that are easier to measure. Investments in environment and sustainability represent significant corporate expenses and off-balance-sheet, intangible assets are difficult to price but can create significant value. Intangible assets comprise an increasing share of a firm's market capitalisation (Ocean Tomo, 2017), demonstrating why current financial decision-making models are less effective now than they were in the 1970s.

We argue that short-termism is the primary barrier to the adoption of sustainability initiatives. As suggested by Gibson (2006), sustainability assessment would be best designed as an integrative process. Adger et al. (2003) advocate using a decision-making framework where outcomes are based on a thick understanding, spanning across various disciplines to gain legitimacy and eventually produce solutions that are equitable, efficient and effective. The current paper integrates the academic with the practitioner literature to first characterise the main contributors to short-termism in corporate decision-making. While the academic literature has focused on the agency framework for understanding managerial decision-making, it has seldom identified financial decision-making models such as net present value (NPV) or return on investment (ROI) as causes for the inherent short-termism within firms. In the current article, we integrate this practitioner-identified shortcoming with widely accepted academic studies to develop a conceptual framework that synthesises them jointly to develop a novel framework that incorporates sustainability to create long-term shareholder value. Esty and Winston's framework highlights the importance of developing new decision-making tools that would capture the economic potential of environment and sustainability investments.

Section 2 presents our research motivations through mapping the business case for embedding environment and sustainability into corporate financial decision-making onto its four underlying value drivers. In Section 3, we apply an agency framework to categorise and integrate sources that incentivise executives to adopt a short-term perspective which we believe to be a key underlying barrier to adopting sustainability. In Section 4, we propose an integrated conceptual framework to drive sustainability from which we derive tangible ways firms could embed environment and sustainability into their long-term financial decision-making framework.

5.3 The Business Case

Under the premise of value-based management, it is commonly accepted that the primary objective of executives should be to maximise the value of the firm for its shareholders (Boatright, 2017; Moyer et al., 2017). Citing economic theory, Pigou (1920) suggested that the firm should not internalise any negative externalities unless it strictly relates to its shareholding stakeholders. Over the past century, most firms have followed this philosophy and have focused on their core business without addressing societal or environmental concerns.

Nobel laureate Milton Friedman was not opposed to firms engaging in social welfare activities that increase long-term shareholder value Friedman (1979). This theory is supported by Michael Jensen, who stated ‘200 years’ worth of work in economics and finance indicate that social welfare is maximized when all firms in an economy attempt to maximize their own total firm value’ (Jensen, 2002). This shareholder approach contrasts with the later-developed stakeholder approach, which seeks to broaden the concept and push it beyond traditional economics (Freeman and McVea, 2001). Corporate decision-making becomes more complex when a firm tries to balance acting responsibly with financial performance (Salzmann et al., 2005).

Sustainability was defined by the World Commission on Environment and Development (WCED) as meeting present needs without compromising the ability of future generations to meet their needs (World Commission on Environment and Development, 1987). In 2000, the United Nations Millennium Development Goals communicated a commitment to environmental sustainability which was followed up with the 2015 Sustainable Development Goals. This put environmental sustainability

on equal footing with economic development (United Nations, 2015).

In the late 1980s, social issues, including life quality and human rights, were at the forefront of the sustainability movement (Sharma and Aragón-Correa, 2005), and the term sustainability became associated with the right and wrongdoing of firms. Public pressure pushed for new problem-solving approaches to integrate environmental protection and economic development to alleviate poverty. Firms now faced the challenge of integrating corporate economic activities while also focusing on social stakeholders such as employees, supply chain, and the community (Dunphy et al., 2003).

From a societal perspective, the lack of sustainable practices might be considered a market failure as it would represent substantial cost to society and therefore represent an implied subsidy, a social grant, or 'legal looting' (Akerlof et al., 1993) as the costs are paid by the public and excess returns are privatised (Chomsky, 2006). Carbon markets, which aim to regulate, price, cap, and reduce the emissions of greenhouse gases (GHGs), are an example of internalising external costs. A study by Linnenluecke et al. (2018) for the fossil fuel industry quantified the socialised costs of carbon ('looted amount') to be between $US525 billion to $US115 trillion for the years 1995–2013.

Executives of the firm strive to be at least as profitable as in previous years or, in the best-case scenario, see profits grow. Dyllick and Hockerts (2002) define 'corporate sustainability' as meeting the needs of a firm's direct and indirect stakeholders without compromising the needs of future stakeholders. This concept encompasses sustainable development, corporate social responsibility (CSR), stakeholder theory, and corporate accountability (Wilson, 2003).

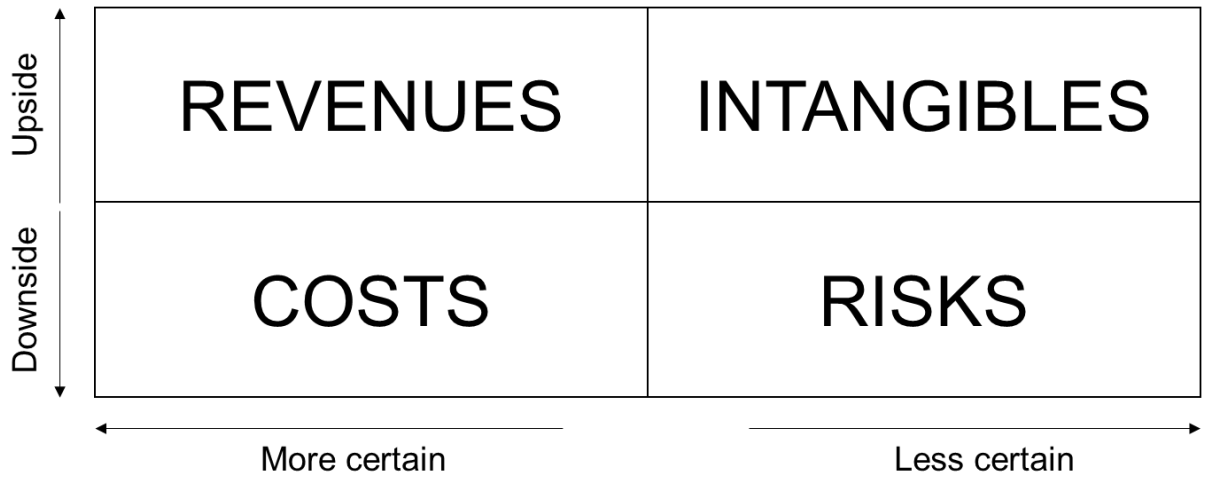
Henderson (2015) and Whelan and Fink (2016) state that the business case against sustainability is that it may be harmful to a firm's competitiveness. Others have argued that environmental sustainability should be handled by the public sector because engaged firms mostly produce 'sophisticated greenwashing at best' (Stavins, 2011; Walker and Wan, 2012). Executives are often reluctant to implement sustainability strategies because they believe the costs outweigh the economic benefits (Henderson, 2015). Earlier studies did not find a causal relationship between sustainable practices and added shareholder value (Hansen et al., 2013; Margolis and

Walsh, 2003). However, public discourse has changed significantly over the past two decades and has put pressure on firms that have been identified as key contributors to environmental problems resulting in climate change (Walker and Wan, 2012).

Artiach et al. (2010) investigated the main factors driving corporate sustainability performance using a stakeholder framework. Their study found that leaders in this field are most likely the largest firms in the industry, which are under more scrutiny by regulators and stakeholders due to their size. Wood and Ross (2006) found stakeholder opinion was a main driver for improving a firm's environmental performance with 42 percent of the executives voting it as the most important element. These results underpin the findings by Schmidheiny and Zorraqu'n (1996) and Gunningham et al. (1999), proving the effectiveness of market forces as a means to influence investment decision-making of firms and the subsequent effect on both environmental and sustainability performance.

Esty and Winston (2009) built their conceptual case for sustainability in business on four key elements: revenues, intangibles, costs, and risks (Figure 11). They classify revenues and intangibles as the upside components, as these have the potential to create value, while costs and risks are potential downsides which can destroy value if not managed adequately.

Figure 11: The case for sustainability: innovation and value drivers



(Esty and Winston, 2009), © Wiley 2009

The cost component comprises the ecological footprint of the firm; improving the efficiency of the firm's spending on water, electricity, and waste reduces costs (Winston,

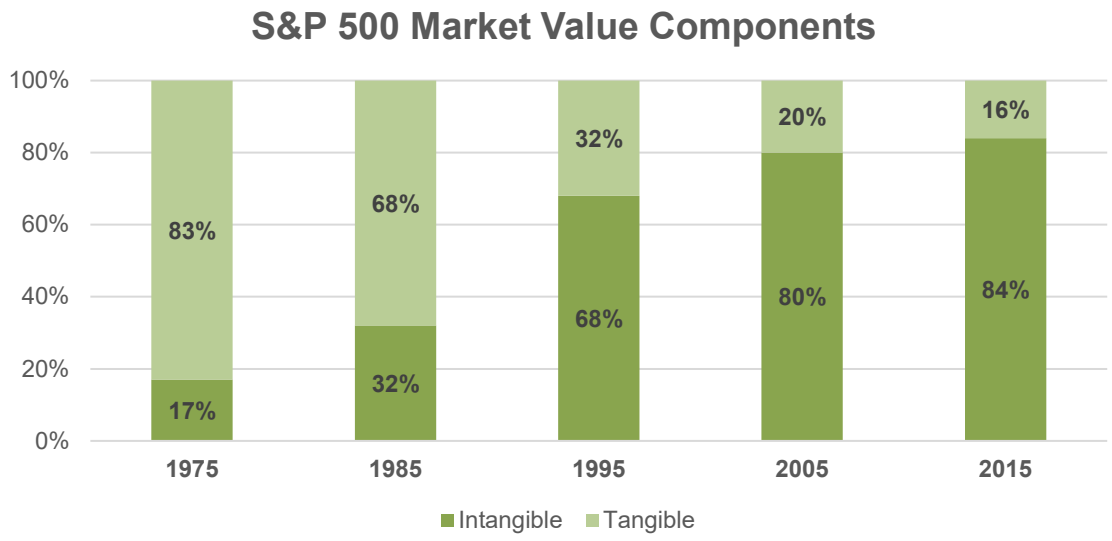
2010). Empirical data on the cost curve for renewable energy has seen a downward trend over the last decade, with the levelised energy costs per megawatt-hour (MWh) of wind falling by 66 percent and solar by 85 percent between 2009 and 2016 (O'Boyle, 2017).

The risk component of sustainability includes future regulatory and environmental policy changes, and can also include items related to the reliability and resilience of the supply chain (Winston, 2017) which are increasing due to climate change (Linnenluecke et al., 2015). Additionally, workplace safety can reduce downside risk. The 2015 Brazilian Samarco mine disaster killed 19 people (Phillips, 2018), destroyed property and resulted in $AU55 billion in compensation, clean-up, and renaturation costs (Macalister, 2016). BHP Billiton's shares dropped 6 percent immediately after the disaster and destroyed more than $AU35 billion in market capitalisation.

With the transformation to a more sustainable economy, the revenue side is gaining momentum as new products and technologies emerge to solve environmental challenges. Additionally, more sustainable products may justify overall higher prices as they have the potential to be advertised under the 'green marketing' concept (Arseculeratne and Yazdanifard, 2013). Linnenluecke et al. (2017) estimate the development of cleantech patents will contribute $US10–15 trillion by 2050, while intergovernmental sources estimate up to $US29 trillion (OECD/IEA and IRENA, 2017).

The most complex factor contributing to sustainability-linked value creation is the intangible component, which includes reputation, brand value, patents, trademarks and copyrights, and trade secrets. Building brand recognition also influences costs, revenues and risks because it enables the firm to build long-lasting customer and employee relationships. The Ocean Tomo (2017) Annual Study of Intangible Asset Market Value reveals intangible assets made up only 17 percent of market capitalisation for S&P 500 firms in 1975 but has continuously risen to 84 percent in 2015. Given this evolution, it is evident there is a need to incorporate this difficult-to-measure but very important value driver (Figure 12).

Figure 12: S&P 500 Value Components



(Ocean Tomo, 2017)

Incorporation of these four value drivers for sustainability saves money, helps make future cash flows more reliable, drives sales, and helps create long-term, sustainable cash flows (Winston, 2017). Not only does it drive innovation, but it also builds a relationship with the (broader) community and can give the firm an SLO (Lacey et al., 2012), which has to be earned through their stakeholders including local communities, employees, customers, and government.

5.4 Short-term Perspective

The relationship between stockholders and executives of a corporation is a pure agency relationship in which the owner of the firm (shareholder) outsources the task of running the business to a third party: the manager (Jensen and Meckling, 1976). This separation of ownership and management results in agency costs, which are defined as the sum of 'monitoring expenditures, bonding expenditures plus the residual loss, which is the total reduction in welfare for the principal as a subsequent result of the divergence from the goals by the agent' (Jensen and Meckling, 1976). Agency theory reconfirms the importance of incentives and serves as a reminder that, within the life of an organisation, most actions are based on self-interest (Barney and Ouchi, 1990). Problems will arise when firms inadvertently create systems which incentivise managers and employees to act in ways that do not maximise shareholder value. One reason why the establishment of the business case for sustainability continues to be

difficult is the short-term view taken by most firms (Barton and Wiseman, 2015; Terry, 2015; Winston, 2010), which makes the implementation of a sustainable business model a complex issue.

The literature has also identified many institutional factors that may hinder sustainability integration. Placet et al. (2005) identified inertia as one of the main barriers to sustainability, especially for mature industries, as it promotes the continuation of business the way it has been done in the past. Linnenluecke and Griffiths (2010) investigated the link between sustainability and culture, concluding various subgroups exist among employees each holding different views, values, and perspectives (Martin, 2001; Zammuto, 2005). It was concluded that while subcultures can provide certain barriers for driving a comprehensive sustainability-related change of culture, integrating key measures of sustainability into employee performance evaluation can help instil the inherent values and beliefs of an organisation (Dunphy et al., 2003; Linnenluecke and Griffiths, 2010). While it is recognised that there are other contributing factors, the scope of this paper will focus on the underlying causes of short-termism that impacts the firm's executives.

It is also acknowledged that alternative theories to agency theory are widely accepted in the sustainability literature. The resource-based view (RBV) has emerged as a popular theory with the aim of gaining a competitive, sustainable advantage (Fahy, 2000). From an RBV point of view, CSR can be seen as worth pursuing as it supports the development of new resources and capabilities and also improves firms' reputation and stakeholder relationships (Branco and Rodrigues, 2006). According to legitimacy theory, a firm needs to hold an SLO in order to gain legitimate access to resources (Deegan, 2002) as firms are subject to a greater acceptance by society (Hahn and Kühnen, 2013), making the acquisition of an SLO a valuable resource (Ashforth and Gibbs, 1990; Dowling and Pfeffer, 1975; Suchman, 1995). Similar to agency theory, signalling theory (Connelly et al., 2011; Spence, 1978) deals with asymmetric information between the firm and its stakeholders. Signalling theory suggests that the firm should proactively reduce information asymmetry through credible sustainability reporting. In doing so, the firm creates positive media coverage and also secures its legitimacy (Hahn and Kühnen, 2013).

A shortcoming of the agency relationship perspective is that the agent will focus

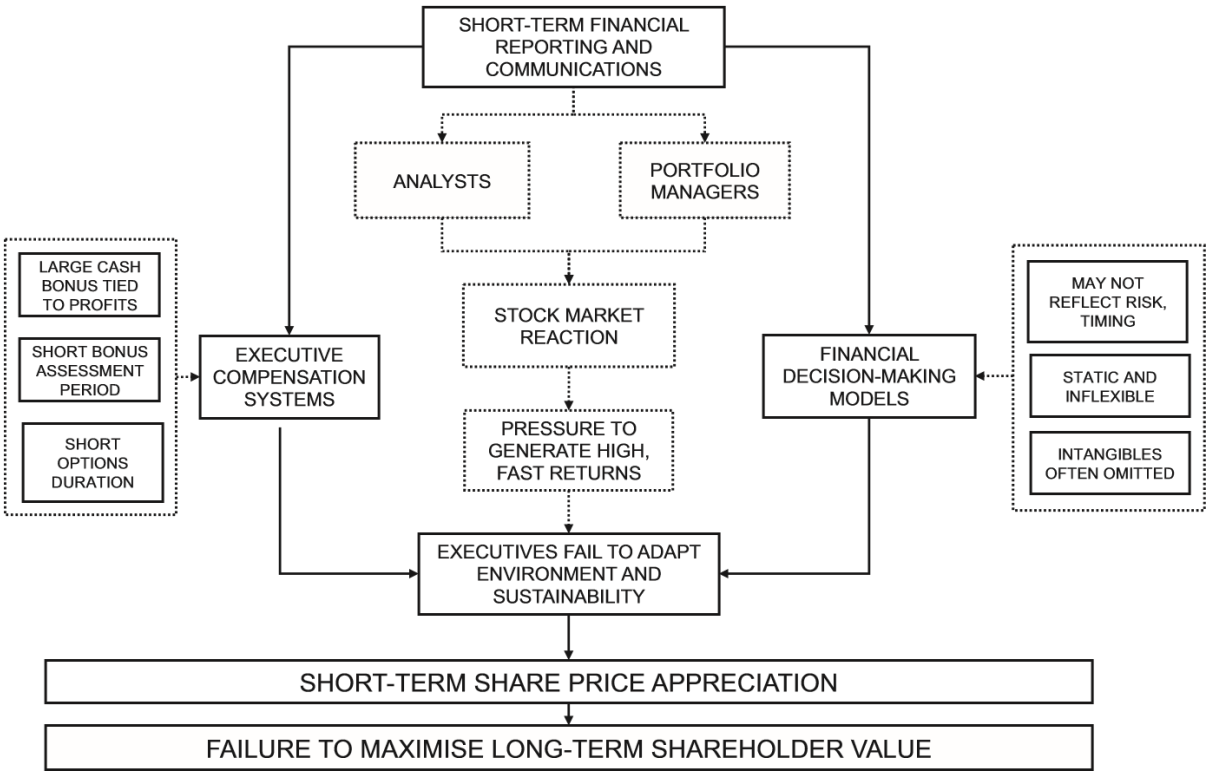
purely on investing in value-maximising projects when making strategic decisions for the firm. In doing so, the agent is potentially sacrificing better investments that would pay off in the far future, beyond the agents' tenure, for short-term gains (Gibson, 2006). This conundrum has been previously described by Laverty (1996) as 'intertemporal choice.' Laverty defined short-termism as 'decisions and outcomes that pursue a course of action that is best for the short term but suboptimal over the long run' (Laverty, 1996). Schumpeter (1942) highlighted problems with only considering the short term while Loewenstein and Thaler (1989) caution us to consider intertemporal choices in which 'the timing of cost and benefits are spread out over time' in our decision-making models to ensure long-term sustainability for the firm.

Business executives continually make decisions where a choice between a long- or short-term investment needs to be made (Bansal and DesJardine, 2015; Terry, 2015). Figure 13 depicts our 'unsustainable business model', which demonstrates mechanisms by which the short-term perspective leads to the erosion of long-term shareholder value. Our current financial reporting and communications are the key input and influence executive actions related to three different paths: (i) executive compensation systems (Brav et al., 2005; Bushee, 1998; Graham et al., 2005; Jensen and Meckling, 1976; Laverty, 1996); (ii) stock price reactions resulting in investor pressure for fast and high returns (Bhojraj et al., 2009; Demirag, 1995; Ernstberger et al., 2019); and (iii) financial decision-making models (Winston, 2017), which all contribute to the short-term time horizon of public firms (Zellweger, 2007).

Annual financial reporting influences executives via their compensation systems, which are designed to curb agency costs by aligning the goals of the executives with those of the shareholder (Eisenhardt, 1989). There is ample research documenting the weak link between executive pay and performance (Pearce et al., 1985; Ungson and Steers, 1984). Unfortunately, most compensation plans include large cash bonuses based on a single year of performance and 'almost all companies rely on some measure of accounting profits' (Murphy, 1999). Giving executives this short assessment period encourages them to make short-term decisions (Cebon and Hermalin, 2014). In theory, executive stock options provide the CEO with an incentive to maximise long-term shareholder value by tying their compensation to the share price, but Chen (2004) outlines various ways in which the design of option plans can destroy shareholder value, and Wyld (2010) suggests that executives 'manipulate the exercise

of options to their personal benefit'. The duration for most option plans is short; typically 25 percent vest annually in each of the four years following the grant (Murphy, 1999). Laverty (2004) posits that executives operate within the given framework; therefore, the system is to blame, not the individual, suggesting the need to revise current compensation plans.

Figure 13: Unsustainable Business Model (own creation)



The release of quarterly financial reports and earnings announcements fuel analyst recommendations which impact stock market prices and have been identified as the main culprit behind short-term behaviour (Dertouzos et al., 1989; Doukas et al., 2005; Hayes and Abernathy, 1983; Jacobs, 1991; Laverty, 1996; Porter, 1992). Additionally, Drucker (2011) contends that 'the need to satisfy the pension fund manager's quest for higher earnings next quarter ... pushes the top executives toward decisions they know to be costly, if not suicidal, mistakes.' In an extensive survey of 400 US financial executives, Graham et al. (2005) report, 78 percent chose to smooth earnings, potentially sacrificing long-term investments, due to pressure from financial markets. Similar findings by Bushee (1998), Dechow and Sloan (1991), Bartov (1993), Penman and Zhang (2002), and Barton and Wiseman (2015) provide empirical support consistent with managers selling assets, reducing spending on research and

development (R&D), or buying back shares to meet quarterly earnings targets at the expense of long-term value creation.

Annual reporting also feeds our current decision-making tools, which fail to reflect the full value of the firm's investments in environment and sustainability. While the ROI metric has utility, return is an accounting measure that fails to incorporate both the risk or timing of future payoffs. NPV is based on the discounted cash flow (DCF) model, which is one of the most common models used in the financial world (Brealey et al., 2014; Marchioni and Magni, 2018). Only projects with a positive NPV should be undertaken (Moyer et al., 2017) as they should create shareholder value (Brav et al., 2005). However, most investment projects take place in a highly flexible environment, and Dixit and Pindyck (1994) showed the static NPV model ignores inherent project flexibility. Neither ROI nor NPV fully encompasses the value of the investment because intangible off-balance-sheet assets are not included. Further, inflated cost of capital rates, as well as short investment time frames, further fuel the short-term perspective and render sustainable, long-term investments less likely (Dobbs, 2009).

Subsequently, finance and accounting systems of firms globally are set up to focus on the management of short-term costing, reporting, and disclosure rather than capturing possible long-term value (Linnenluecke et al., 2015). As an investment decision may take several years to reveal its true value, the timing of dealing with these trade-offs as well as the tools utilised to make said decision become apparent and are central to the notion of sustainability (Laverty, 1996). Investments in R&D and other intangible expenses such as human capital and corporate culture also require a long-term view (Henderson, 2015). As the cost of investments is borne in the present, executives are tempted to forgo long-term returns for short-term results (Terry, 2015). In quantifying the macro impact of short-termism, Terry (2015) concluded that the pressure to deliver short-term results every quarter cuts US growth by about 0.1 percentage points per annum.

5.5 Driving Sustainability

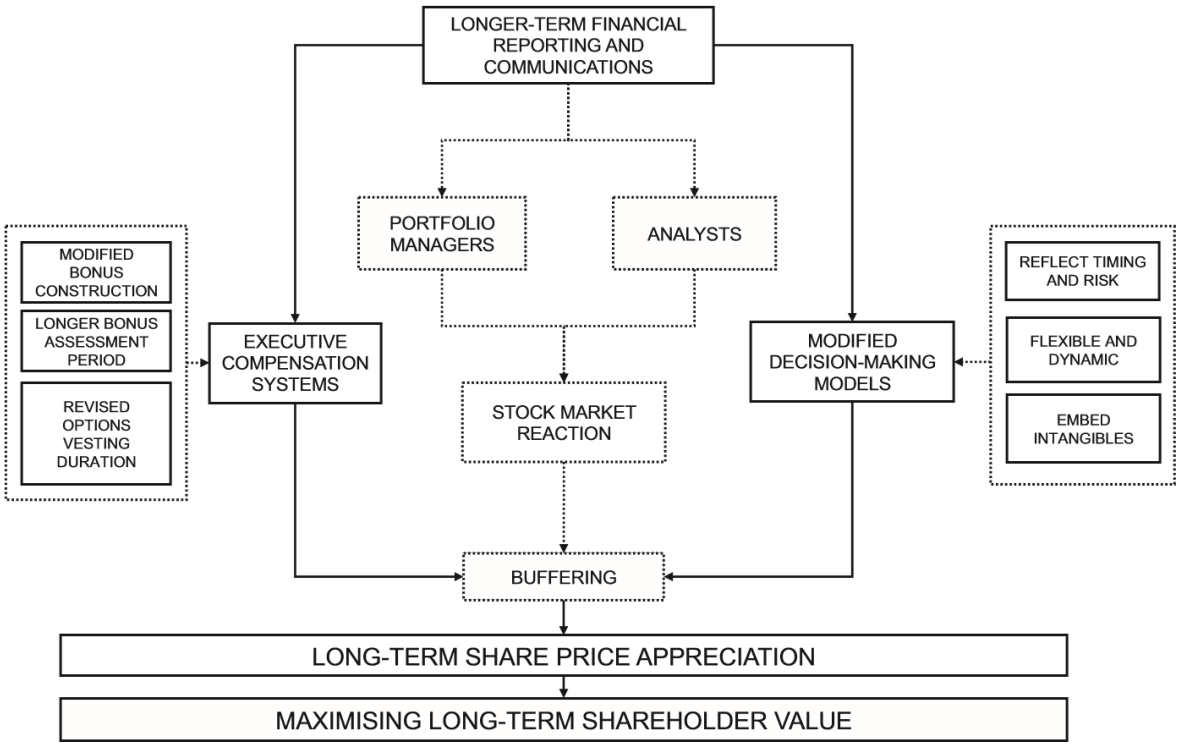
To challenge the status quo and launch sustainable business practices with a positive return, a long-term scope is necessary (Christensen, 2014; Tushman and Romanelli, 1985). In order to capture long-term value accordingly, reporting and accounting systems need to be set up as they play an integral part of both strategy and risk management (West and Berereton, 2013). Hollindale et al. (2017) highlight the importance of integrating high-quality disclosure of GHG emissions, and reporting that integrates both financial and sustainability performance (Dumay et al., 2016) has been promoted as a solution to the shortcomings of financial reporting (Linnenluecke et al., 2015). Unfortunately, a recent study reports that less than a third of mainstream global equity market participants are positive about the 'decision usefulness of integrated reporting and its relevance to them' and raised concerns about lack of comparability and consistency with the framework (Slack and Tsalavoutas, 2018). Further, participants in the Pilot Programme Business Network of the International Integrated Reporting Council state, that integrated reporting is not relevant to analysts as the reports do not provide the information required by analysts in sufficient detail or preferred format (Abhayawansa et al., 2018).

Although early work on business models focused on economic value creation more recently, the literature has identified business models as a core component in embedding sustainability into organisations and relates to how the firm translates strategy into activities (Bocken et al., 2014). This sustainable business model innovation framework embodies the process of transforming business models in order to balance economic, social, and environmental concerns (Schaltegger et al., 2012). Mitchell et al. (2007) advocate that firms that extend to a triple bottom line (social, ecological, and economic) will continue to operate in the long run. However, per the triple bottom line, the framework is missing an interconnection of the three pillars (Elkington, 1998). Gibson (2006) argues these sustainability frameworks fail to deliver the expected outcomes, and he advocates a more integrative approach rather than trading off and balancing the needs of various stakeholders.

The model shown in Figure 14 depicts changes to executive compensation, financial reporting, and decision-making models which could support the creation of long-term, sustainable shareholder value.

First of all, executive compensation systems could be decoupled from considering only last year's accounting figures. Pozen (2014) suggests extending the 1-year assessment period for management incentive systems to 3–5 years to reduce short-termism. The structure of executive compensation plans is very similar across firms, but firms could diverge from the pack and link the bonus to longer-term measures. Additionally, the design of executive stock options could tie vesting to measures other than simply the passage of time. Gopalan et al. (2014) developed a novel measure of executive pay duration in an attempt to quantify the extent to which executive compensation is short term, which represents a promising first step in developing optimal compensation structures.

Figure 14: Sustainable Business Model (own creation)



Secondly, firms could eliminate quarterly reporting to encourage organisations to focus on the long run. Unilever CEO Paul Polman opted to cease quarterly reporting, shunning shareholders that do not buy into the long-term, value-creation model which offers equitability, sustainability, and shared values (Boynton, 2015). This view is reinforced by Warren Buffet (Berkshire Hathaway) and Jamie Dimon (JP Morgan Chase). As shown in the 'sustainable business model', longer-term financial reporting would act as a buffer between the stock market reaction and the firm and thus enable a long-term view and subsequent adoption of environment and sustainability.

Thirdly, firms must rely on modified decision-making models. Firms need to move away from ROI, which fails to consider the timing and risk of the cash flows and focuses entirely on short-term profit maximisation. In order to overcome the lack of flexibility of the NPV model, Dixit and Pindyck (1994) proposed the use of real options models, which more realistically model how managers make decisions as they capture the inherent value in the managers' flexibility to invest, abandon, grow, or shut down a project in response to new information (Moyer et al., 2017). These models have the potential to uncover the hidden value of longer-term investments and can help firms better understand and capitalise on uncertainty (Chung et al., 2013). Firms must seek decision models that can adequately quantify the intangible values of an investment, given it is the most important constituent of market capitalisation for today's firms. Revamping the decision-making instruments could be done in various ways. Ulrich and Smallwood (2005) suggest a new metric for human resources, 'Return on Intangibles', which would incentivise organisations to take actions that create sustainable, intangible value.

If a firm chooses to adopt the sustainable business model on a longer timescale, it would reinforce resilience, reduce risk, increase sales, improve brand value, and create a corporate culture that attracts human capital. Having pilot firms with sustainable goals on their agenda and leading the trend towards sustainability around the globe sets a benchmark for the competition and act as a call-to-action. With customer appreciation of said practices, the 'green marketing' effect can give a firm a competitive advantage which the competition cannot ignore over the long run (Arseculeratne and Yazdanifard, 2013). This would help to move the market in the right direction as the cost curve for sustainable technologies and strategies is driven downwards. Examples of leaders in the field are manifold: Google, Wal-Mart, Apple, Facebook, and others have committed to power their direct energy usage from 100 percent renewable source (Gade, 2017). In 2013, Microsoft was a pioneer in assigning an internal price on their carbon emissions which resulted in a reduction of 9.6 million tonnes of CO_2 and has inspired 1,200 firms to follow suit (Microsoft, 2018).

Institutional investors have expressed their support for environmental, social, and governance initiatives (Ernst & Young, 2017a), and in 2016 Larry Fink, the CEO of BlackRock, the world's largest hedge fund, sent a letter to fellow CEOs advising them to focus more on long-term value creation. The most recent letter (Fink, 2018)

highlights BlackRock's focus on firms that drive sustainable, long-term growth. He further noted, 'a company's ability to manage environmental, social and governance matters demonstrates the leadership and good governance that is so essential to sustainable growth, which is why we are increasingly integrating these issues into our investment process'.

5.6 Conclusions

This study proposes an integrated conceptual framework highlighting how firms could embed environment and sustainability into their long-term financial decision-making. From a practitioner's viewpoint, Esty and Winston (2009) propose a business case for sustainability that highlights the current focus on revenue, cost, and risk management that largely ignores intangible resources as a value driver. Given that intangibles make up the majority of today's corporate market capitalisation, firms should not continue to base financial decisions on tools from the 1970s. The recent failure of governments to provide sustainability and environmental solutions has seen society looking to business to address societal issues. Today's public holds firms to more exacting standards with greater expectations of the firms they work for, buy from, and invest in.

We have explicitly applied an agency framework to understand the underlying motivations for executive short-term decision-making. This led us to identify and categorise three key input factors fuelling short-term behaviour. Compensation packages designed to curb agency costs often incentivise executives to sacrifice sustainable investments with longer time horizons. Similarly, pressure to meet investor demand for fast and high returns discourages executive investments in sustainability in order to protect short-term earnings. Inflexible and outdated financial decision-making models do not account for the full value of intangible resources and may even fail to adequately price the risk and timing of the cash flows. Overarching, short-term financial reporting and communications strategy drive these three key decision-making inputs.

While many existing models identify potential barriers to embedding sustainability and environment, our study focuses solely on understanding executive short-termism as a rationale for firms' failure to adopt sustainability. Executives often make

intertemporal choices that can undervalue, overlook, or intentionally ignore the true potential of the investments and create an imbalance that poses a threat to a firm's long-term sustainability (Bansal and DesJardine, 2014). There is an extensive academic literature on investor pressure and compensation as causes for executive short-termism, but by integrating a practitioner viewpoint, we highlight how decision-making models may be a key and often overlooked culprit. Gibson's (2006) critique of the triple bottom line is that it leads to frequent trade-offs because it considers the economic, environmental, and social levels individually and not in an integrative manner, whereas our study brings together the academic and practitioner viewpoints to yield an integrative model of the underlying causes of executive short-term behaviour that results in the unsustainable business model.

Our conceptual framework highlights three ways in which firms could encourage executives to adopt a longer-term perspective and therefore embed more environment and sustainability into their financial decision-making. First, executive compensation plans with extended assessment and duration periods with an adjusted compensation mix would create goal congruence between the executives and their shareholders' long-term interests. Second, rethinking financial reporting to include a longer-term perspective would counteract the constant investor demand to produce short-term earnings. Third, modifying current financial decision-making models to embed intangibles, adjust for risk and timing of investments, and include real options could help reveal the true value of investment decisions.

This paper highlights the need for revised decision-making tools to address the short-termism inherent in firms which has pedagogical implications. Despite the headway that has been made with real options over the past two decades, introductory and MBA finance courses continue to teach the same financial decision-making models. This paper also stresses the need to capture intangible resources into our financial reporting and models in order to create sustainable, long-term shareholder value. Future studies could involve empirically testing the hypothesis that embedding modified decision-making tools are beneficial for the long-term creation of shareholder value.

On the practical side, this paper proposes three primary areas which firms can focus on to move towards long-term value creation. First, firms can alter executive compensation systems to truly align the goals of the executives with the goals of the

firm. Second, firms can move away from quarterly reporting and be open to alternatives to the current annual financial reporting systems, which would allow the firm to concentrate on long-term rather than short-term investors. Third, we recommend modified decision-making models that take real options into account, value intangibles that may currently be omitted, and adequately adjust for time and risk. This would increase investment into environmental and sustainable projects whose outcomes could create novel technologies to further improve natural resource utilisation.

Chapter 6: Conclusion

6.1 Summary of Findings

The commitment to the Paris Agreement has left countries searching for pathways that lead to decarbonising their economies. Australia established various ways, dismissing carbon mineralisation in the process. While the heat and pressure-induced method has poor energy economics, rendering it financially unviable, new biogeochemical approaches utilising naturally occurring bacteria have shown promising lab results. The motivation of this thesis is to assess the potential of bacteria-mediated carbon mineralisation with the intent to help resurface this dismissed method as a means to sequester CO_2. In order to achieve this goal, I assess the sequestration potential from an Australian and Global perspective, leveraging feedstock from both past and future nickel and diamond mines. Furthermore, the aim is to understand what is keeping firms from investing early on into such promising technologies. Here, I identify key short-termism roadblocks as well as highlight ways on how to overcome them. The results provide an insight into the potential of this technology that can support the government, the industry, and practitioners in their efforts to provide policies, incentives, and ideas on how to decarbonise their economic activities.

Chapter 3 assessed the carbon mineralisation potential for Australian nickel mines, being the world's fifth-largest producer in 2018 with a global share of approximately ten percent (Australian Government, 2018b). The research looked at both active and abandoned nickel mines and identified potential feedstock from both past excavations as well as from future estimated reserves. This research helped to gain an understanding and appreciation of the impact that carbon mineralisation could have with regards to the decarbonisation of the Australian economy.

Chapter 4 further expands the geographic scope, going from an Australian to a global perspective. Extending the above-mentioned methods and data-gathering techniques, this chapter estimates the worldwide suitable feedstock and quantifies the bacterial-mediated CO_2 sequestration potential. The additional element in this chapter is the financial quantification of this sequestration method. Offsetting CO_2 through carbon mineralisation could be assigned a (hypothetical) value, dependent on a price on carbon. With this in mind, a simple net present value (NPV) model has been worked out to quantify the value of this method. Furthermore, having a break-even cost of carbon for this method, calculated at US$ 7.311 is much more promising than the non-

biological carbon mineralisation process estimates from Dipple & Hitch (2012), which required a price of US$200 per tonne of CO_2 to reach financial viability. This approach follows the suggestion of Pezzey (2019) whereby the marginal abatement costs of a ton of CO_2 should be used instead of trying to model social costs of carbon.

The second part of the thesis, represented by chapter 5, explores the relationship between short-termism behaviour with regards to corporate financial decision-making and the subsequent impediments for the creation of long-term shareholder value. The driving force was to understand how the business case for sustainability and environment can be justified and how it fits into the current understanding of the firm. This chapter provides insights as to why firms show little interest in adopting carbon sequestration technologies despite the recognition that emitting CO_2 will lead to an eventual erosion of long-term shareholder value. This chapter aims to decompose the current corporate decision-making framework concerning the environment and sustainability in order to understand what is motivating short-termism behaviour. Lastly, a modified framework is created with key propositions that need to be implemented in order to enable a firm to move away from a short-term toward a long-term, sustainable business model.

Chapter 3 assesses feedstock for the carbon mineralisation process from nickel mine sites in Australia. The motivation for this was the commitment of the Australian government to lower their GHG emissions by twenty-six to twenty-eight percent in 2020 as pledged under the Paris Agreement. In order to achieve said goal, various actors in the government and the industries will have to do their part in reducing and optimising their emissions. The mining industry, consuming up to ten percent of Australian energy (SunSHIFT Pty Ltd., 2017), has a vested interest in economically viable methods that contribute to the reduction of their GHG footprint. The potential for carbon mineralisation can be magnified through the example of Mount Keith, a large nickel mine in Western Australia. The complete carbonisation of its 11 Mt of tailings it produces each year would sequester the equivalent of 10 times the annual emissions of the Mount Keith mine site, making it a carbon sink (Power et al., 2014). The estimated that could be sequestered through the utilisation of mineral waste from mining companies equates to 2,171 million tonnes of CO_2. To put this into perspective, Australia has an annual output of approximately 500 million tonnes of CO_2 equivalents annually. It becomes clear that utilising carbon mineralisation to sequester CO_2 from

mine sites could become a viable contributor to the decarbonisation of the Australian economy and more specifically, the mineral industry.

Chapter 4 expanded the focus and looked at the global potential of both nickel and diamond (Kimberlite) mine sites. In total, more than seventeen countries were assessed with a count of 145 mine sites scattered across the globe. Applying the same methods as in chapter 3, whereby the respective geological setting of the mine site is assessed for feedstock type, and potential, a total sequestration potential of 7,254 million tonnes of CO_2 was calculated. This includes both the past production feedstock of mine sites as well as estimated future reserves. The countries with the highest sequestration potential are Australia (twenty-six percent), South Africa (twenty-five percent), Canada (fourteen percent), Russia (six percent), and Zimbabwe (five percent). Furthermore, this chapter pursued the idea of assigning a value to the carbon mineralisation potential in order to estimate financial viability. In order to do so, a simplified carbon pricing model was created, whereby future cash-flows from an initial price on carbon of US$20 were discounted to today's value (NPV). The total estimated NPV equates to approximately US$13.3 billion. This merely presents the first step to the creation of a business model in order to remove the hurdle faced by the potential deployment of the carbon mineralisation technology.

Tackling a grand challenge, such as the decarbonisation of an economy, must encompass various spheres and pathways. While the global community has managed to get together and outline ideas on how to tackle decarbonisation on a global level, in order to prevent an increase in global warming, it needs to be noted the Paris Agreement is a legally non-binding document. In the absence of clearly defined formal laws, rules, and regulations, it is the informal institutions that become more relevant. Therefore, it becomes apparent that much of the change necessary could stem from individual leadership through the firm.

Chapter 5 assesses the business case for implementing sustainability into the existing landscape of corporate financial decision-making. It investigates some of the obstacles present that currently prevent the firm from challenging the status quo and start to integrate externalised costs, such as a price on carbon, into their corporate financial decision-making framework. Taking a long-term strategic view and stepping away from short-term decision-making through the implementation of a sustainable

framework could assist firms in maximising the long-term creation of shareholder value. It was found that many financial assessment models utilised in the decision-making process have not been revised to meet the ever-changing landscape of the firm, including the increased pressure for sustainability from the governmental side, customer, and competition alike. Furthermore, executive compensation systems are heavily focused on short-term gains, which could be alleviated by stretching the compensation period to encourage a long-term perspective. Additionally, due to the constant pressure on the firm for delivering quarterly results, a culture of short-termism is fostered whereby executives aim at beating the market expectations, potentially sacrificing shareholder value-adding investment projects for the attainment of the said quarterly goals.

The process of using geological feedstock to sequester CO_2 emissions has been investigated for several decades (Seifritz, 1990; Zevenhoven et al., 2011). Estimates have shown that this process has the potential to sequester CO_2 worth centuries at various locations across the globe (Metz et al., 2005). In the past, it was the unfavourable energy economics standing in the way of deploying carbon mineralisation in an economically viable manner. Recent developments have the potential to overcome this drawback. Utilising mineral feedstock is the most promising method of absorbing CO_2 via the bio-technological approach due to the readily availability and conveniently crushed material, increasing sequestration rates (Mervine et al., 2018; Power et al., 2014). With these newly found methods of leveraging carbon mineralisation, this thesis aims to investigate what the potentially available feedstock from nickel mine sites is, both from an Australian and a global perspective, potentially becoming part of the solutions necessary to decarbonise the economies. While it is known that much of the outer layer of the earth is comprised of mafic and ultramafic rock, suitable for carbonation, there was a gap in the literature as to how much feedstock is available at adequate mine sites.

Chapter 5 highlights the need to focus on intangibles, and in conjunction with adjusted decision-making, models could facilitate the process of embedding a sustainable, long-term oriented business case. The fact that the intangible proportion of an average S&P 500's firm value is over eighty percent (Ocean Tomo, 2017) highlights the necessity of re-thinking the decision-making tools, as they are based on decade-old financial models. The chapter further suggests real options as a method

for the valuation of investments, such as the utilisation of carbon mineralisation for the absorption of CO_2 at a mine site. Using real options in such cases can turn a financially unviable project into a potentially worthwhile investment by capitalising on the upside in case of an appreciating price on carbon in the future. A modest investment today can create a substantial upcoming advantage, create long-term shareholder value, and tap into the cleantech market, which could contribute up to US$29 trillion by 2050 (Linnenluecke, Han, et al., 2017).

The chapter suggests various pathways to curbing the inherent short-termism prevailing individuals and subsequentially the firms. It is recommended to design executive compensation packages in a way that aligns with the long-term goals of the firms. Furthermore, some evidence suggests that abandoning quarterly reports helps to curb investor pressure, helping the firm to regain focus on their core activities as supported by institutional investors such as Warren Buffet and Larry Fink (Davis and Chiglinsky, 2018; Fink, 2018, 2019).

Societal Innovation

Decarbonisation methods matter to the mining industries in various ways. First, mining firms find themselves increasingly pressured by a change of societal values and attitudes in regard to how they conduct their business and what the effects are, both on the natural environment and the society. Social licenses to operate need to be earned by demonstrating the willingness to operate a mine in a way that satisfies not only legislation but also the expectations of local communities in the area. Carbon mineralisation leveraging the waste rocks (feedstock) while simultaneously reducing the carbon footprint of a mine site could be an ideal method of positively contributing to the overall impression necessary to retrieve and keep a social license to operate.

Furthermore, the mining industry, which consumes ten percent of Australia's energy, will have to play its part in the attempt to reduce overall GHG emissions, as is the case with Australia's pledge. Mine sites are a long-term strategic investment with a lifespan ranging from twenty to seventy years, therefore undertaking such investments require factoring in the likelihood of facing a price on carbon in the future. Real options as an investment decision-making tool to evaluate mines offer the possibility to incorporate the underlying volatility of a future price on carbon as well as

the flexibility of being able to make dynamic upcoming decisions. The utilisation of adequate decision-making tools in combination with the possibility of absorbing CO_2 at a mine site presents an interesting opportunity for the mining industry to contribute to the decarbonisation of an economy.

It should be noted, however, that the current absence of a clear price on carbon, for the majority of economies globally, poses a problem to the relevant industries as it provides them little incentive to incorporate the arising social cost from CO_2 emissions into their corporate financial decision-making framework. Subsequently, this sends the wrong signals with regards as to which projects to invest in as well as in their efforts to reduce their emissions and become more energy efficient. This would be an ideal setting for the government to step in and provide incentives for firms to invest in novel CO_2 sequestration technologies, such as carbon mineralisation.

The bio-technological carbon mineralisation method can be of significance for practitioners. This is shown in the case of De Beers Group, one of the world's leading diamond company. De Beers identified six of their diamond mine sites as having the potential to sequester large amounts of CO_2 through this method. It is estimated that the annual tailings production can offset one hundred percent of each mine site's CO_2 emissions through mineralisation (Mervine et al., 2018). This plays into the long-term strategy of De Beers Group, who announced the achievement of having carbon-neutral mining operations as part of their current R&D projects within the next five to ten years (De Beers Group, 2018).

Governments worldwide are investigating solutions and pathways to reach the goals set under the Paris Agreement. Australia has pledged to reduce its GHG emissions by around twenty-six to twenty-eight percent in 2030 (Australian Government, 2015b). It has been recognised that the pathway to such a reduction will come from a combination of various methods such as switching to more renewable energy and increased energy efficiency (Deep Decarbonization Pathways Project (2015), 2015; Denis et al., 2014a, 2014b). While carbon mineralisation has been excluded as a potential solution, the new biotechnological approach could render this method worthwhile. In combination with the quantities of CO_2 that could be sequestered by nickel and diamond mine sites, as identified in this thesis, carbon mineralisation could resurface as a means to contribute to the decarbonisation of the

countries such as Australia, South Africa or Canada.

Seeing that the environmental sphere is interlinked with humanity, society has an interest in having sustainable economic growth in a way that 'meets the needs of the present without compromising the ability of future generations to meet their own needs' (World Commission on Environment and Development, 1987).

One area where human activity has a significant impact on the environmental sphere is the emission of greenhouse gases. While the theory and magnitude are still being refined, the overwhelming majority of scientists have concluded that the release of greenhouse gasses warms the Earth (NASA, 2016). The impact of a warmer climate is manifold; however, the net effect is negative, resulting in a loss of global GDP of five to twenty percent, according to Stern (2007). Stern is one of the most prominent advocates for a price on carbon, arguing that it should be economic actions providing market signals about the underlying cost of goods, services, and activities in order to overcome the current market failure (Stern, 2007).

The failure to charge externalised costs to the emitter causing said costs is an implied subsidy or society grant and defined as the 'legal looting amount' (Akerlof et al., 1993). In finance and economics, the term looting is used to describe a situation where society agrees to permit a government to legally and contractually binding inefficiencies which persist through time. Profits are privatised, whereas the losses are paid by the public and are socialised (Chomsky, 2006), allowing investors to engage in higher risk without having to pay for the consequences in full. Therefore, society has a high stake in correcting this failure and ensuring that the emitters pay their fair share instead of offloading the cost to the public.

Finance academia

Seeing that academia has used the same financial decision-making models for decades, the proposed application of real options as means for executives to valuate investments is a novel approach. While real options as a tool have been known for decades, it is underrepresented as a practitioner's application. The meteoric rise of the proportion of intangible value of a firm further exacerbates the need for new value measurement and decision-making tools to supplement or substitute the current tools such as ROI or NPV.

6.2 Limitations of the study

Carbon mineralisation could have a potential impact on the decarbonisation goals of countries around the globe. However, it needs to be recognised that this process would merely be part of an array of solutions. This view is consistent with what has been proposed in various reports that analysed ways of achieving the goals from an Australian perspective (Burgess et al., 2011; Denis et al., 2014a, 2014b). Furthermore, it needs to be noted that the focus of this thesis was on nickel and diamond mine sites, omitting other potential minerals. Based on annual figures, it is estimated that nickel and diamond tailings equate to approximately 230 Mt. With a global, annual output of 416 Mt (Power et al., 2014), nickel and diamond make up fifty-five percent of the estimated mafic and ultramafic tailings suitable for carbon mineralisation. Future investigations will incorporate further potential mafic and ultramafic feedstock in order to get a holistic potential of the carbon mineralisation method. A proposal for further investigations can be found below under 'future investigations.'

Moreover, it needs to be acknowledged that only a few countries have a current price on carbon, most of which are below the range of social costs that occur due to the net-negative effects of a change in the climate. In conjunction with missing policy incentivisation and knowledge on how to price carbon into their corporate financial decision-making framework properly, firms lack the financial viability to deploy such methods as carbon mineralisation. While it is recognised that real options could be a solution to overcome the current negative valuation drawbacks of this method, an enforced, higher price of carbon would genuinely incentivise the mining sector to develop and deploy carbon mineralisation at a large scale.

Interdisciplinary research has a very broad approach, which is also the case for this thesis. It merges multiple disciplines, ranging from chemistry, geology, economy to business and finance. This broad scope approach of using interdisciplinary topics diminishes the merits of this thesis, which results in narrower theoretical contributions.

6.3 Future Investigations

Time Value of Carbon

The months following the submission of this thesis will be spent investigating the time value of carbon. The notion of the time value of money states that money today is worth more than money at any given time in the future; therefore, the present value is higher than the future value. This is because money today holds earning capacity for the future when invested at a positive interest rate.

The idea around the time value of carbon is built on two main components: how much carbon can be absorbed or prevented, and what the timeframe is for these carbon savings. Marshall and Kelly (2010) have looked at the second component (time) and quantified a price on the option of storing CO_2 temporarily, such as pumping it underground and releasing it decades later for permanent absorption. The reasoning lies in the deferred effects of CO_2 released into the atmosphere today, buying time to develop further and refine CO_2 absorption technologies which will presumably be cheaper in forty years. After the release of the stored CO_2, it is absorbed at a lower cost compared to the present time. The assessed net present value of delaying a tonne of CO_2 for forty years (2010 to 2050) and subsequently releasing it is between US$2.47 and US$10.89 (Kelly and Marshall, 2010).

Another way of looking at the time value of carbon is the fact that permanently absorbing CO_2 today rather than tomorrow, such as it is the case with carbon mineralisation, has a value. The rationale for CO_2 absorbed today is worth more than CO_2 absorbed in the future lies, amongst other factors, in the carbon-cycle or climate feedback effect (Stocker et al., 2014). Here, it is observed that the release of CO_2 accelerates global warming, which in turn accelerates the melting of the ice caps. The reduced areas covered with snow lead to more heat absorbed, furthering the rising temperatures. Assuming the ongoing net-negative economic effect resulting from climate change, absorbing CO_2 today should be more valuable than absorbing it at some other point in the future.

Worldwide Paper

Chapter 5 of this thesis looked into the worldwide potential of utilising carbon mineralisation as a means to absorb CO_2 at mine sites. However, the scope of said chapter is limited to nickel and diamond mine sites. Scientific research shows that there is a variety of other minerals with an adequate feedstock that could be used to absorb CO_2 and contribute to the decarbonisation of economies around the globe. The literature suggests that other minerals, such as gold, platinum, and abandoned asbestos (chrysotile) mines are also hosted in adequate feedstock, suitable for the carbon mineralisation process (Azadi et al., 2019; McCutcheon et al., 2016). According to Power et al. (2013), the annual, mafic, and ultramafic tailings suitable for carbon mineralisation is roughly 419 Mt per annum, which includes nickel, platinum group elements, asbestos (chrysotile), diamond, chromite, and talc (Power et al., 2014).

In order to put this into perspective, we need to look at the global nickel production, which was 2.3 Mt in 2018 (U.S. Geological Survey, 2019). Assuming a simplified, average nickel concentration of one percent, the tailings stemming from nickel mines equate to 230 Mt, making up fifty-five percent of the estimated mafic and ultramafic tailings suitable for carbon mineralisation. It is therefore concluded that the assessment of nickel mines, with some additional kimberlite diamond mines in this thesis, represents a substantial share of the potential mine sites suitable for carbon mineralisation.

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