FEASIBILITY AND SENSITIVITY ANALYSIS OF INTEGRATING MINING AND MINERAL CARBONATION: A CASE STUDY OF THE TURNAGAIN NICKEL PROJECT

by

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ABSTRACT

Proposed carbon reduction measures such as cap-and-trade appear poised to have a significant impact on the financial feasibility of mining operations as point-source emitters of carbon dioxide (CO_2). It is therefore necessary to proactively assess the ways in which these effects may be mitigated. Carbon sequestration through mineral carbonation is well suited for integration into mining operations of suitable geology for its ability to make use of waste rock to trap and store CO_2 and offset carbon emissions. The Turnagain Nickel site, a low-grade high-tonnage Ni-sulphide deposit located in Northern BC, contains an abundance of Mg-silicate minerals in its waste rock that have significant potential for use in mineral carbonation. This has the potential to produce an additional revenue stream through the generation and sale of carbon credits in the presence of a mandatory cap-and-trade scheme in North America. Results of financial modeling have yielded a net present value (NPV) at an 8% discount rate of $131.5 million for the integration of mineral carbonation into proposed mining operations at Turnagain, suggesting that the project may be viable from a financial standpoint. Sensitivity analysis has also demonstrated that the parameter with the greatest influence on project NPV is the CO_2 avoidance ratio. This ratio, which takes into consideration the amount of CO_2 released in the mineral carbonation process to determine the net amount of CO_2 avoided, is critical in order to maximize the amount of carbon credits available for sale in a cap-and-trade environment.

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CCS	Carbon capture and storage
CCX	Chicago Climate Exchange
CO_2	Carbon dioxide
CSR	Corporate social responsibility
DCF	Discounted cash flow
ERA	Environmental risk assessment
EU ETS	European Union Emissions Trading Scheme
GHG	Greenhouse gas
HNC	Hard Creek Nickel Corporation
IRR	Internal rate of return
NPV	Net present value
TSX	Toronto Stock Exchange
WCI	Western Climate Initiative

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1 INTRODUCTION

1.1 Project Overview

Global climate change and the need for improved environmental accountability have recently jumped to the forefront of our attention, both at home and around the world. As a result, government legislation appears inevitable in an attempt to help achieve emissions targets and progress towards improved environmental standards. Current plans suggest that market-based incentives, such as cap-and-trade, are the most effective way in which to adequately reduce greenhouse gas (GHG) levels; this will ultimately require a price to be put on carbon dioxide (CO_2) (Government of Canada, 2009). Whatever form these regulatory changes may take, the consequences of such legislation on the mining industry may be significant given the environmental footprint commonly attributable to mining operations (Norgate et al., 2007). The implications on mine economics may be immense, and as such it is important that we begin to understand how they may affect project feasibility and the ways in which we might offset these impacts. Ultimately, restrictions or limitations on carbon emissions may become a deciding factor when considering and evaluating the overall feasibility of developing a deposit. In response, it is necessary that corporations anticipate and prepare for such a scenario, and have a plan in place outlining the necessary steps required to operate under a proposed cap-and-trade regulatory environment. Being proactive in planning for these effects will help ensure and protect the viability of current and future mining projects.

1.2 The Turnagain Nickel Site

The focus of this research is on the Turnagain nickel deposit (Turnagain) in Northern British Columbia, 100% owned by Hard Creek Nickel Corp. (TSX-V: HNC) (Hard Creek). The Turnagain deposit was chosen as the focus of this case study due to its geologic propensity as an attractive site for the sequestration and storage of carbon. This is primarily due to its ultramafic mineralogy, with abundant quantities of magnesium-rich olivine found within the waste rock of the deposit. The ultramafic material found at Turnagain has significant potential to trap and store CO_2 through a process known as mineral carbonation. A more detailed discussion of mineral carbonation is found in Chapter 2. Turnagain is a prime example of a deposit amenable to the integration of mineral carbonation directly into the mine plan, thus enabling the corporation to take advantage of a regulatory environment of governmental carbon management and cap-and-trade as it sequesters CO_2.

The Turnagain nickel deposit is located in north-central British Columbia, approximately 70 km east of the nearest town of Dease Lake, BC, as shown in Figure 1.1. The deposit is hosted within the Turnagain ultramafic complex, an Early Jurassic Alaskan-type mafic-ultramafic intrusive pluton with a total area of ~24 km^2 (~8x3 km) (Scheel, 2007). This complex is found within greenschist facies metasedimentary and metavolcanic rocks of ancestral North America, and is fault bounded on all sides (Scheel, 2007; Gabrielse, 1998; Clark, 1980).

The Turnagain complex is dominated by ultramafic lithology, primarily characterized by a well-exposed dunite core, surrounded by an outer zone of poorly exposed wehrlite, olivine clinopyroxenite, pyroxenite and minor hornblendite. There is weak to intense serpentine alteration throughout the complex, with a characteristically black colour. This is attributed to magnetite formation during serpentinization (Clark, 1980; Nixon, 1998; Scheel, 2007). The presence of abundant olivine found in the dominant rock-types at Turnagain makes this site well suited for applications to carbon sequestration via mineral carbonation due to the availability of rich sources of MgO.

The Turnagain ultramafic complex is also a host to disseminated and semi-massive pyrrhotite (FeS) and pentlandite ($(Fe,Ni)_9S_8$) mineralization, as well as more minor late-stage hydrothermal Pt-Pd-Cu deposits (Scheel, 2007; Nixon, 1998). This mineralization is the focus of exploratory drilling, resource characterization and economic assessment currently being done by Hard Creek.

Figure 1.1 Location of the Turnagain Nickel site, situated in North-Central British Columbia (modified after Hard Creek Nickel Corp., 2011).

1.3 Purpose & Objective

Carbon sequestration has the potential to be highly influential in reducing overall atmospheric carbon dioxide levels, particularly when considering the widespread applicability of this process to sites around the world (Oelkers et al., 2008; Huijgen and Comans, 2003; Zevenhoven and Kohlmann, 2001). At issue with this are the high costs associated with mineral carbonation technology (Lackner et al., 1995; IPCC, 2005; Gerdemann et al., 2007; Huijgen et al., 2007; Huijgen and Comans, 2005; Chen et al., 2006). It is therefore necessary that the cost of mineral carbonation be evaluated in relation to the environmental and financial benefits that may be available in order to determine its propensity as a promising project for future development.

It is difficult to predict exactly how a future carbon dioxide cap-and-trade program may develop (if at all), however the relative success of the European Union's Emissions Trading Scheme (EU ETS) has set the stage for the development and implementation of a similar system in North America (Skærseth and Wettestad, 2008; Karling, 2007; Victor and House, 2004). Should a cap-and-trade program similar to the EU ETS come into effect in North America in the near future, it would undeniably have significant financial ramifications for large point-source emitters of CO_2 such as mine sites. It is crucial that operations in a position to be affected by such policy changes be thoroughly prepared to handle the consequences that result from climate change legislation. This may include consideration of the ways in which mines can help make meaningful emissions reductions, as well as managing the financial considerations of reducing compliance costs in order to protect and maximize their return on investment.

In addition to the environmental impacts that carbon capture and storage (CCS) may be able to achieve, it is also essential that that the economics of it are properly demonstrated (Huijgen and Comans, 2005; O'Connor et al., 2004; Zevenhoven et al., 2006). While business decisions made purely based on environmental impacts would be laudable, this is not always realistic when shareholder accountability and the need to ultimately uphold the financial well-being of a company are paramount (Lasher, 2008). This suggests that weighing the costs of environmental stewardship against the potential consequences of the alternative is necessary. Although unfortunate, environmental actions must be economically and financially viable before they have a chance to become widely employed and ultimately make meaningful a change.

The appeal of bringing about a viable CCS project at the Turnagain Nickel site is the potential to make meaningful environmental contributions while simultaneously improving business interests. This may occur either by reducing compliance costs and/or the possible realization of additional revenue streams through carbon credit trading. This research aims to evaluate the degree to which the integration of a mineral carbonation project would impact the mine economics of the Turnagain nickel site in the presence of a cap-and-trade system. Through an analysis of cost versus efficiency for various mineral carbonation options and the subsequent development of a comprehensive cost model and discounted cash flow (DCF) model, the long-term feasibility of such a project was evaluated.

The purpose of this research is the development of a preliminary analysis investigating how the introduction of cap-and-trade may affect mine economics and the ways in which operators can help mitigate these effects. It is undeniable that putting a price on carbon emissions will have detrimental effects on the viability of mining operations, however it is likely that the introduction of carbon sequestration technology such as mineral carbonation may be able to counteract these effects in suitable locations. In fact, the production of carbon credits via mineral carbonation, and the revenue generated through the sale of excess credits, may be able to contribute to improved project economics. In particular, the Turnagain Nickel deposit in Northern BC is amenable to implementing mineral carbonation technology alongside mining operations, and will likely be a viable method by which to generate additional cash flow and improve overall project valuation in a cap-and-trade environment.

A holistic approach to this research allowed for the integration of considerations stemming from a wide variety of fields, including mining, geology, environment, policy and finance. Through an inter-disciplinary approach, visually represented in Figure 1.2, a more comprehensive analysis was developed in order to consider the many factors that feed into project valuation, the relationships that exist between them, and how each may influence project feasibility.

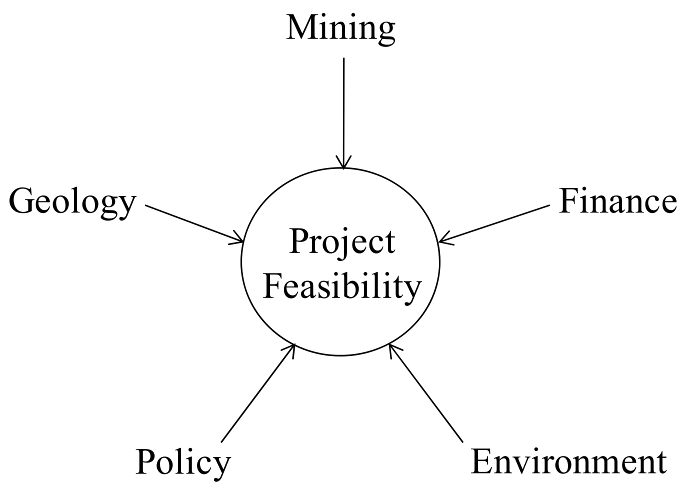

Figure 1.2 Flowchart outlining the holistic approach to evaluating the feasibility of integrating mineral carbonation into proposed mining operations at Turnagain.

2 MINING & CO_2: A LITERATURE REVIEW

Carbon sequestration, otherwise known as carbon capture and storage (CCS), is the mechanism by which carbon dioxide (CO_2) is captured and stored in order to reduce overall atmospheric levels of CO_2 and help mitigate global climate change (Gibbins and Chalmers, 2008). Although environmental options such as fuel switching, increased efficiency and policy changes are currently being implemented, these solutions are only capable of reducing the amount of new emissions released into the atmosphere. The enhanced use of CCS technologies are the only options capable of significantly reducing overall atmospheric CO_2 levels to help us meet government-set emissions reduction targets (Jaccard and Rivers, 2007; Stephens and Keith, 2008). As such, it is important that research efforts are focused on bringing CCS technologies towards reality on an industrial scale.

Carbon sequestration encompasses a wide variety of carbon capture and storage options, including oceanic storage, geologic storage, biomass storage and mineral storage (Voormeij and Simandl, 2004; Stephens and Keith, 2008). While these are all viable options that are currently under intense investigation by the research community, mineral storage (better known as mineral carbonation) has a number of unique benefits that make it a promising long-term CO_2 storage solution. These benefits, including a more detailed description of mineral carbonation, are presented in the following section.

2.1 Mineral Carbonation

Mineral carbonation is quickly gaining recognition as one of the most effective ways of removing excess CO_2 from the atmosphere (Khoo and Tan, 2006; Rock, 2007; Voormeij and Simandl, 2004; Lackner et al., 1995). First proposed by Seifritz in 1990, mineral carbonation takes advantage of the natural weathering process of silicate minerals, whereby the alkalinity extracted from silicate minerals through weathering and water-rock interactions react with ambient atmospheric CO_2 to produce newly formed carbonate minerals (Huijgen and Comans, 2005; Lackner, 2002). Specifically, the weathering of abundant calcium (Ca) and magnesium (Mg) rich silicate minerals to form Ca- and Mg-carbonates in the presence of CO_2 forms the basic concept behind mineral carbonation technology. The acceleration of this natural process to allow for greater quantities of CO_2 to be captured and stored in a much shorter period of time represents the goal of initiating mineral carbonation on an industrial scale.

The silicate minerals most aptly suited for mineral sequestration are those containing the greatest molar ratios of CaO (calcium oxide) and MgO (magnesium oxide) (O'Connor et al., 2000; Lackner et al., 1995; Huijgen and Comans, 2003). By increasing the molar ratio of Ca- and Mg-oxides, more reactant oxide is available to react with CO_2 in accordance with the simplified exothermic reactions seen in Equations 1 (Lackner et al., 1995, Huijgen and Comans, 2003).

$$CaO + CO_2 \rightarrow CaCO_3 \quad (\Delta H_r = -179\ kJ/mol) \qquad [1]$$

$$MgO + CO_2 \rightarrow MgCO_3 \quad (\Delta H_r = -118\ kJ/mol) \qquad [2]$$

The reactions contained in Equations 1 and 2 derive from the general equation for the reaction of Ca- and Mg- silicates with CO_2 to produce carbonates as seen Equation 3 (Goldberg et al., 2001), whereby Mg-Ca-silicates react with CO_2 to produce Mg-Ca-carbonates, silica and water respectively.

$$(Mg,Ca)_xSi_yO_{x+2y+z}H_{2z\,(s)} + xCO_{2\,(g)} \rightarrow x(Mg,Ca)CO_{3\,(s)} + ySiO_2 + zH_2O_{(l/g)} \qquad [3]$$

It is both calcium and magnesium that are best suited for use in mineral carbonation, however research thus far has predominantly focused on Mg-rich silicate minerals such as olivine and serpentine that contain a high wt% of MgO. These minerals are preferred due to their widespread abundance in ultramafic rocks such as peridotites and serpentinites. The forsterite end-member of olivine (Mg_2SiO_4) and serpentine ($Mg_3Si_2O_5(OH)_4$) typically contain the highest molar ratios of MgO and are composed of approximately 45-50 wt% MgO for forsterite and 38-45% wt% MgO for serpentine (Chizmeshya et al., 2008). By comparison, Ca-silicates contain only 12-15 wt% CaO and are therefore much less reactive as less contained oxides are available to react with CO_2. They are therefore less effective in trapping and storing large amounts of CO_2 through mineral carbonation (Lackner, 2002; Lackner et al., 1997; Yegulalp et al., 2001).

Magnesium silicate minerals react with gaseous CO_2 to produce magnesite ($MgCO_3$) and quartz (SiO_2), as well as water in the case of a serpentine reactant. The reactions of forsteritic (Mg-end member) olivine and serpentine are exhibited in Equations 4 and 5 respectively (Chizmeshya et al., 2008; Goldberg et al., 2001; Huijgen and Comans, 2003; Kojima et al., 1997; Yegulalp et al., 2001).

$$Mg_2SiO_{4\,(s)} + 2CO_{2\,(g)} \rightarrow 2MgCO_{3\,(s)} + SiO_{2\,(s)} \quad (\Delta H_r = -90\ kJ/mol) \qquad [4]$$

$$Mg_3Si_2O_5(OH)_{4\,(s)} + 3CO_{2\,(g)} \rightarrow 3MgCO_{3\,(s)} + 2SiO_{2\,(s)} + 2H_2O_{(l)} \ (\Delta H_r = -64kJ/mol) \qquad [5]$$

The production of various hydrated forms of magnesite are also common depending on the pressure-temperature (P-T) conditions of formation (Chizmeshya et al., 2008; Wilson et al., 2006).

Mineral carbonation is a viable long-term CO_2 storage solution due to its long-term stability and the benign nature of its products (Huijgen and Comans, 2003; Maroto-Valer et al., 2005; Fauth et al., 2000; Zevenhoven et al., 2006). Carbonate is the most thermodynamically stable form that carbon can take, exhibited in the exothermic reactions of Equations 1-5 and by their respective negative enthalpies of reaction (ΔH_r) (Lackner, 2002). The stability of carbonates on a geologic time scale make them extremely useful for carbon sequestration applications due to their benign nature and the associated reduction (or possible elimination) of leakage risks (Yegulalp et al., 2001; Lackner et al., 1998; Cipolli et al., 2004; Guthrie et al, 2001). The reduction in long-term liability and the reduced need for prolonged monitoring efforts makes mineral carbonation an extremely effective method of carbon sequestration.

2.1.1 State of the Science

While these reactions proceed slowly at ambient P-T conditions, elevated P-T levels have produced greatly accelerates rates of reaction and conversion efficiencies (Chen et al., 2006; Gerdemann et al., 2003; Oelkers et al., 2008; Huijgen and Comans, 2003;

O'Connor et al., 2000; IPCC, 2005). Previous studies at the Albany Research Centre were able to attain 90% conversion within 24 hours at T=185ºC, P_{CO2}= 115 atm and particle size of -37 μm (O'Connor et al., 2000) in an autoclave, attesting to the relatively high P-T conditions and grinding requirements needed for effective mineral carbonation. Subsequent work has focused on the impact of passive layer formation, and its significant role in limiting the extent of mineral carbonation. McKelvey et al. (2006) and Béarat et al. (2006) outlined the need for continuous particle abrasion and exfoliation in order to reveal fresh surfaces for reaction, suggesting that grind size and slurry flow are critical factors to consider in enhancing rates of reaction. Maroto-Valer at al. (2001) outlined the need to achieve faster reaction routes under milder process conditions in a continuous feed loop in order for mineral carbonation to become a cost-effective technology (Penner et al., 2004). The need for continuous flow loop reaction in mineral carbonation is of particular importance when considering its implementation on an industrial scale, where capacity will have to be sufficient to process large quantities of material and maximize the sequestration of CO_2 in the minimum amount of time.

Consideration must also be given to the amount of CO_2 emissions directly attributable to the process of mineral carbonation itself. Estimates by O'Connor et al. (2004) suggest that only ~77% of sequestered CO_2 can be claimed as CO_2 avoided, resulting in a CO_2 avoidance ratio of 0.77 as calculated from the relationships seen in Equations 6 and 7.

$$CO_2\ avoided = CO_2\ sequestered - CO_2\ emitted \quad [6]$$

$$CO_2\ avoidance\ ratio = CO_2\ avoided : CO_2\ sequestered \quad [7]$$

It is important to note that the emissions produced, and consequently the CO_2 avoidance ratio, will ultimately be dependent on the process conditions of reaction as well as the source of energy utilized in the process. More generalized estimates by O'Connor et al. (2002) have suggested that an energy penalty of 11.5 kWh/t ore processed is reasonable. The extreme conditions required for efficient conversion adversely affects not only the amount of energy required and the amount of CO_2 released, but also the process operating costs. In consideration, there appears to be a number of conflicting priorities in the research. Although some attempt to maximize the efficiency of reaction, others look to minimize costs or reduce process emissions. This research focuses on the impact and sensitivity of each of these contributing factors on the overall financial feasibility of mineral carbonation, therefore allowing research priorities to be set. These concepts are further explored in Section 4 and discussed in Section 5.

2.1.2 Integration into Mining and Mineral Processing

The availability of Mg-rich minerals worldwide in mineable deposits, combined with the high MgO content within Mg-silicate minerals such as olivine and serpentine, make Mg-silicates aptly suited for use as feedstock material in mineral carbonation (Lackner et al., 1995; Yegulalp et al., 2001; Béarat et al., 2002; Cipolli et al., 2004; Goff and Lackner, 1998). In addition, the common association of Mg-silicates with certain mineral deposit types increases the feasibility of extraction, both of ore and of suitable feedstock material for use in mineral carbonation. This occurs primarily due to the ability to share the cost of extraction. Kohlmann et al. (2002) and Gerdemann et al., (2004) outlined the importance of integrating the extraction of Mg-silicates for mineral carbonation with pre-existing or planned mining activities in order to reduce mining and transportation costs. More specifically, mineral carbonation is well suited for integration into mining operations in deposit areas dominated by mafic and ultramafic mineralogy that host associated economic mineral deposits such as nickel, chromite, PGE and diamond deposits (Robb, 2005). This has the ability to make marginal projects more profitable and improve overall project economics by lowering the mine cut-off grade and bringing value to otherwise value-less waste rock (Hitch et al., 2010; Zevenhoven et al., 2006).

On a geologic timescale, mineral carbonation proceeds spontaneously and naturally (Goldberg et al., 2001) and is observed in locations around the world. This includes observances at the Atlin and Cassiar chrysotile deposits in British Columbia, and at Clinton Creek in the Yukon (Wilson et al., 2009b; Wilson et al., 2006; Power et al., 2009). These studies demonstrated that carbon is trapped and stored in Mg-carbonate minerals such as magnesite ($MgCO_3$), as well as more dominant hydrated forms of Mg-carbonate such as hydromagnesite ($Mg_5(CO_4)(OH)_2 \bullet 4H_2O$, nesquehonite ($MgCO_3 \bullet 3H_2O$) and dypingite ($Mg_5(CO_4)(OH)_2 \bullet 5H_2O$). Similar observances have also been found at the Mount Keith Nickel mine in Western Australia, where hydromagnesite has been found to precipitate within the mine tailings, simultaneously sequestering approximately 58,000 tCO_2/yr (Wilson et al., 2009a). Work by Rollo and Jamieson (2006) and Lee (2005) has also investigated the ability of kimberlite rock at diamond mines in the Northwest Territories to sequester CO_2, with additional work done by Wilson et al. (2009c). This demonstrates that the potential to integrate mineral carbonation into various mining operations around the world may be possible.

The life cycle of the mineral carbonation process is shown conceptually in Figure 2.1. Beginning with the mine as a source of reactive material, the waste rock of mining operations provides a steady source of feed for mineral carbonation. A constant input of CO_2 is also required, derived either from mine process emissions, outside sources via a pipeline, or a combination of the two. Following reaction, the resulting benign product may follow a number of paths, including use as aggregate or mine backfill to aid in construction or mine reclamation. Alternately, the carbonate could be safely disposed of with little to no need for prolonged monitoring efforts.

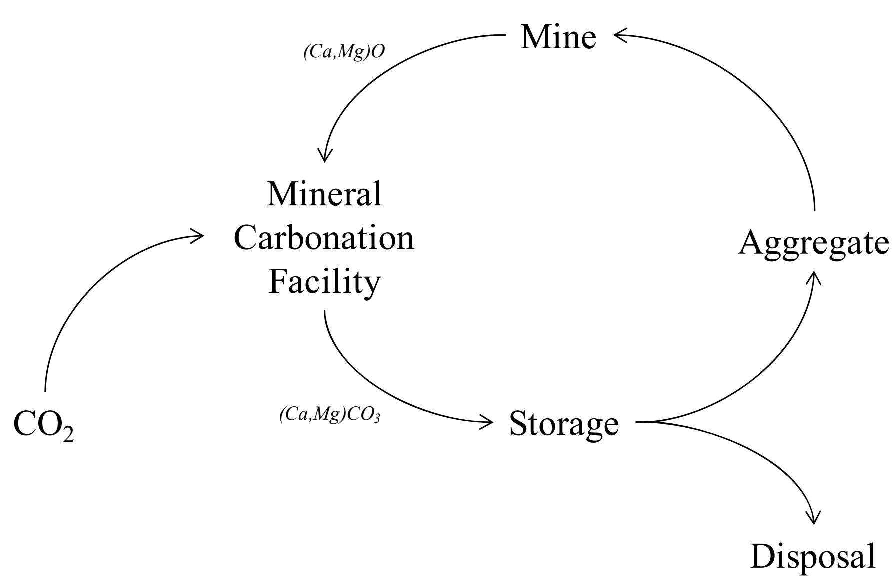

Figure 2.1 Conceptual life cycle of mineral carbonation (modified after Huijgens et al., 2004).

The mutual benefits made possible through the integration of mining and mineral carbonation highlight the importance of integrating Mg-silicate extraction with mineral carbonation in order to enhance viability.

2.2 Relation & Importance to Mining

Successfully integrating carbon capture and storage into the mining industry will require incentives to spur development and increase the likelihood of widespread implementation across the industry. These incentives will be required in order to offset the significant costs associated with CCS projects (Newell et al., 2006). Incentive structures to help curb CO_2 emissions have already been implemented in Europe through the development of the European Union Emissions Trading Scheme (EU ETS), and a similar North American pursuit appears imminent (Western Climate Initiative, 2010; Government of Canada, 2009). These policy structures are designed to cap the allowable amount of emissions from a point source emitter of CO_2. Given the contribution of the mining industry to total greenhouse gas emissions (OECD, 2004), it is anticipated that a cap on emissions will create a notable impact on mining operations from both a financial and operational standpoint. The degree to which mining operations will be impacted is highly dependent on the imposed greenhouse gas reduction requirement, in addition to the incentives provided through market mechanism such as cap-and-trade. The imposition of a limit on the total amount of CO_2 permitted for release by a single point source emitter will need to be addressed by emitters either through technological change to reduce emissions, or through the capture and storage of emission that do result from operations. Alternately, excess emissions may also be offset through financial means through the purchase of carbon offset credits in the market. The operational and/or financial impacts of carbon reduction mechanisms, such as cap-and-trade, are something that must be carefully considered by corporations as environmental policy measures continue to develop.

2.2.1 Carbon Policy & Incentive Structures

In order to meet the Government of Canada emissions reduction targets of 20% below 2006 levels by 2020 and 65% by 2050, it is imperative that a price be put on carbon through the use of market-based policy mechanisms (Government of Canada, 2009). Market-based environmental control is useful in its ability to stimulate adaptation as each source sees best fit, allowing for effective innovation through the most economical means for each individual entity (Dales, 1968; Crocker, 1966; Montgomery, 1972; Tietenberg, 1985; Freeman and Kolstad, 2007). Forecasts have estimated that in order to achieve such deep emissions reductions, carbon prices will have to rise to approximately $200/t CO_2 (Government of Canada, 2009; Jaccard et al., 2008). It is undeniable that a significant financial incentive will be necessary in order to achieve the deep emissions reductions set forth by the Government of Canada. Point-source emitters of CO_2 who are quickly able to adapt to low-emissions technology or offset emissions via other means such as CCS will have a significant advantage over their competitors, becoming more and more important as carbon prices increase to meet set reduction targets. As point-source emitters of CO_2 (i.e. BHP Billiton, 2004; OECD, 2004), mining operations must be aware of the implications that an impending price on carbon may pose. The financial impacts may even have the potential to significantly affect the operational viability of mining activities (Ho et al., 2008).

Traditional command-and-control regulatory mechanisms focus on environmental reform through the delineation of specific management practices required for compliance (Kolstad, 1986). In contrast, the trend towards market-based incentives such as cap-and-trade has become increasingly prominent in the implementation of environmental policy

(Hahn and Hester, 1989; Jaccard and Rivers, 2007). It has been suggested that market-based incentives are more efficient, offering the freedom and flexibility to stimulate research and development in new areas of emissions reduction/mitigation in order to meet emissions limits as each source sees fit. This also allows point sources to exercise their least-cost option to meet set targets, providing valuable flexibility for each unique source (Dales, 1968; Crocker, 1966; Montgomery, 1972; Tietenberg, 1985; Freeman and Kolstad, 2007). While much discussion has revolved around the most appropriate and effective mechanisms of environmental protection, the development of the European Union Emissions Trading Scheme (EU ETS) as well as the voluntary Chicago Climate Exchange (CCX) has set the stage for the future development of a North American emissions trading platform with general consensus converging on the merits of a market-based approach (Hanjürgens, 2005; Jones and Levy, 2007). Supported by the experience of other greenhouse gas trading systems for SO_2 and NO_x (Aulisi et al., 2005; Ellerman et al., 2000; Tietenberg, 2006), it appears only inevitable that comprehensive emissions trading will become a prominent tool in environmental management going forward. Initiatives at the regional level are taking charge to implement emissions regulations on point-source emitters of CO_2. For example, a regional cap-and-trade mechanism is currently under development by the Western Climate Initiative (WCI) through the collaboration of independent jurisdictions from Canada and the United States (Western Climate Initiative, 2010).

A cap-and-trade scheme functions through setting a limit or cap on allowable emissions. Tradeable permits are then allotted, giving permission for an entity to emit a specified amount of CO_2. If the amount of actual emissions exceeds their allocation of permits, emitters must trade or pay for additional permits. On the other hand, an emitter may end up with excess permits if emissions are below the set cap, allowing them to sell their permits to other emitters who have exceeded the cap (Labatt and White, 2007).

It has become increasingly apparent that opportunities may exist in an emissions trading environment, contrary to what many may predict as a negative political force on corporate affairs. Outlined by Boyd et al. (1995), the net benefits that are likely to arise through the implementation of carbon reduction measures promotes their steadfast development. The increasing concern about climate change and the need for environmental action appears to have revealed the numerous risks associated with inaction and the need for a proactive approach to impending policy. It also seems apparent that there is tremendous value to be had in the financial markets for those companies ready to embrace climate change (Jones and Levy, 2007; Labatt and White, 2007). Explored by Cogan (2006), firms may no longer be looking at GHG reduction as a burden, but rather as an opportunity to capitalize on business opportunities presented in new and emerging markets surrounding climate change. Through the development of a well-functioning carbon market such as a cap-and-trade program, those corporations able to adequately reduce their emissions will be rewarded, further encouraging other firms to follow suit. Ultimately, this has the possibility to lessen CO_2 emissions and help achieve the deep GHG reduction targets outlined by the government.

2.3 Feasibility

Significant opportunities exist with regards to CCS projects, however feasibility must first be established in order to determine a viable path going forward to bring these projects to reality. Cogan (2006) outlined the profit potential of the carbon market for those companies ready to embrace the innovative technologies related GHG reductions, however it is first necessary to consider the associated costs (Alberta Carbon Capture and Storage Development Council, 2009).

Feasibility studies are commonly employed in order to determine whether or not a project should be undertaken and/or to select between multiple projects when funds are limited (Mishan and Quah, 2007). This is done to ensure an efficient and effective allocation of resources and to maximize shareholder value in the case of public companies (Lasher, 2008). This is commonly done in financial analysis by reducing costs and benefits to a unique value known as the net present value (NPV), which takes into account the time value of money by bringing all associated cash flows back to time zero for proper comparison of their present value (Park, 2001; Campbell and Brown, 2003). Cash flows are discounted by the required rate of return for the investment ‘r’, typically defined as the cost of capital, adjusted for project risk. Project NPV is represented by Equation 8 (Lasher, 2008; Clayment et al., 2008), where where CF_i represents the cash flow at time ‘i’ and and CF_0 represents the initial cash outlay at t_0.

$$NPV = CF_0 + CF_1/(1+r)^1 + CF_2/(1+r)^2 + \ldots + CF_n/(1+r)^n \text{ , or} \qquad [8]$$

$$NPV = \sum CF_i/(1+r)^i$$

A positive NPV value indicates that undertaking the project at hand will add value to the firm, such that any project for which NPV greater than 0 should be accepted for its ability to increase shareholder wealth. Conversely, any project where NPV less than 0 should be rejected. Under circumstances in which funds are limited and only one project may be selected, the project with the greatest NPV is preferred (Pearce et al., 2006; Vance, 2003). This is the typical selection criteria employed in the capital budgeting process, however exceptions to the rule exist where it may be advantageous to consider a project with a negative NPV. Benefits may exist where investment in negative NPV projects will aid a firm in accessing an emerging market where future benefits are expected, treating the initial investment as an intermediary step (Bhimani, 2006; Moyer et al., 2009). Selection criteria should also be modified to reflect the instance where investment in a negative NPV project is required in order to avoid the more significant losses expected from the alternative. This may exist where new policy or governmental regulations require firm action of some form. In this case, it is necessary to revisit the standard investment criteria to select the project with the greatest NPV, regardless of whether or not it is positive or negative. This suggests that in certain circumstances, where project investment is required in order to comply with new regulations or standards, investment in negative NPV projects may be necessary in order to reduce the cost of compliance and limit shareholder loss.

2.3.1 Previous Cost Estimates

Previous cost estimates of implementing carbon sequestration by way of mineral carbonation have yielded a wide variety of estimated values, illustrative of the high degree of uncertainty surrounding the valuation of mineral carbonation projects. A summary of sample cost estimates are shown in Table 2.1 with associated references therein. The uncertainty among previous cost estimates is magnified by the inconsistent use of feedstock material and process parameters employed amongst these estimates. It is also often unclear exactly which aspects of the lifecycle of mineral carbonation, including all the components necessary to complete the lifecycle outlined in Figure 2.1, are included in these cost estimates. Herzog (2002) indicated the need to add ~$50-$60/t CO_2 for CO_2 capture and transport costs alone, attesting to the significant impact that such omissions could create in conducting an economic evaluation of mineral carbonation. The additional need to incorporate other significant factors into the lifecycle of mineral carbonation, such as mining, processing and disposal, further delineates the need for improved clarity in the estimation and presentation of mineral carbonation costs. Research presented in Section 4 attempts to addresses this need.

Table 2.1. Previous cost estimates of mineral carbonation.

Cost	Reference
\$70 /t CO_2	Lackner, 2002
\$50-\$100 /t CO_2	IPCC, 2005
\$65 /t CO_2	O'Connor et al., 2005
\$54 /t CO_2 sequestered \$78 /t CO_2 avoided	O'Connor et al., 2004; Gerdemann et al. 2007
\$60-\$100 /t CO_2	Newall et al., 2000
\$69 /t CO_2	Lyons et al., 2003; Penner et al. 2004

3 ANALYTICAL METHODS

Financial analysis was done in order to determine an estimate of the overall viability of integrating mineral carbonation into proposed mining operations at Turnagain. Although project development is currently only at the conceptual design phase, it is still important that the project economics are carefully considered in order to determine whether or not to further proceed with project development. As is inherent in most natural resource project, a relatively high degree of uncertainty will undoubtedly be present throughout (Park et al., 2001), and must be taken into careful consideration upon analysis of the overall project economics. Further model refinements will be necessary as project parameters become more accurately known.

In this financial analysis, a discounted cash flow (DCF) approach has been utilized for its simplicity in gaining a relatively sound general understanding and perspective on estimated project value given the assumptions made in the base case scenario. While adequate as a preliminary analysis, it is important to further consider the value inherent in real options and the flexibility held by management to expand, contract, defer or abandon a project, as the conditions of operation become more precisely known. This allows for added value in the ability to mitigate losses while maximizing on upside potential (Schwartz and Trigeorgis, 2004). Further analysis of the added value of building real options into project development and decision-making are briefly considered and discussed in Section 5.

In order to quantify uncertainty inherent in this project, as well as in any determininstic modeling approach to project forecasting and evaluation, it was necessary to test the numerous assumptions employed. Sensitivity analyses were performed in order to capture the influence of the most highly uncontrollable factors in project advancement and to evaluate how output uncertainty can be apportioned to the uncertainty of the model inputs (Saltelli et al., 2004). By no means is this a method of eliminating risk, but merely a means to more accurately understand risks and uncertainty that may significantly impact project economics (Pergler and Freeman, 2008). This enabled a greater awareness of the uncertainties in project development to be assessed, providing a gauge by which to measure the overall impact of such uncertainty. Modeling has come under scrutinty for the false sense of security it may provide, particularly owing to the principle of 'garbage in, garbage out', however it can still be a useful tool in the strategic decision making process insofar as the users understand the limitations of the model and the meaning of the results produced (Bowman and Moskowitz, 2001; Pergler and Freeman, 2008).

This methodology was chosen to enable the quantification of the potential value in a proposed mineral carbonation process, taking into consideration the time value of money. This is a common analysis tool used in the securities industry as well as throughout the mining industry for the evaluation of potential projects. In comparison to more qualitative approaches to project valuation, financial modeling and sensitivity analysis allows for a more robust and quantifiable measure of the potential value inherent in a project.

Within the realm of financial modeling, both discrete and continuous modeling options exist. Both approaches to financial modeling carry distinct advantages, however the most commonly employed method of financial modeling is discrete in nature. This does not preclude the use of continuous modeling, for it is the dynamic nature of continuous modeling that can allow for more complex sensitivities to be investigated. This is of particular importance when considering the effects of time on cash flows, both in terms of cash flow timing and duration. However, given the relative infancy of the present investigation, the developed models were created using discrete modeling techniques. This was primarily done to facilitate the presentation of a simple and straightforward financial model for presentation to the corporate mining community to which it would ultimately impact.

3.1 Conceptual Framework

The tradeoff of cost versus efficiency for the various mineral carbonation technologies under investigation is an important factor when considering how best to proceed with project development. The obvious benefits of high sequestration efficiency through the use of high P-T mineral carbonation in an autoclave are offset by the high costs needed for extensive processing and elevated process conditions. Conversely, low efficiencies of reaction associated with engineered heap leach piles or bio-inoculated piles (Power et al., 2009) may be justified by the minimal cost requirements. This is a critical aspect in the evaluation of mineral carbonation, as it is the cost of the technology, and what you get for that cost, that will ultimately dictate its feasibility of implementation on an industrial scale. It is this tradeoff of cost versus efficiency shown in Figure 3.1 that may also be highly influenced by the parameters set forth by governmental regulations and/or the carbon management scheme put into place, namely the cost of carbon and the cap on emissions. It is anticipated that the trace of this relationship will be a stepwise function due to the significant jump, both in terms of cost and efficiency of reaction, which would result when transitioning from more passive to more active mineral carbonation technologies. These presently include active mineral carbonation technologies such as agitated tank leaching (autoclave reaction), and more passive technologies such as heap leaching. Figure 3.1 represents the conceptual cost vs. efficiency curve developed for mineral carbonation, with corroborating data points gathered from: a) Wilson et al. (2006) for natural attenuation in abandoned mine tailings at Clinton Creek, YT, and Cassiar, BC; b) Stolaroff et al. (2005) in conjunction with heap leach sequestration in industrial residue piles, and c) derived through cost modeling in this study and further supported by Lackner et al. (2008) for agitated tank leaching. The step-wise form of this relationship demonstrates the significant cost differences that are expected between active and passive sequestration technologies. However, within each general sequestration method, this figure suggests that relatively minimal increases in cost should have an incrementally larger impact on efficiency as the technology is refined through further research and development until a more active form of sequestration becomes necessary. Thus far, sequestration efficiency appears to be capped at around 90%, represented graphically in the near vertical regression line shown on the right hand side of the figure.

For detailed financial modeling, autoclave reaction was chosen for further consideration as it is the only method thus far proven to store adequate amounts of CO_2 and that was supported by detailed research to bring it past the proof-of-concept stage. While the option to implement mineral carbonation through engineered heap leach piles is not entirely unreasonable in the future, adequate research in this area has not been done to date to be able to provide reasonable parameters and warrant further analysis. This may, however, change in the future should more research be focused in this area.

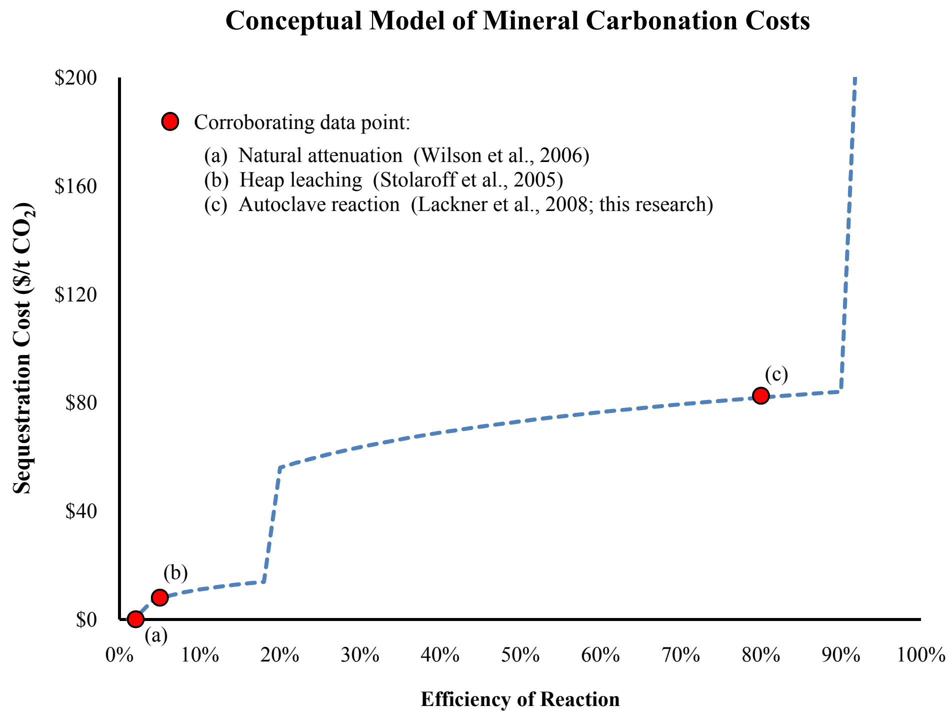

Figure 3.1 Conceptual tradeoff of cost versus efficiency for various methods of mineral carbonation.

Figure 3.1 presents the critical tradeoff of cost versus efficiency in the mineral sequestration of CO_2, however is important to note that the addition of time may be integral in further developing this graph. The inclusion of this third dimension would likely impact decisions regarding mineral carbonation technology, as the low cost-low efficiency reactions would also likely correlate with a high time-frame to achieve the resulting extent of reaction. Conversely, it is anticipated that high cost-high efficiency reactions would be able to proceed in a much shorter amount of time. More detailed analysis and further study is required to quantify the effects of time and the impact that this additional dimension might have on the economics of implementing mineral carbonation on an industrial scale, and whether it would preclude the use of low efficiency-low cost technologies as a result of the slow reaction rates and long timelines for reaction. This concept is briefly considered in Section 5.

3.2 Financial Modeling

Preliminary analysis was done through the use of financial modeling in order to gain a more complete understanding of mineral carbonation costs and valuation at the Turnagain Nickel site. A detailed spreadsheet of the financial models developed, including both the cost model and the DCF model, are found in Appendix A and B respectively, with a summary of inputs found in Tables 4.1 and 4.2. Once cost estimates were determined, project cash flow was forecasted taking into consideration capital costs, variable operating costs as well as revenue potential available from a carbon incentive scheme. Preliminary financial analysis was performed through the use of pro forma financial modeling in Excel in order to determine an estimate of project valuation. By combining the required costs necessary in supporting such a project, as well as the potential revenue and/or cost reductions created (Sawyer, 2009; Park et al., 2001), cash flows both in an out of the project were determined and a comprehensive discounted cash flow (DCF) model was developed. Financial analysis utilizing a discounted cash flow approach is commonly used in the mining industry to assess the net present value of a proposed project and to aid in the making of investment decisions, both from a company and investor perspective. There are numerous advantages to financial analysis through cash flow modeling, which has resulted in its widespread use in project valuation. Discounted cash flow models can be developed to be as simple or as complicated as needed or possible, thus allowing even the most primitive of projects to be quantified and evaluated.

Financial models do, however, have distinct limitations in their ability to account for the qualitative aspects of a particular project, whether positive or negative. This is especially prudent in the case of environmental projects, which may have the ability to impact perceptions and garner goodwill for the company in addition to the intrinsic environmental benefits. These qualitative aspects of a project can be extremely important to consider, and may have the ability to sway an investment decision even if the project valuation is marginal. Ultimately, investment decisions come down to project economics, however the intrinsic value inherent in environmental endeavours must still be kept in mind.

In addition, models are relatively limited in their ability to value options. For example, a project with built-in flexibility to alter their schedule to take advantage of market fluctuations holds more value than a project following a strict schedule. Options even extend to the ability to delay or abandon a project to minimize loss should tough situations arise. In these cases, however, it remains difficult to quantify the value that these options bring. Most commonly, DCF modeling results in the undervaluation of a project that has built-in real options (Trigeorgis, 1993; Kulatilaka and Marcus, 1992). It is therefore extremely important that these additional value-add parameters are considered in conjunction with the results of financial models. It is only through combining the information available from these multiple sources that the most thorough evaluation of a project can be made.

3.2.1 Cost Modeling

The cost model formulated though this research was developed such that it would allow for a series of user inputs that could be adjusted based on various factors such as the proposed technology, feedstock assay values, distance between facilities and production capacity to generate a discrete estimate of the total unit cost of sequestration in terms of \$/t CO_2. The cost model was developed based on the methodology of Lackner et al. (2008) for cost estimation of integrating steel production with mineral carbon sequestration and appropriately adapted as necessary for integration into nickel mining operations.

3.2.2 DCF Analysis

Discounted cash flow analysis was performed in order to garner an estimate of project value to aid in the decision making process. While up front it is relatively simple to evaluate a project in terms of revenue versus costs, it is important to consider the time value of money and the impact that significant up-front capital costs may have. Financial analysis through DCF modeling is the most commonly used methodology in evaluating potential investments for its ability to quantify the added value to shareholders (Lasher, 2008; Park, 2001; Campbell and Brown, 2003).

3.2.3 Assumptions

A wide variety of options exist that will allow proposed mining operations at Turnagain to become integrated with carbon management programs in British Columbia and elsewhere. These options exist mainly in relation to location and transportation issues, namely the site of mineral carbonation and the source of sufficient quantities of CO_2. While many large sources of CO_2 exist in heavily populated areas, the primary sources of mineable feedstock material tend to be located in more remote locations, such as that found at Turnagain. Emissions from the mine and the processing plant will undoubtedly be significant given precedent operations such as the Mt. Keith Nickel Mine (BHP Billiton, 2004), however it is likely that mineral carbonation at Turnagain will require an external supply of CO_2 in order to take advantage of the significant amount of available feedstock. The development of a mine may draw point-source CO_2 emitters towards the area and consequently improve CO_2 transport logistics, however it is impossible to predicted or rely on this fact at the moment. As such, it is necessary to locate and source potential alternatives in order to supply sufficient quantities of CO_2 to maximize sequestration via mineral carbonation and justify project implementation.

Turnagain may benefit from its relative proximity to the Fort Nelson area of North-Eastern British Columbia, where abundant oil and gas exploration and development is resulting in large quantities of CO_2 being emitted from the area (Voormeij, 2004). Matching these major sources of CO_2 with the available sinks is a key factor in ultimately determining the viability of carbon sequestration schemes.

Due to the high costs of transporting large quantities of waste rock for use as mineral carbonation feedstock, it will be necessary to locate a mineral carbonation facility proximal to the mine site (Kohlmann et al., 2002; Gerdemann et al., 2004). Ultimately, the required supply of CO_2 to the site will be dependent on the CO_2 emission at the mine and in the surrounding vicinity, which will need to be determined as mining parameters and infrastructure are more definitively outlined. For the purposes of this study, a CO_2 transport distance of 250km was used as an approximation.

Given the preliminary nature of this investigation, a number of additional estimates were used to develop a base case scenario for mineral carbonation at Turnagain. Estimates and references for both the cost model and DCF model are found in Tables 4.3 and 4.5 respectively. It is important to accurately estimate the operating parameters of a mineral carbonation scheme at Turnagain, however revisions to these values are unavoidable as further research and development of mineral carbonation and mining operations at Turnagain are outlined. For this reason, sensitivity analysis became essential in the overall valuation determined through this research. It is only through assessing the range and magnitude of the impact for the various inputs can we begin to get a more complete understanding of the project economics and viability.

3.3 Sensitivity Analysis

Sensitivity analysis was essential in order to obtain a more complete and thorough understanding of the input factors and how the uncertainty surrounding each one would impact model outputs. Consequently, sensitivity analysis was first performed on the cost model inputs, allowing each input to be delineated in terms of its dependent factors respectively. This enabled an analysis of the deviations from the base case to assess the impact of various factors. The sensitivity of each of these inputs allowed for a more accurate estimate of the sensitivity of project value, as determined through DCF modeling and its respective sensitivity analysis (Saltelli et al., 2004).

Spider plots of each variable assessed in the sensitivity analysis allowed for simplified visual comparison of the importance of each factor (Perry and Hayes, 1985; Perry, 1986). Those factors with the greatest slope (whether positive or negative) have the greatest sensitivity per unit of movement away from the base value, as measured by $\Delta x/x$. In contrast, tornado plots were formulated to graphically show the impact of the sensitivity of each parameter as an absolute change from the base value. This method of presentation is more heavily reliant upon the degree of uncertainty in estimation as dictated by the range of values possible for a given factor (Eschenbach, 2006). While tornado plots are a valuable tool in visualizing the potential impact of various input factors overall and the need for further estimate refinement, the sensitivity of factors is primarily distinguished based on the absolute value of the slope of each parameter as determined from the spider plots (Flanagan and Norman, 1993).

3.3.1 Effect of Correlation

Following sensitivity analysis, it was necessary to consider the effects of correlation. This was particularly important given the strong relationship between the price of carbon and the CO_2 reduction requirement. Although the nature of this relationship is unknown, and will never likely be accurately known given the uncertainties of market mechanisms, the principles of supply and demand suggest a strong positive relationship will exist between these two key parameters.

Integrating the nature and strength of relationships between interdependent variables in financial modeling will be an important step in further developing these models and in future research. This research has served to evaluate the importance and sensitivity of various input parameters in the development of a mineral carbonation scheme at Turnagain, however further analysis will require a more detailed investigation into the specific relationships that may exist between parameters and how this will ultimately affect project value.

One of the most notable relationships in the financial modeling of a mineral carbonation scheme is the relationship between carbon credit price and the CO_2 reduction requirement. Following the principles of supply and demand (Baumol and Blinder, 2009), the relationship between these two parameters will undoubtedly demonstrate positive correlation; as the CO_2 reduction requirement rises, the price of carbon credits will increase as well. This idea is demonstrated in Figure 3.2, showing the estimated relationship between the CO_2 reduction requirement and the price of carbon credits. This relationship is based on the Government of Canada (2009) CO_2 reduction targets, which aims to achieve a 20% reduction in CO_2 emissions below 2006 levels by the year 2020, ramping up to a 65% reduction by 2050. Corresponding carbon credit prices were estimated based on a straight-line price increase to \$300/t CO_2 according to carbon credit price forecasts provided by the Government of Canada (2009).

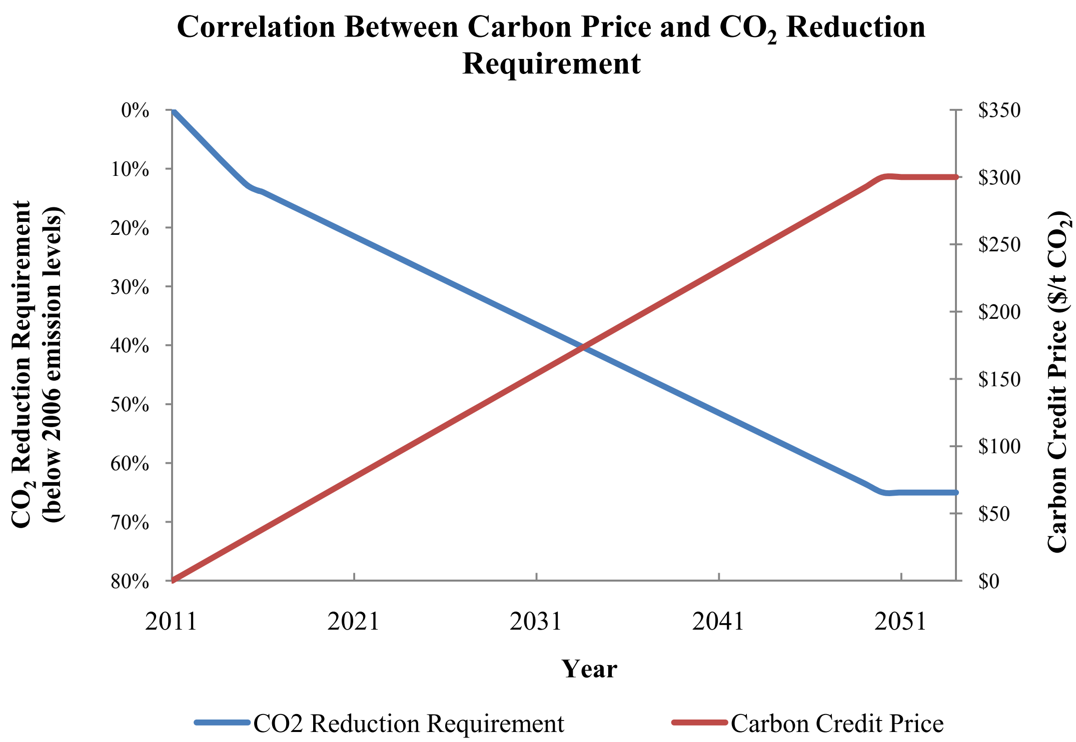

Figure 3.2. Estimated relationship between the CO_2 reduction requirement and carbon credit price.

4 RESULTS

4.1 Base Case Scenario

The base case scenario constructed for analysis of integrating mineral carbonation into proposed mining operations at the Turnagain nickel site is composed of two parts. Firstly, cost modeling was performed in order to evaluate the life cycle cost of mineral carbonation by evaluating all the necessary steps and phases involved from start to finish. Secondly, the results determined through cost modeling were incorporated with other influential parameters into a discounted cash flow (DCF) analysis in order to assess overall project value taking into account the time value of money. The results of these two evaluations are presented here.

4.1.1 Cost Modeling

Results derived for cost modeling aimed at providing an estimate of the unit cost of mineral carbonation in terms of \$/t CO_2. Input parameters and results are summarized in Table 4.1 below.

Table 4.1. Cost model input parameters and base case scenario results.

Input parameters	Unit	Base case value
Throughput	tpd	87,000
Strip ratio	-	0.74
Dunite in waste	%	20
wt. % MgO	wt. %	48.54
Processing cost	$/t feed	8.00
Sequestration efficiency	%	80
Sequestration operating cost	$/t CO_2	32.39
CO_2 capture cost	$/t CO_2	25.00
CO_2 transport distance	km	250
CO_2 transport cost	$/km	0.02
Base Case Result		
Total operating cost	$/t CO_2	82.51
Best case scenario	$/t CO_2	27.98
Worst case scenario	$/t CO_2	237.91

Taking into account all the separate steps and process requirements necessary in the complete life cycle of mineral carbonation, this cost modeling incorporated cost items such as: mining, processing of feed, capture and transport of CO_2, mineral carbonation reaction, disposal and monitoring. Of these items, many of the associated costs were minimized or eliminated through integration with proposed nickel mining at the Turnagain nickel site. Mining costs were effectively eliminated from the cost of mineral carbonation, as the movement of waste rock is already a necessary component of mining and the costs are borne as such. Disposal costs of mineral carbonation by-products were also significantly reduced due to the presence of waste rock disposal facilities already on-site, thus eliminating lengthy haulage requirements. Although minimal costs may still be incurred in relation to disposal of dominant $MgCO_3$, these were ignored for all intents and purposes due to its relative insignificance and the potential for waste $MgCO_3$ to alternatively be used as a value-added product such as aggregate or back-fill. Due to the benign nature of the by-products of mineral carbonation, cost associated with waste management and monitoring is also effectively eliminated. Although it may be necessary to undergo some form of verification process to ensure that trapped and stored CO_2 is appropriately contained, reported and credited, this is an unknown variable at this point that will likely be dependent on governmental regulations and requirements. This aspect of the mineral carbonation process has been omitted in the present analysis, to be further developed and investigated as the guidelines surrounding CO_2 reduction measures are clarified.

Results derived through cost modeling generated a unit cost of \$82.51/t CO_2 for mineral carbonation, taking into consideration the complete life cycle of process requirements. This included major cost factors such as feed processing, CO_2 capture, CO_2 transport and the reactions costs of mineral carbonation itself. Figure 4.1 demonstrates the anticipated break down of the complete cost of mineral carbonation. Although other more minor cost items may be necessary, these four parameters are anticipated to be the major contributors to the overall operating cost of mineral carbonation.

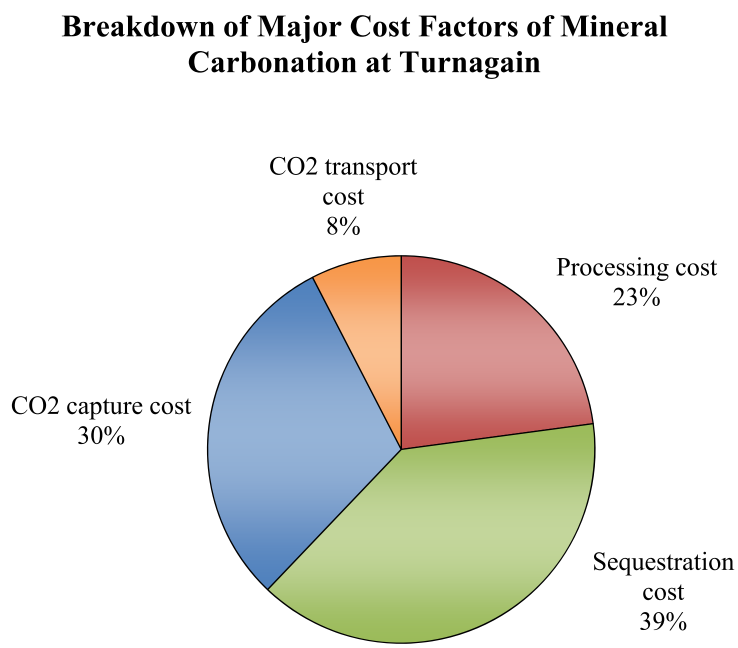

Figure 4.1 Breakdown of major cost factors of mineral carbonation at Turnagain.

In addition, best and worst case scenarios were evaluated through the input of maximum or minimum values for each parameter as appropriate. This generated a best case scenario total operating cost of \$27.98/t CO2 and a worst case value of \$237.91/t CO2.

These extreme values were further used in DCF modeling sensitivity analysis as the upper and lower bounds on the total operating cost of mineral carbonation at Turnagain.

4.1.2 DCF Analysis

Discounted cash flow analysis allowed for evaluation of value potential for mineral carbonation at Turnagain. Input parameters and results are summarized in Table 4.2 below.

Table 4.2. DCF model input parameters and base case scenario results.

Input parameters	Unit	Base case value
Capital cost	$	139,668,169
Development phase duration	yrs	2
Mine life	yrs	24
Operating cost	$/t CO_2	82.51
Total sequestered CO_2	tpy	1,992,518
CO_2 avoidance ratio	-	0.77
Site CO_2 emissions	tpy	1,089,197
Carbon credit price	$/t CO_2	200
CO_2 reduction requirement	%	20
Decommissioning	$	20,000,000
Discount Rate	%	8
Inflation Rate	%	2
Base Case Result		
NPV_8	$	131,449,380
IRR	%	25.1
Simple payback	yrs	3.72
Discounted payback	yrs	4.77

Figures 4.2 through to 4.6 graphically present the results of DCF analysis, demonstrating discrete cash flows, net cash flows, discounted net cash flows, cumulative cash flow and discounted cumulative cash flow respectively. It was important to consider and present discounted versus un-discounted cash flows in order to demonstrate the importance of the time value of money.

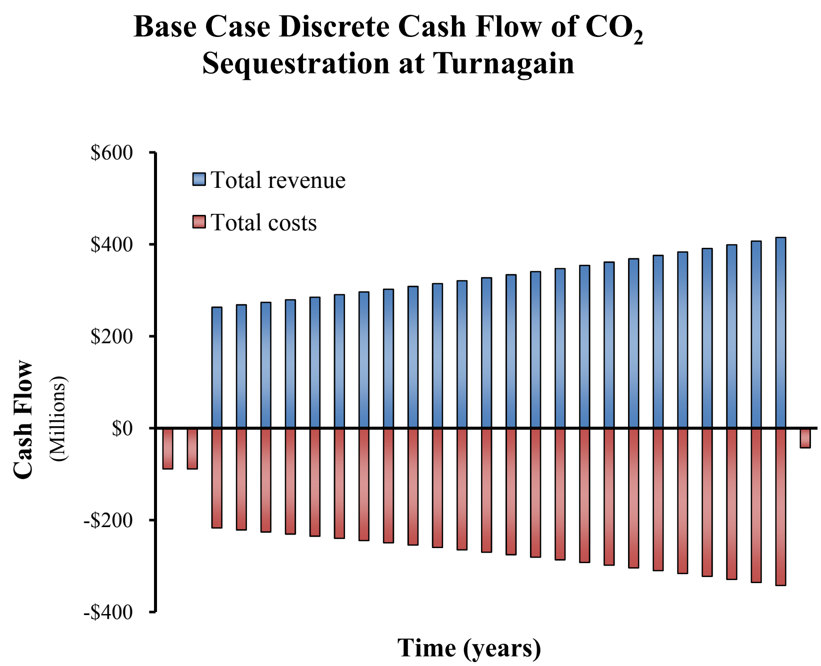

Figure 4.2 Base case discrete cash flow of CO_2 sequestration via mineral carbonation at Turnagain.

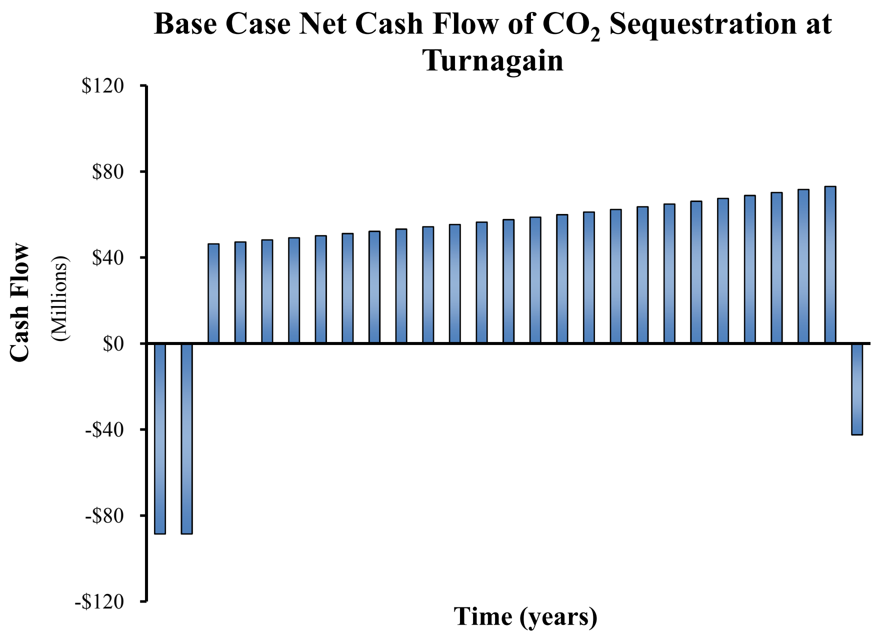

Figure 4.3 Base case net cash flow of CO_2 sequestration via mineral carbonation at Turnagain.

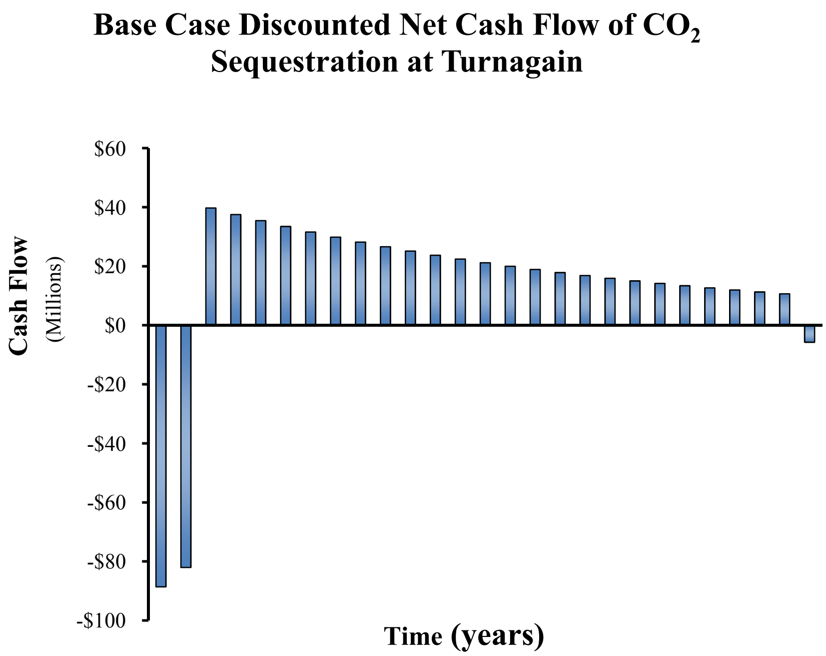

Figure 4.4 Base case discounted net cash flow of CO_2 sequestration via mineral carbonation at Turnagain.

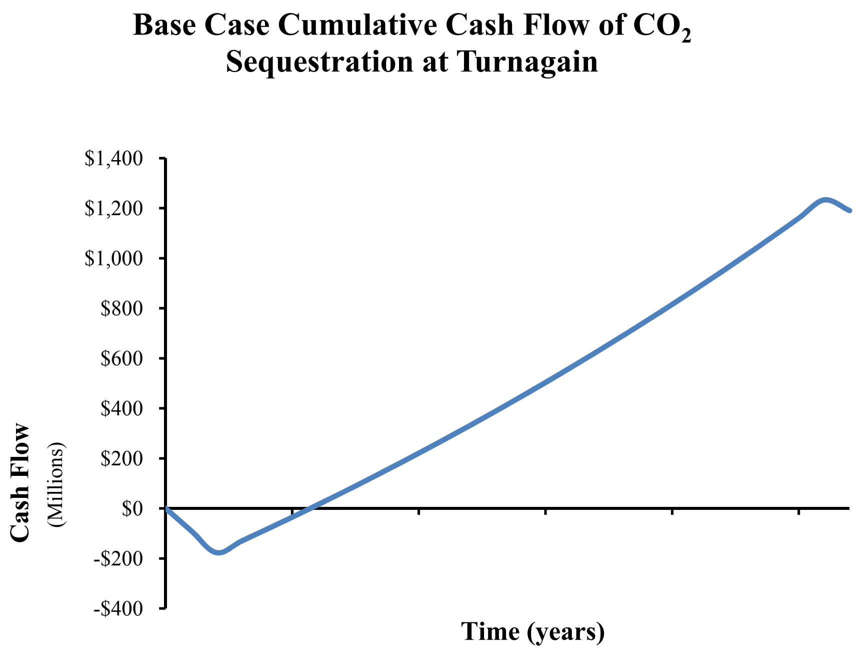

Figure 4.5 Base Case cumulative cash flow of CO_2 sequestration via mineral carbonation at Turnagain.

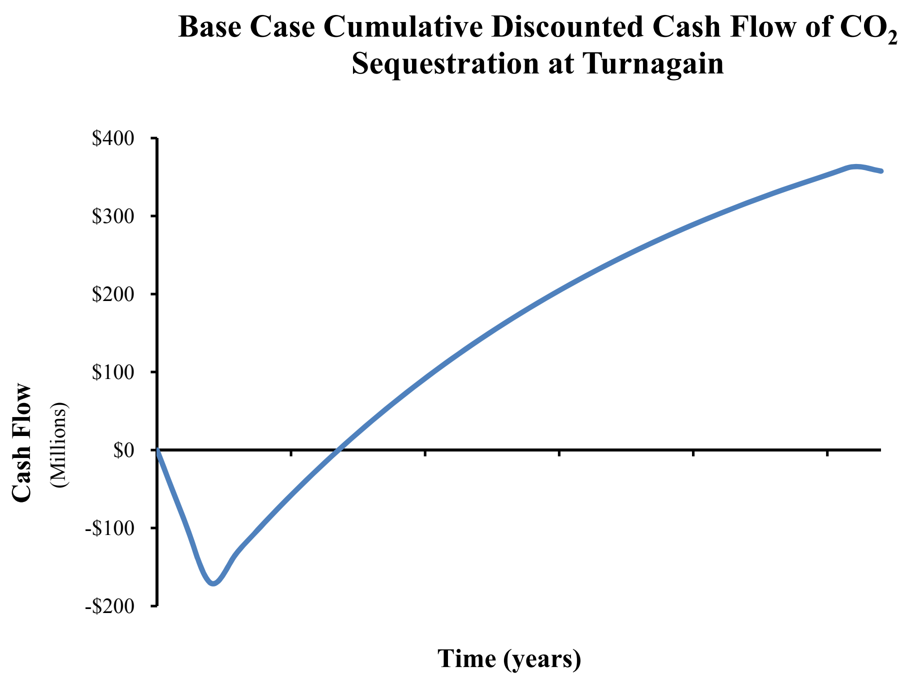

Figure 4.6 Base case cumulative discounted cash flow of CO_2 sequestration via mineral carbonation at Turnagain.

4.2 Sensitivity

Sensitivity analysis was performed in order to gauge the variability present in attempting to accurately estimate the cost of mineral carbonation. This was particularly important in this research given the inherent uncertainty surrounding a number of the input parameters and the conceptual nature of such an investigation. Sensitivity analyses allowed for a more complete presentation of the results obtained through this research, as well as a basis for the evaluation of the most sensitive factors in order to assist in guiding future research efforts.

4.2.1 Cost Model Sensitivity

Initial sensitivity testing was done on the cost model to determine the anticipated sensitivity of the unit cost of mineral carbonation in response to variety of contributing factors. The inputs investigated are summarized in Table 4.2, showing the base value used in the base case scenario as well as the upper and lower bounds as a percentage change from the base.

The sensitivity results are graphically presented in Figures 4.7 and 4.8 as a spider plot and a tornado diagram respectively. The tornado diagram allows for a visual representation of the range of influence of each parameter on the total cost of mineral carbonation at Turnagain. This information is extremely useful in evaluating the factors that present the greatest uncertainty and that required more detailed analysis to reduce the range of potential deviations from the base case scenario. It is, however, the spider plot that ultimately presents the ranking of variable sensitivities. Those input parameters with the steepest slope, whether positive or negative, represent the inputs with the greatest influence per unit of change, as represented by $\Delta x/x$ giving the percentage change from the base case value. The ranking of sensitivities of the cost model input parameters are presented in Table 4.3.

From the spider plot in Figure 4.7 and the rankings seen in Table 4.3 it is apparent that the parameter with the greatest range of influence on the sequestration cost per unit of change is the sequestration efficiency. Further consideration of the sensitivity rankings of all investigated parameters are discussed in Section 5.

Table 4.3 Cost model input parameters, including upper and lower bounds, used in sensitivity analysis.

Input	Unit	Base Value	Lower Bound % Change	Lower Bound Value	Upper Bound % Change	Upper Bound Value	Reference
Throughput	tpd	87,000	-43%	50,000	+15%	100,000	Wardrop, 2010
Strip ratio	-	0.74	-41%	0.44	+35%	1.00	Wardrop, 2010
Dunite in waste	%	20	-50%	10	+100%	40	Wardrop, 2010
wt.% MgO	%	48.54	-16%	41.00	+5%	51.00	Scheel, 2007
Processing cost	$/t	8	-50%	4	+100%	16	Lackner, 2008
Sequestration efficiency	%	80	-25%	60	+13%	90	O'Connor et al., 2000
Sequestration operating cost	$/t CO_2	32.39	-38%	20	+116%	70	Lackner, 2008; Lackner, 2002
CO_2 capture cost	$/t CO_2	25	-100%	0	+120%	55	Singh et al., 2003; Simbeck, 2001
CO_2 transport distance	km	250	-100%	0	+300%	1000	Voormeij, 2004
CO_2 transport cost	$/t km	0.02	-80%	0.004	+60%	0.032	IPCC, 2005; Rao and Rubin, 2002

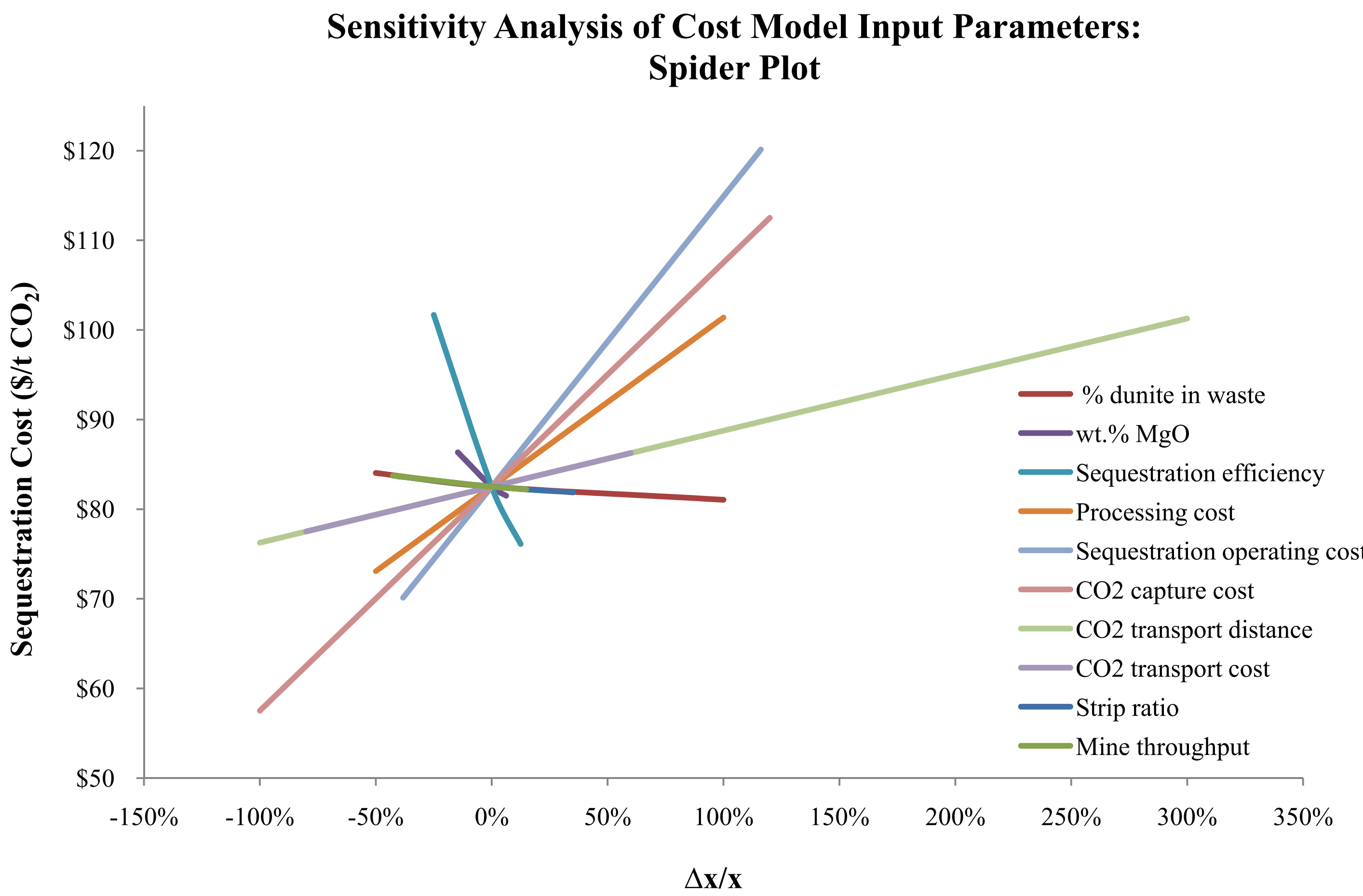

Figure 4.7 Spider plot outlining sensitivity of cost model input parameters and their proportional contribution to the unit cost of sequestration.

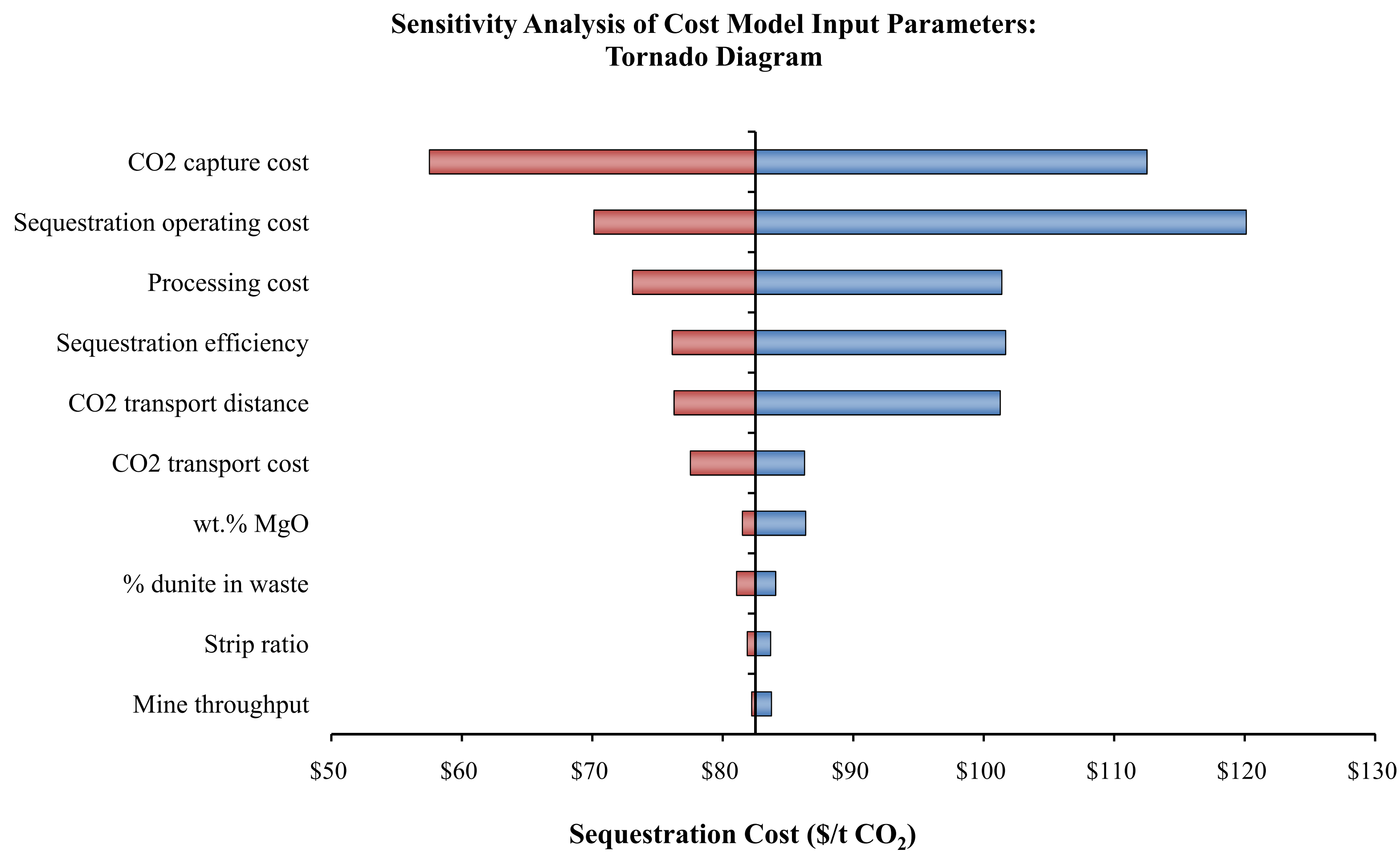

Figure 4.8 Tornado diagram showing sensitivity of cost model input parameters in terms of their range of influence on the unit cost of sequestration.

Table 4.4 Overall sensitivity ranking of cost model input parameters.

Rank	Parameter
1	Sequestration efficiency
2	Sequestration operating cost
3	CO_2 capture cost
4	wt. % MgO
5	Processing Cost
6	CO_2 transport distance
7	CO_2 transport cost
8	Mine throughput
9	Strip ratio
10	% dunite in waste

4.2.2 DCF Model Sensitivity

Further sensitivity testing was done on the DCF model to determine the anticipated sensitivity of the NPV of mineral carbonation at Turnagain in response to variety of input parameters. Investigated parameters are summarized in Table 4.4, showing the base values used in the base case scenario as well as the upper and lower bounds as a percentage change from the base.

The sensitivity results are graphically presented in Figures 4.9 and 4.10 as a spider plot and a tornado diagram respectively. The tornado diagram allows for a visual representation of the range of influence of each parameter on the NPV of mineral carbonation at Turnagain. While the tornado diagram is useful in determining the variables with the greatest range of influence on the NPV of mineral carbonation, it is highly influenced by upper and lower bounds placed on the base case values. This is therefore heavily dependent on the amount of information available for a particular parameter and the confining bounds able to be applied to it. It is for these reasons that it is the spider plot that ultimately presents the ranking of variable sensitivities. Those input parameters with the steepest slope represent the inputs with the greatest influence per unit of change, as represented by $\Delta x/x$ giving the percentage change from the base case value. The sensitivity ranking of the input values used in DCF modeling are presented in Table 4.5.

From the spider plot in Figure 4.9 and the rankings seen in Table 4.5 it is apparent that the parameter with the greatest range of influence on NPV per unit of change is the CO_2 avoidance ratio. Further consideration of the sensitivity ranking of all investigated parameters is discussed in Section 5.

Table 4.5 DCF model input parameters, including upper and lower bounds, used in sensitivity analysis.

Input	Unit	Base Value	Lower Bound % Change	Lower Bound Value	Upper Bound % Change	Upper Bound Value	Reference
Capital cost	$	139,668,169	-74%	36,292,765	+128%	318,251,010	Lackner, 2008
Construction period	yrs	2	-50%	1	+50%	3	Assumption
Mine life	yrs	24	-17%	20	+67%	40	Wardrop, 2010
CO_2 site emissions	t CO_2/yr	1,089,197	-50%	544,599	+50%	1,633,796	BHP Billiton, 2004
Total CO_2 sequestered	t CO_2/yr	1,992,518	-89%	215,670	+267%	7,316,512	Derived from cost model
CO_2 avoidance ratio	-	0.77	-35%	0.50	+30%	1.00	O'Connor et al., 2004
Operating cost	\$/t CO_2	82.51	-66%	27.98	+188%	237.91	Derived from cost model
Reduction requirement	%	20	-100%	0	+225%	65	Government of Canada, 2009
Price of carbon	\$/t CO_2	200	-98%	5	+50%	300	Government of Canada, 2009
Decommissioning	$	20,000,000	-100%	0	+150%	50,000,000	Assumption

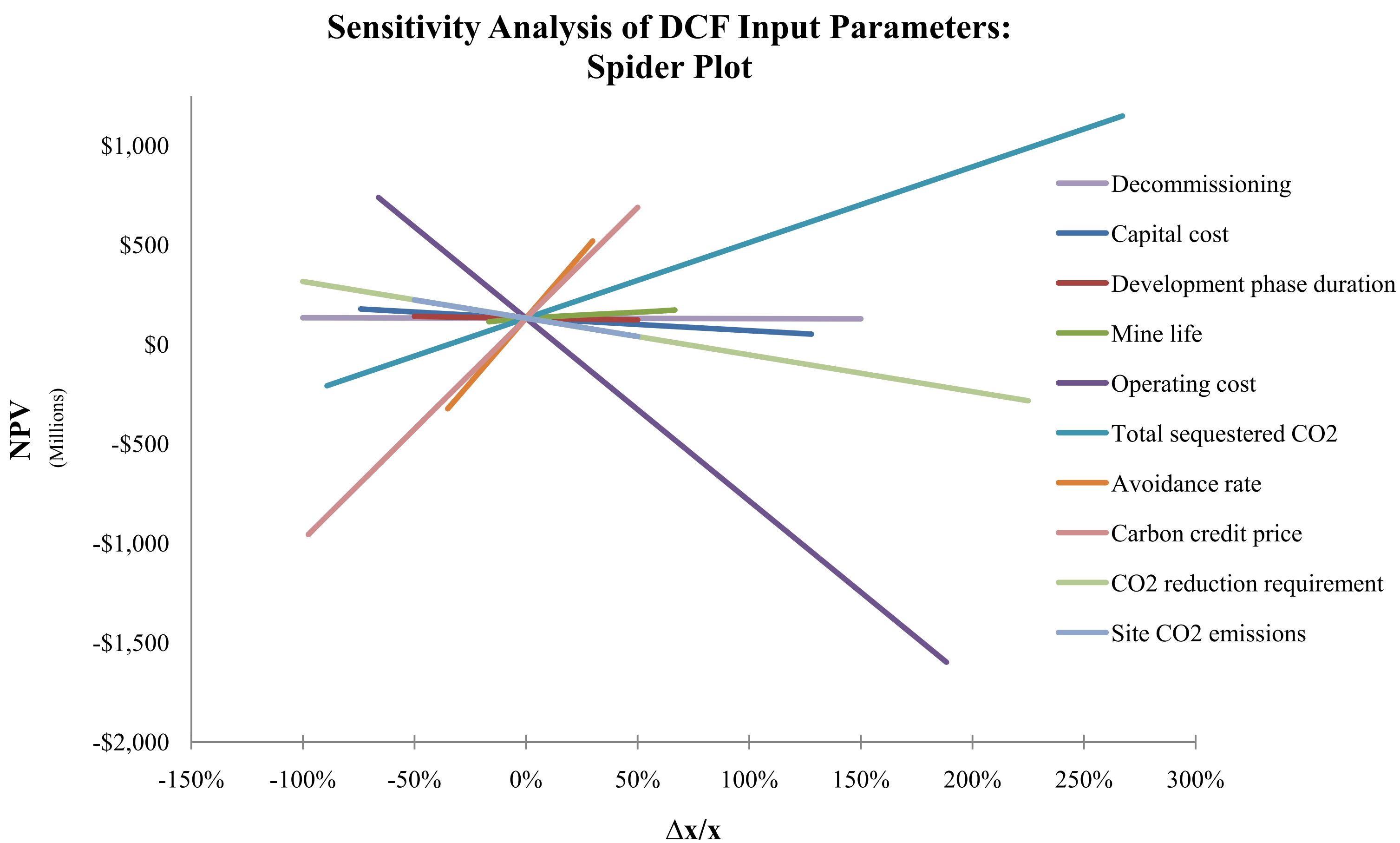

Figure 4.9 Spider plot showing sensitivity of DCF model input parameters and their proportional contribution to the NPV of mineral carbonation at Turnagain.

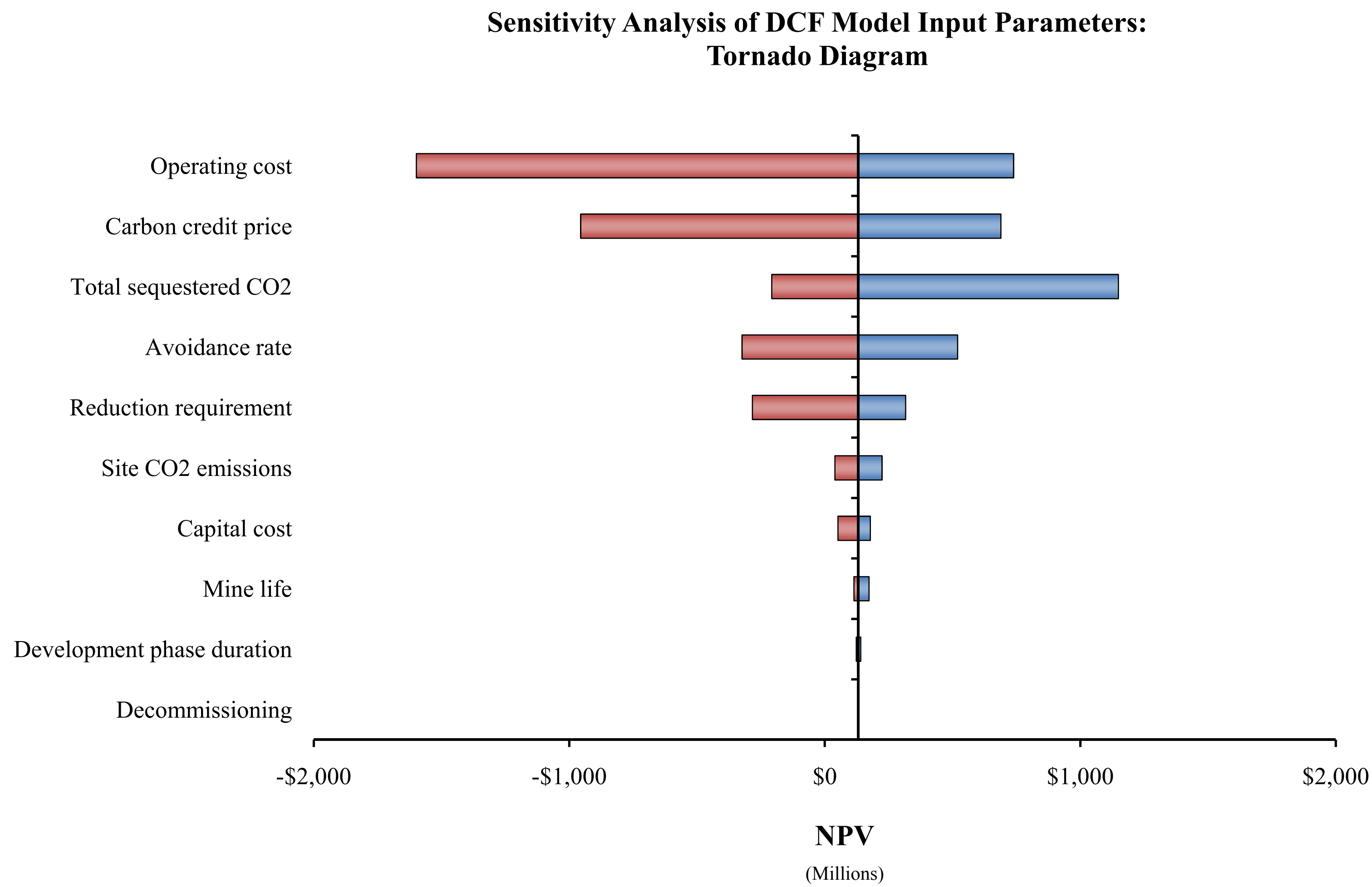

Figure 4.10 Tornado diagram showing sensitivity of DCF model input parameters in terms of their range of influence on the NPV of mineral carbonation at Turnagain.

Table 4.6 Overall sensitivity ranking of DCF model input parameters.

Rank	Parameter
1	CO_2 avoidance ratio
2	Carbon credit price
3	Operating cost
4	Total sequestered CO_2
5	Site CO_2 emissions
6	CO_2 reduction requirement
7	Mine life
8	Capital Cost
9	Development phase duration
10	Decommissioning

4.3 Correlation

Further investigating the impact of correlation on project valuation, a DCF scenario was built to demonstrate the effects of correlation between the price of carbon and the CO_2 reduction requirement. This scenario involved holding all other parameters from the base case constant, however the carbon credit price and the CO_2 reduction requirement were altered to coincide with the relationship seen in Figure 3.2. In this relationship, the CO_2 reduction requirement increased in a straight line fashion based on the Government of Canada (2009) CO_2 reduction targets, which aims to achieve a 20% reduction in CO_2 emissions below 2006 levels by the year 2020, ramping up to a 65% reduction by 2050. Corresponding carbon credit prices were estimated based on a straight-line price increase to \$300/t CO_2 according to carbon credit price forecasts developed by the Government of Canada (2009). Results of this scenario are summarized in Table 4.7.

Table 4.7 Correlation scenario results.

Correlation Case Result		
NPV_8	$	-195,499,203
IRR	%	N/A
Simple payback	yrs	N/A
Discounted payback	yrs	N/A

From these results it is evident that the correlation between the carbon credit price and the CO_2 reduction requirement plays an extremely important role in project valuation and ultimately the viability of implementing a mineral carbonation scheme at Turnagain. Figures 4.11 through to 4.15 graphically present the results of correlation analysis, demonstrating discrete cash flows, net cash flows, discounted net cash flows, cumulative cash flow and discounted cumulative cash flow respectively. The results and implications of these analyses are further discussed in Section 5.

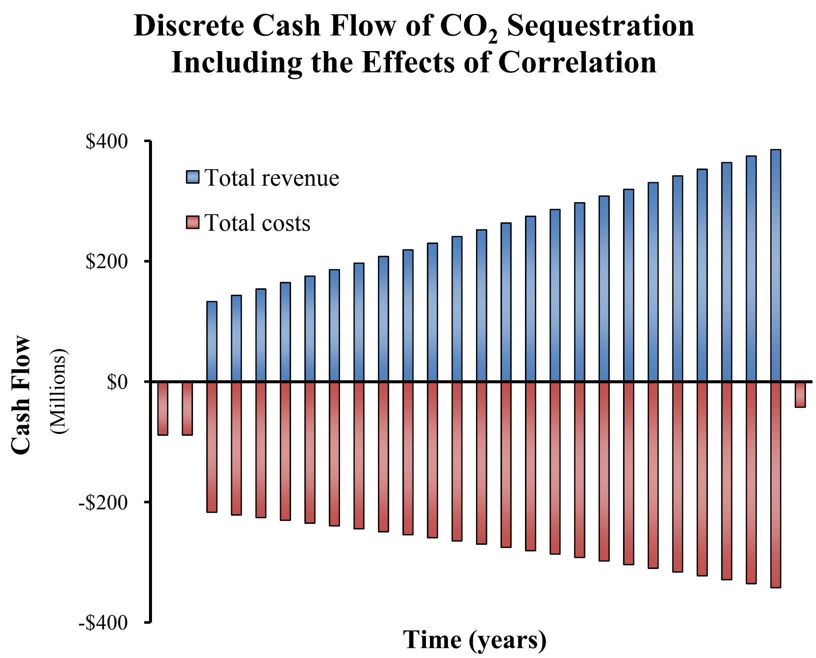

Figure 4.11 Discrete cash flow of CO_2 sequestration via mineral carbonation at Turnagain including the effects of correlation between carbon credit price and CO_2 reduction requirement.

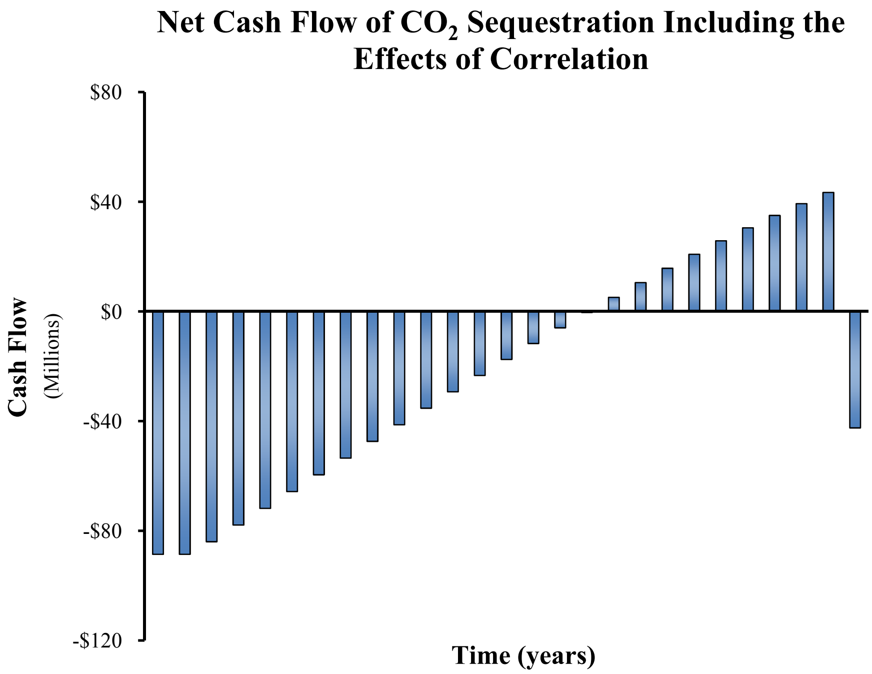

Figure 4.12 Net cash flow of CO_2 sequestration via mineral carbonation at Turnagain including the effects of correlation between carbon credit price and CO_2 reduction requirement.

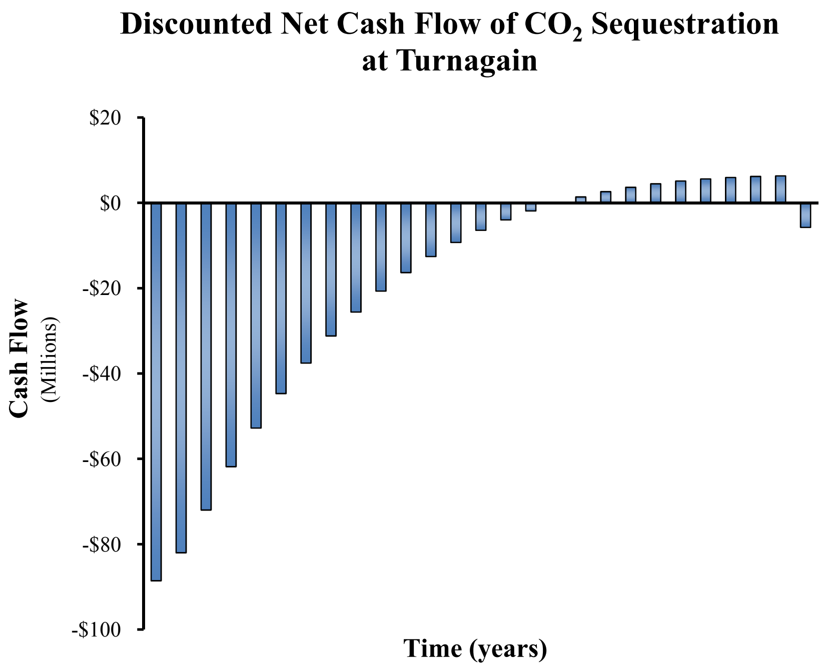

Figure 4.13 Discounted net cash flow of CO_2 sequestration via mineral carbonation at Turnagain including the effects of correlation between carbon credit price and CO_2 reduction requirement.

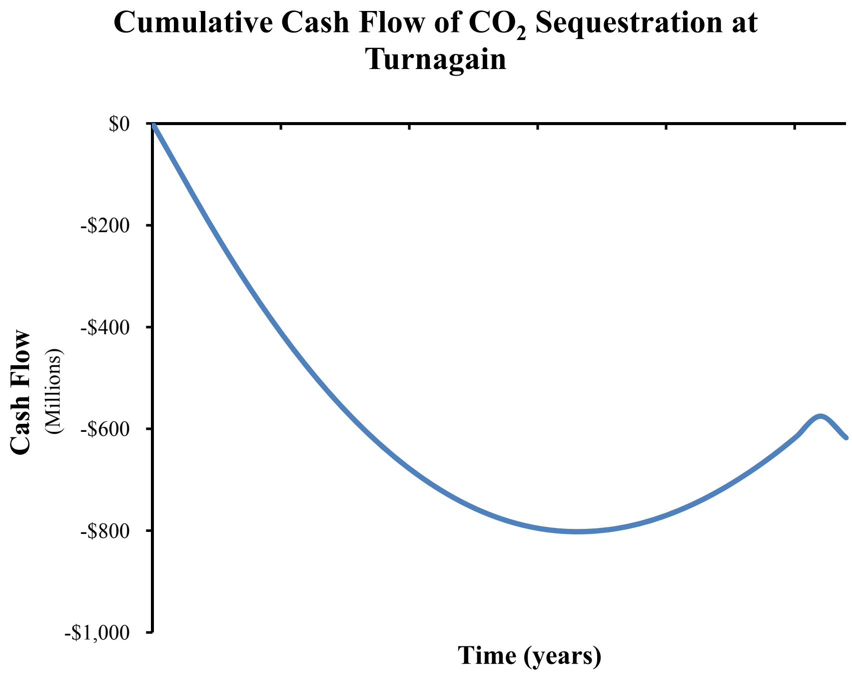

Figure 4.14 Cumulative cash flow of CO_2 sequestration via mineral carbonation at Turnagain including the effects of correlation between carbon credit price and CO_2 reduction requirement.

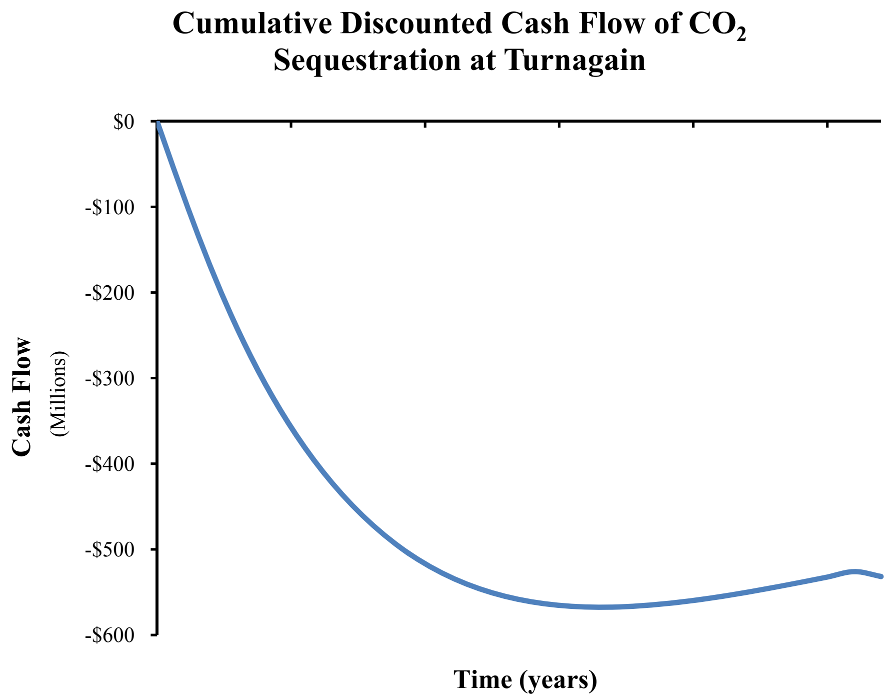

Figure 4.15 Cumulative discounted cash flow of CO_2 sequestration via mineral carbonation at Turnagain including the effects of correlation between carbon credit price and CO_2 reduction requirement.

5 DISCUSSION

Following feasibility and sensitivity analyses outlined in Chapter 4, full consideration and discussion of the results obtained through this research is warranted. This chapter will explore the reasons behind and supporting the finding of this research, in addition to demonstrating the research significance of the contained work and suggestions for future research.

5.1 Base Case Scenario Results

Results of the base case scenarios generated a cost estimate of \$82.51/t CO_2 and an NPV_8 of \$131.5 million with an IRR of 25.1% for the cost model and the DCF model respectfully. The positive NPV of the base case suggests that mineral carbonation at Turnagain may be a viable development path from the perspective of project economics. It is important, however, to remain mindful of the conceptual nature of this investigation and the inherent uncertainty surrounding model input parameters. As such, sensitivity analysis allowed for a more thorough investigation into the impacts of this uncertainty on overall project valuation. The results of sensitivity analysis are discussed further in Section 5.2.

In considering the valuation produced through financial modeling of the base case scenario, consideration must also be given to the financial consequences of the alternative. Should a cap-and-trade mechanism develop whereby emitted CO_2 must be offset financially, this scenario would generate an NPV_8 of -\$186.6 million. In this case, the base case NPV should no longer be evaluated based on whether or not it is greater than zero, but instead whether or not it is greater than the NPV of financial compliance. This increases the attractiveness of pursuing a mineral carbonation scheme as a way in which to adapt to incoming cap-and-trade mechanisms and the financial consequences that may result.

As proposed cap-and-trade policy is developed and refined, further consideration must also be given to the penalties that would be imposed in the case of non-compliance. Having sufficiently severe penalties in place for those who fail to meet set emissions reduction requirements will be necessary in order to create further incentive for those who chose to implement emissions reduction measures. The impact of these penalties will be an important factor to further consider in the evaluation of alternative scenarios in the context of overall project valuation.

5.2 Sensitivity Rankings

The sensitivity rankings seen in Tables 4.3 and 4.5 are integral outcomes of this research that justify further discussion. The inter-relationships between the various modeling input parameters, including their individual effects on the value of the entire process, are critical for the development of future research with the ultimate goal of implementing mineral carbonation on an industrial scale. A further look into the reasons supporting these rankings will allow for a more thorough understanding of the process as a whole and how each parameter may impact project valuation.

5.2.1 Cost Model Sensitivity

Considering the rankings in order of sensitivity, the most sensitive parameter outlined through sensitivity analysis of the cost model was the sequestration efficiency of reaction. Unit changes in this parameter are the most influential on the cost of sequestration, primarily due to the requirements and associated costs that go into preparing feedstock for sequestration. Maximizing the amount of CO_2 sequestered from the input feedstock enables costs to be minimized per unit sequestered. Given the substantial requirements in bringing input feedstock and CO_2 to a suitable state at the site of reaction, the amount of CO_2 sequestered per unit of input is extremely important in determining the unit sequestration cost in the lifecycle of mineral carbonation. As the determinant of the total amount of CO_2 sequestered, sequestration efficiency also directly affects other cost inputs by influencing the size of the denominator for the calculation of unit cost per tonne of CO_2 sequestered. It is therefore important that this parameter is maximized in striving towards minimizing the overall unit cost of sequestration.

Operating cost was the second most sensitive parameter determined through sensitivity analysis. As the most significant contributor to total cost in determining unit cost per tonne CO_2, operating cost for the autoclave was found to be rather sensitive, resulting from the significant P-T conditions required and the associated cost of power. Reducing the dependency on extreme conditions will help reduce unit costs, keeping in mind that the sequestration efficiency has a greater overall impact and must remain the priority for further research. The cost of CO_2 capture follows in sensitivity, also resulting from the significant power and energy requirements necessary in removing CO_2 from flue gas.

The wt. % of MgO in the waste rock was found to the fourth most sensitive parameter in cost modeling, as it directly impacts the amount of MgO available for reaction with CO_2. Initially, it was thought that this parameter would have a greater effect on the total unit cost of sequestration as it directly impacts the amount CO_2 sequestered, however this was not the case. Similar to the reasons supporting the sensitivity of the sequestration efficiency, a decrease in the amount of MgO in the waste rock results in less MgO available for reaction with CO_2. This causes a reduction in the amount of CO_2 sequestered and therefore decrease the size of the denominator in calculating unit sequestration cost per tonne of CO_2. The opposite effect would occur if the wt. % of MgO in the waste rock increased.

Following in sensitivity of the cost model is the processing cost, and consequently the grind size required in the reaction process. This has cost implications arising from the power requirements necessary to obtain finer grind sizes. Carbon dioxide transport distance and cost are also important to consider in terms of their influence on the total unit cost of sequestration, however less so than the preceding factors. The majority of the cost in bringing a significant source of CO_2 to the site of reaction is the separation and capture of CO_2, however one major item to consider is the availability of pipeline infrastructure. Without an available pipeline network in which to transport significant amounts of CO_2, a mineral carbonation project such as this would have to rely on the separation and capture of CO_2 from flue gases on site which would not likely provide an adequate supply.

Finally, the least sensitive parameters investigated were the throughput, strip ratio and percentage of dunite in the waste rock. All three of these parameters were influential in determining the amount of CO_2 sequestered and therefore impacting the denominator in calculating the total unit cost of sequestration. These factors, however, had only a very minimal impact in terms of sensitivity. Their primary importance would be in terms of determining the scale of a mineral carbonation facility, which may ultimately be dictated by the on-site emissions that must be offset plus the availability of waste rock and CO_2 supply. These last factors are heavily dependent on mining operations at Turnagain will likely be determined by the mine economics of such.

5.2.2 DCF Model Sensitivity

Hand in hand with the significant influence of sequestration efficiency in cost modeling is the sensitivity attributed to the CO_2 avoidance ratio in DCF modeling. This parameter is the most sensitive for a number of the same reasons mentioned above, namely that it is imperative to maximize the efficiency at which CO_2 is sequestered given the required inputs both in terms of feed materials and costs. The main difference however, is the need to balance the ultimate amount of CO_2 sequestered versus the amount of CO_2 emitted through the sequestration process itself. In this case, the CO_2 avoidance ratio is critical in order to maximize the amount of net CO_2 sequestered and available to sell as carbon credits. If, during the lifecycle of the mineral carbonation process, there is an excessive amount of CO_2 emitted, the efforts and costs put into the process are negated. As such, ensuring that a minimal amount of CO_2 is emitted during the mineral carbonation lifecycle will ensure that the maximum number of carbon credits are available for sale. As a consequence, it is ultimately the CO_2 avoidance ratio that is the most sensitive parameter in determining the NPV of mineral carbonation at Turnagain. These results have a direct impact on continued research efforts in the field of mineral carbonation. Going forward, the development of mineral carbonation technologies and methodologies will need to take the net amount of sequestered CO_2 into primary consideration in order to maximize efforts towards the development of a feasible process. Previous efforts have been aimed towards the maximum sequestration efficiency of reaction, however this research has demonstrated that this is not the best course of action when considering the overall feasibility of mineral carbonation. Focusing on the CO_2 avoidance ratio and net sequestration effect will not only be beneficial from an environmental standpoint, it will also result in a process that has the greatest value for investors. By maximizing the value of the process, the likelihood of implementing a mineral carbonation scheme on an industrial scale is greatly increased. It is this aspect of mineral carbonation that should therefore be the focus of further research and development.

Following CO_2 avoidance ratio, the price of carbon credits has the second greatest influence on the value of mineral carbonation. As the sole source of revenue in the mineral carbonation process, the price per tonne of CO_2 available through the sale of carbon credits has significant ramifications in terms of overall project feasibility by directly controlling the total available revenue. Without a significant price on carbon, there will not be an adequate source of revenue in order to offset the associated costs. This parameter is also particularly important to consider since it is uncontrollable from the perspective of research and development. The decisions leading towards implementation of a broad-ranging cap-and-trade program ultimately lie with government officials, and are inherently dependant on their stance towards the environment as well as public sentiment at the time. However, the highly sensitive and influential nature of carbon price on the feasibility of implementing carbon reduction programs such as mineral carbonation may provide significant leverage in order to lobby policymakers in support of research and development efforts. This point will become increasingly important as more information comes to light regarding climate change and the need for drastic carbon reduction measures.

There are a number of other investigated parameters that have a noticeable effect on the feasibility of mineral carbonation, albeit with more minimal sensitivity in terms of overall influence. Operating cost is a significant factor in determining the feasibility of mineral carbonation. Similar to the importance of carbon price, the operating cost directly influences the total available cash flow and consequently influences NPV. Following in sensitivity, the total amount of sequestered CO_2 is influential in being the denominator of all unit costs; a larger amount of sequestered CO_2 is able to more widely distribute costs, therefore lowering costs on a per tonne basis. Site emissions will impact project feasibility in determining the total amount of sequestered CO_2 available to sell as carbon credits. This follows the need to first offset site emissions prior to claiming sequestered CO_2 as credits to sell in the market. The influence of the reduction requirement stems from the same principle by determining the amount of site emissions that are required to first be offset before carbon credits can be claimed. By impacting the amount of carbon first required to be offset prior to receiving carbon credits, both the site emissions and the reduction requirement are directly determining the total amount of CO_2 available to be sold and consequently the total revenue available.

Factors of more minimal influence include the mine life, capital cost, development phase duration and the cost of decommissioning. Mine life did not have a significant impact on the feasibility of mineral carbonation due primarily to the impact of the time value of money. Although an extended mine life will impact cash flow, when discounted back to the present time the effect of mine life is minimal. Capital cost, while initially thought to have a greater influence on project valuation due to the front-loaded nature of the cash flows, did not significantly impact project valuation. The capital cost required may however have a more dramatic impact on the ability to secure project financing, either through debt or equity. While this does not necessarily impact project valuation, it may ultimately have an impact on project feasibility in determining the ability to generate funding for project construction. Similar to the impact of capital cost, the development phase duration also did not have a significant influence on NPV primarily due to the subdued impact of capital cost combined with the effect of the time value of money. Finally, decommissioning costs had a relatively insignificant influence because of the cash flow timing far in the future. Again, the time value of money is extremely influential in negating the effects of this parameter. However, the required decommissioning of such a project may have alternative effects in the need for significant environmental bonds to be held prior to project commencement.

We cannot ignore the significance and contribution of each of the individual parameters investigated through this research, however the ranking of sensitivity has provided a means by which to prioritize further research and focus efforts on parameters that will results in the greatest influence on project valuation.

5.3 Correlation

The NPV_8 of -$195.5 million produced from this modeling scenario suggests that the impacts of correlation between carbon credit price and the CO_2 reduction requirement are very important in project valuation and ultimately determining the feasibility of project implementation. Unfortunately it is precisely these relationships that are unknown at this point and are heavily dependent on both governmental decisions and regulation coupled with unpredictable market mechanisms of cap-and-trade. This uncertainty therefore will play a large part in the decision-making process when deciding whether or not to proceed with project development. At the moment, further clarity is needed on this subject in order to help guide the future of mineral carbonation research and development.

Although this scenario generated a negative NPV which would typically result in the decision not to proceed with development, consideration must be given to the financial consequences of the alternative. Should a cap-and-trade mechanism develop where emitted CO_2 must be offset financially, this scenario would generate an NPV_8 of -$355.8 million. Therefore, the negative NPV generated from implementation of a mineral carbonation scheme would, although still negative, be greater in value. In this case, the implementation of mineral carbonation would be the better option from a financial point of view in order to avoid greater loss. Again, this increases the attractiveness of pursuing a mineral carbonation scheme as a way in which to adapt to incoming cap-and-trade mechanisms and the financial consequences that may result.

5.4 Research Significance and Contributions

The use of mineral carbonation for the sequestration of CO_2 is an emerging field of research that is gaining attention for its ability to sequester vast amounts of CO_2 in a permanent and benign way. Prior research in this area has focused on the technological aspects of maximizing the efficiency of reaction, however little works has been put towards the economics of integrating the technology into an industrial setting. This research has developed a preliminary cost model and DCF financial model for estimating the unit cost of mineral carbonation and the NPV of a mineral carbonation scheme at Turnagain. Sensitivity analysis has allowed for the delineation of the most sensitive input parameters in order to help focus future research efforts to minimize the costs of mineral carbonation and to maximize the project NPV.

Through this research, it has been demonstrated that the sequestration efficiency of reaction is an integral factor in minimizing the cost of mineral carbonation, however this must be achieved while considering the CO_2 avoidance ratio in order to maximize project NPV. It is the CO_2 avoidance ratio that is the most sensitive parameter, and thus the most important to consider in order to develop a project with the greatest value and consequently has the greatest chance of further development on an industrial scale. This research has outlined the importance of focusing research efforts towards maximizing the sequestration efficiency of reaction while minimizing the amount of CO_2 produced through the mineral carbonation process. It is this balance that will ultimately help lead towards the development of a viable mineral carbonation scheme. Demonstrating the sensitivity of such a project to the price of carbon credits will also aid in lobbying for a price to be put on carbon in order to facilitate and encourage the further development of mineral carbonation schemes such as that proposed for the Turnagain nickel site.

5.5 Next Steps

This research has led to a number of new ideas that may be valuable additions to future work in the area of mineral carbonation. Brief consideration of each of these aspects and the ways in which they may further contribute to improved understanding of the feasibility of mineral carbonation schemes is discussed herein.

5.5.1 Options Pricing

Options are a valuable aspect of project structuring for the value they provide in the form of built-in flexibility (Cardin et al., 2008). It is therefore important that any mineral carbonation scheme should incorporate and further explore the benefits that options may provide. This is particularly important for projects containing a high degree of uncertainty and in cases where new technology or new markets are explored. Building the flexibility of options into the long-term plan allows for adaptation in the presence of forecasting errors, market variability and operating conditions in order to capitalize on project success while mitigating losses (Mayer and Kazakidis, 2007).

Integrating the use of DCF analysis with option valuation is important in order to obtain an accurate understanding of the project in question and to adequately evaluate investment opportunities. Employing DCF analysis as part of traditional NPV analysis may undervalue those project with embedded options by ignoring the value inherent in their available flexibility (Kulatilaka and Marcus, 1992). In situations where early investments into new markets or elaborate R&D schemes may yield negative NPV values, being solely reliant on DCF analysis and NPV values in decision-making may cause the true value of an investment in terms of future potential to be undervalued. It is these initial stages of project development and investment that may be able to open the gateway for future growth potential and eventual project profitability as the markets and technology continues to develop (Jägle, 1999; Myers, 1984).

5.5.2 Qualitative Benefits

While the numerous costs associated with carbon sequestration via mineral carbonation can be reasonably estimated and quantified, difficulties arise when trying to fully evaluate the benefits. From a purely quantitative perspective, financial benefits may be possible from a variety of different sources depending on the regulatory framework in place. In situation where a carbon tax is in effect, offsetting mine site emissions may be able to reduce the financial burden of these taxes. The possible development of a cap-and-trade scheme in North America would also allow for mine emissions in excess of a set cap to be offset, with additional sequestered carbon available for sale as carbon credits on a publicly traded carbon market. Other revenue streams may also be possible if waste rock or mine tailings are sold directly as a by-product to a separate entity for their independent use. There are numerous speculative means by which carbon sequestration may provide financial benefits if the associated costs are adequately low by comparison. However, the relatively infant nature of mineral carbonation technology on an industrial or field-scale basis creates relative uncertainty as to the precise magnitude of these cost and revenue streams. Therefore it is also important to consider the non-quantifiable benefits that may arise from implementing a carbon sequestration project to improve its appeal as a potential investment. These qualitative benefits may aid in the decision-making process and help make a marginal carbon management project become more appealing.

Environmental benefits are likely the most prominent asset arising from mineral carbonation and for many, this is justification enough for the implementation of drastic CCS mechanisms such as this. However, aside from the more obvious CO_2 reductions to help curb atmospheric GHG levels, the integration of mineral carbonation into mining operations may have the ability to reduce overall quantities of waste and/or tailings by using these materials as mineral carbonation feedstock and thereby transforming the material into benign, and possibly saleable, by-products. Recent reports suggest that the market for magnesite as a source of magnesium metal or refractory magnesia is relatively limited in due to the Chinese domination of the market (Simandl et al., 2006), thereby hindering the sale of these by-products as a source of additional revenue. It is possible, however, that their use as aggregate material or mine backfill may still be able to provide value to mining operations. It is important to consider the promising reductions to the overall environmental impact of mining that may be achievable through mineral carbonation, potentially aiding in the ERA (environmental risk assessment) approval stage of mine development.

Incorporating carbon sequestration practices into mining operations may be appealing to the ethically conscious investor and may hold value for stakeholders looking to associate with environmentally conscious corporations or who utilize a specific set of social-screens or criteria when selecting investments (Pava and Krausz, 1996). Particularly in an industry plagued by prominently negative perceptions, it is conceivable that those organizations involved in meaningful corporate social responsibility (CSR) programs may be favoured by investors. It has also been suggested that there exists a positive relationship between corporate social practice and financial performance (Waddock and Graves, 1997). This idea was further examined by Hillman and Keim (2001), indicating that the careful management of primary stakeholders (including the environment) can provide intangible yet valuable assets that may be able to provide a significant competitive advantage against competitors. With the proposed implementation of carbon management policies looming ahead, businesses incorporating carbon management practices should also be better equipped to handle the additional burden imposed by such incoming policies, which would further improve shareholder value by minimizing or eliminating certain costs.

Integrating such aggressive carbon management strategies into mine development may help foster new and improved perceptions towards the mining industry. With climate change and CO_2 emission currently taking a prominent stand on the world scale, the development of realizable carbon mitigation strategies by the mining industry may be able to provide a beneficial boost to its image. By positioning itself correctly, the mining industry stands to make significant strides in improving its negative reputation of accountability by implementing a culture of innovation and forward thinking towards the environment.

5.5.3 Effects of Time

The effects of the time value of money plays a very important role in project valuation. In further evaluating the positive effects that may result from the qualitative benefits of mineral carbonation, it is meaningful to consider how these factors may also lead to quantitative benefits resulting from expedited development timelines. A reduction in permitting time or mitigated political opposition may enable cash flows to brought forward, therefore reducing the impact of discounting on project valuation.

Time may also play a key role in ultimately determining the most appropriate technology to use for mineral carbonation at Turnagain. Although high efficiency forms of mineral carbonation are also associated with high costs, one of the main benefits of more active technologies is the fast rates of reaction. This allows for carbon credits generated through CO_2 sequestration to be claimed sooner, allowing for costs and revenues to be more closely aligned. In contrast, more passive mineral carbonation technologies are likely to be hindered by slow reaction rates. This would result in a significant gap between the time at which the costs of mineral carbonation are incurred and the resulting revenues are realized. Applying the time value of money to these cash flows, this lag would diminish the value of the revenue received through the sale of carbon credits. Although further research is necessary to fully quantify the effects of time on project feasibility, it is likely that the time value of money would be a significant hindrance to implementing more passive mineral carbonation technologies on an industrial scale.

6 CONCLUSION

It is becoming increasingly evident that governmental bodies around the world are searching for meaningful ways in which to help mitigate and reduce atmospheric levels of CO_2. It is likely that this will come in the form of a cap-and-trade mechanism due its ability to provide meaningful incentives to spur innovation and effect change. As such is it imperative that point source emitters of CO_2 prepare for the potential adverse effects that may result from putting a price on carbon. This is particularly important in the mining industry, where mine economics may be significantly impacted by the financial implications of cap-and-trade. Carbon sequestration through mineral carbonation may be a viable option in order to offset mine emissions and potentially generate an additional revenue stream through the sale of excess carbon credits. The implementation of mineral carbonation as opposed to many of the other suggested forms of carbon sequestration has the advantage of producing a stable by-product with a reduced risk of CO_2 leakage, as well as the potential for more a more accurate verification process in order to quantify the amount of CO_2 sequestered.

This research has produced a preliminary analysis of the financial feasibility of integrating mineral carbonation into proposed mining operations at the Turnagain Nickel site in Northern BC. Through the initial development of a conceptual cost model for the life cycle of mineral carbonation, an operating cost of \$82.51/t CO_2 was determined. This was necessary due to the wide array of cost estimates in the literature and the inconsistent inclusion of all the necessary steps in the life cycle of mineral carbonation. This research has therefore attempted to generate a more comprehensive and all-encompassing estimate of the cost of mineral carbonation in order to more accurately approximate input costs for further financial modeling. A preliminary financial model using a discounted cash flow approach was then developed, generating a base case NPV_8 of $131.5 million and an IRR of 25.1% in the presence of a cap-and-trade program. This suggests that project implementation may be viable from a financial perspective. However, consideration must be given to the conceptual nature of these analyses and as such a comprehensive sensitivity analysis was necessary. From the cost model, the most influential parameter was found to be the sequestration efficiency of reaction, whereas the most influential parameter in DCF modeling was found to be the CO_2 avoidance ratio of reaction. The importance of these two parameters solidifies the fact that a balance must be struck between maximizing sequestration efficiency and minimizing CO_2 emitted during the mineral carbonation process. This will help ensure that project economics remain favourable for the industrial implementation of mineral carbonation in conjunction with mining operations. Sensitivity analyses performed in this research have also aided in directing further research towards those inputs that will result in the greatest impact on project viability going forward.

In addition to sensitivity analyses, the effects of correlation between carbon credit price and the CO_2 reduction requirement were investigated. This was found to be extremely influential on project NPV, generating a negative valuation that indicates that project implementation is not viable from a financial perspective when considering the currently proposed relationships between carbon credit price and CO_2 reduction requirement set forth by the Government of Canada. As a result, it is important that policy makers take into consideration the potentially negative financial effects that may arise from the improper design of CO_2 management schemes, and how they will impact the viability of the sequestration projects they are designed to promote.

This research demonstrates that, while feasible from a preliminary financial perspective, the viability of implementing mineral carbonation on an industrial scale is highly dependent on decisions made outside the control of research and development. This primarily includes the design and introduction of a comprehensive cap-and-trade framework that will put a price on carbon. Although proposed, it is unknown at this point how, when or if such a regulatory framework will be developed. However, should cap-and-trade become a reality in Canada, this research has demonstrated that it is possible for the implementation of mineral carbonation at Turnagain to be a viable means by which to achieve compliance with set emissions reduction limits and potentially generate additional revenue from the sale of excess carbon credits. Although highly dependent on future governmental decisions, the mining industry must keep a watchful eye on CO_2 reduction initiatives and how they may impact mine economics. Mineral carbonation has the unique ability to potentially mitigate these effects, however the viable development of industrial mineral carbonation schemes such as that proposed for Turnagain will ultimately be reliant on the development of appropriate governmental policies that must keep financial viability in mind. It is only by striking a balance between environmental policy and financial viability that projects such as mineral carbonation at Turnagain will become a reality.

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APPENDIX A – Cost Model

HIGHLIGHTED BOXES REQUIRE USER INPUT

MINING*

	unit	value
Mine life	yrs	29
Operating days per year	days	365
Daily production rate (throughput)	tpd	87,000
Strip ratio (waste:ore)	-	0.74
Amount of dunite in waste rock	%	0.20
Waste production rate	tpd	12,876
Tailings ratio (throughput:tailings)	-	0.98
CO2 ratio (tailings:CO2)	-	0.035
CO2 production rate	tpd	2,984

* Mining costs borne by Ni-mining operations and therefore not included

PROCESSING

Composition

	assay (wt %)	output (tpd)
SiO2	38.17%	4,915
TiO2	0.04%	5
Al2O3	0.32%	41
Fe2O3	7.15%	921
MgO	48.54%	6,250
MnO	0.10%	13
CaO	0.29%	37
Na2O	0.02%	3
K2O	0.20%	26
P2O5	-	-
LOI	5.06%	652
S	0.09%	12
Total	99.98%	12,873

Processing Costs**

	unit	value
Required grind size	µ	75
Unit processing cost at required grind size	$/t	8.00
Daily processing cost	$/day	103,008
Annual processing cost	$/yr	37,597,920
Unit cost of processing	$/t feed	8.00
	$/t CO2	18.87

SEQUESTRATION

Input

	unit	value
Waste feed	tpd	12,876
Ratio feed:CO2 for complete conversion	-	2.06
MgO available	tpd	6,250
Sequestration efficiency	%	0.80
CO2 from direct source	tpd	2,984
CO2 required for complete reaction w/ available MgO	tpd	6,824

Output***

	unit	value
MgCO3	tpd	10,459
Waste (SiO2)	tpd	3,727
Total for disposal	tpd	14,186
Daily amount of CO2 sequestered	tpd	5,459
Annual amount of CO2 sequestered	tpy	1,992,518
CO_2 avoidance ratio	-	0.77
Annual CO_2 avoided	tpy	1,534,239

*** Output assumed to follow the generalized equation for olivine reaction

Operating Costs****

	unit	value
Operating cost A	$/day	50.684
Operating cost B	$/day	0.9333
Daily operating cost	$/day	176,834
Annual operating cost	$/yr	64,544,500
Unit operating cost of sequestration	$/t feed	13.73
	$/t CO2	32.39

**** Cost estimates from Lackner et al., 2008 using cost relationship y=AX^B where X represents the output of MgO (tpd)

CO_2 CAPTURE

CO2 separation and capture from flue gas	$/t CO2	25.00

TRANSPORTATION

	unit	value
Waste rock from pit to processing facility	km	-
CO2 from direct source	km	-
CO2 from external source	km	250
Unit feed transportation cost per km	$/t km	0.02
Unit CO2 transportation cost per km	$/t km	0.02
Total feed transportation cost	$/yr	-
Total CO2 transportation cost	$/yr	12,453,235
Total transportation cost	$/yr	12,453,235
Unit cost of transportation	$/t feed	2.65
	$/t CO2	6.25

DISPOSAL

	unit	value
Distance from sequestration facility to dump	km	-
Total output for disposal (MgCO3 + waste)	tpd	14,186
Unit disposal cost per km	$/t km	0.02
Total disposal cost	$/yr	-
Unit cost of disposal	$/t feed	-
	$/t CO2	-

TOTAL

	unit	value
Processing cost	$/t CO2	18.87
Sequestration cost	$/t CO2	32.39
CO_2 capture cost	$/t CO2	25.00
Transportation cost	$/t CO2	6.25
Disposal cost	$/t CO2	-
Total operating cost	**$/t CO2**	**82.51**

APPENDIX B – DCF Model

Year	2011	2023	2024	2025	2026	2027
Time since present (yrs from 2011)	0	12	13	14	15	16
Capital spending ($)		88,566,505	88,566,505			
Site CO2 emissions				1,089,197	1,089,197	1,089,197
Total sequestered CO2 (t CO2)				1,992,518	1,992,518	1,992,518
Total avoided CO2 (t CO2)				1,534,239	1,534,239	1,534,239
CO2 reduction requirement				20.0%	20.0%	20.0%
Sequestered CO2 available to sell as CCs (t CO2)				1,316,399	1,316,399	1,316,399
Operating costs ($/t CO2)				108.87	111.05	113.27
Decommissioning cost ($)						
Carbon credit price ($/t CO2)				200.00	204.00	208.08
Total costs	$ -	$ (88,566,505)	$ (88,566,505)	$ (216,933,649)	$ (221,272,322)	$ (225,697,768)
Total revenue	$ -	$ -	$ -	$ 263,279,847	$ 268,545,444	$ 273,916,353
Net cash flow	$ -	$ (88,566,505)	$ (88,566,505)	$ 46,346,198	$ 47,273,122	$ 48,218,585
Discounted net cash flow	$ -	$ (88,566,505)	$ (82,006,023)	$ 39,734,395	$ 37,526,929	$ 35,442,099
Cumulative cash flow	$ -	$ (88,566,505)	$ (177,133,009)	$ (130,786,811)	$ (83,513,688)	$ (35,295,103)
Cumulative discounted cash flow	$ -	$ (88,566,505)	$ (170,572,527)	$ (130,838,132)	$ (93,311,203)	$ (57,869,104)

NPV8	$ 131,449,380
IRR	25.1%
Simple payback (yrs)	3.72
Discounted payback (yrs)	4.77

2028	2029	2030	2031	2032	2033	2034	2035	2036
17	18	19	20	21	22	23	24	25
1,089,197	1,089,197	1,089,197	1,089,197	1,089,197	1,089,197	1,089,197	1,089,197	1,089,197
1,992,518	1,992,518	1,992,518	1,992,518	1,992,518	1,992,518	1,992,518	1,992,518	1,992,518
1,534,239	1,534,239	1,534,239	1,534,239	1,534,239	1,534,239	1,534,239	1,534,239	1,534,239
20.0%	20.0%	20.0%	20.0%	20.0%	20.0%	20.0%	20.0%	20.0%
1,316,399	1,316,399	1,316,399	1,316,399	1,316,399	1,316,399	1,316,399	1,316,399	1,316,399
115.54	117.85	120.21	122.61	125.06	127.56	130.11	132.72	135.37
212.24	216.49	220.82	225.23	229.74	234.33	239.02	243.80	248.67
$ (230,211,724)	$ (234,815,958)	$ (239,512,277)	$ (244,302,523)	$ (249,188,573)	$ (254,172,345)	$ (259,255,792)	$ (264,440,907)	$ (269,729,726)
$ 279,394,680	$ 284,982,574	$ 290,682,225	$ 296,495,870	$ 302,425,787	$ 308,474,303	$ 314,643,789	$ 320,936,665	$ 327,355,398
$ 49,182,957	$ 50,166,616	$ 51,169,948	$ 52,193,347	$ 53,237,214	$ 54,301,958	$ 55,387,997	$ 56,495,757	$ 57,625,672
$ 33,473,094	$ 31,613,478	$ 29,857,173	$ 28,198,441	$ 26,631,861	$ 25,152,313	$ 23,754,963	$ 22,435,243	$ 21,188,840
$ 13,887,853	$ 64,054,469	$ 115,224,417	$ 167,417,764	$ 220,654,978	$ 274,956,936	$ 330,344,934	$ 386,840,691	$ 444,466,363
$ (24,396,010)	$ 7,217,467	$ 37,074,640	$ 65,273,082	$ 91,904,943	$ 117,057,257	$ 140,812,219	$ 163,247,462	$ 184,436,302

2037	2038	2039	2040	2041	2042	2043	2044	2045
26	27	28	29	30	31	32	33	34
1,089,197	1,089,197	1,089,197	1,089,197	1,089,197	1,089,197	1,089,197	1,089,197	1,089,197
1,992,518	1,992,518	1,992,518	1,992,518	1,992,518	1,992,518	1,992,518	1,992,518	1,992,518
1,534,239	1,534,239	1,534,239	1,534,239	1,534,239	1,534,239	1,534,239	1,534,239	1,534,239
20.0%	20.0%	20.0%	20.0%	20.0%	20.0%	20.0%	20.0%	20.0%
1,316,399	1,316,399	1,316,399	1,316,399	1,316,399	1,316,399	1,316,399	1,316,399	1,316,399
138.08	140.84	143.66	146.53	149.46	152.45	155.50	158.61	161.78
253.65	258.72	263.90	269.17	274.56	280.05	285.65	291.36	297.19
$ (275,124,320)	$ (280,626,807)	$ (286,239,343)	$ (291,964,129)	$ (297,803,412)	$ (303,759,480)	$ (309,834,670)	$ (316,031,363)	$ (322,351,991)
$ 333,902,506	$ 340,580,556	$ 347,392,167	$ 354,340,011	$ 361,426,811	$ 368,655,347	$ 376,028,454	$ 383,549,023	$ 391,220,004
$ 58,778,186	$ 59,953,750	$ 61,152,825	$ 62,375,881	$ 63,623,399	$ 64,895,867	$ 66,193,784	$ 67,517,660	$ 68,868,013
$ 20,011,682	$ 18,899,922	$ 17,849,927	$ 16,858,264	$ 15,921,694	$ 15,037,155	$ 14,201,758	$ 13,412,771	$ 12,667,617
$ 503,244,549	$ 563,198,299	$ 624,351,124	$ 686,727,005	$ 750,350,404	$ 815,246,270	$ 881,440,054	$ 948,957,714	$ 1,017,825,727
$ 204,447,984	$ 223,347,907	$ 241,197,833	$ 258,056,097	$ 273,977,791	$ 289,014,946	$ 303,216,704	$ 316,629,475	$ 329,297,092

2046	2047	2048	2049
35	36	37	38
1,089,197	1,089,197	1,089,197	
1,992,518	1,992,518	1,992,518	
1,534,239	1,534,239	1,534,239	
20.0%	20.0%	20.0%	
1,316,399	1,316,399	1,316,399	
165.02	168.32	171.68	
			42,445,976
303.13	309.20	315.38	
$ (328,799,030)	$ (335,375,011)	$ (342,082,511)	$ (42,445,976)
$ 399,044,404	$ 407,025,292	$ 415,165,798	$ -
$ 70,245,373	$ 71,650,281	$ 73,083,286	$ (42,445,976)
$ 11,963,861	$ 11,299,202	$ 10,671,468	$ (5,738,771)
$ 1,088,071,100	$ 1,159,721,381	$ 1,232,804,667	$ 1,190,358,691
$ 341,260,953	$ 352,560,155	$ 363,231,623	$ 357,492,852