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Energy efficiency and carbon dioxide emissions across different scales of iron ore mining operations in Western Australia

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Energy efficiency and carbon dioxide emissions across different scales of iron ore mining operations in Western Australia

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Master of Science

School of Science,

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Abstract

During the last two decades, Western Australian iron ore mining industry experienced an exponential production growth arising from increased global demand for steel. The upturn in the iron ore price and considerably lower production cost encouraged extensive mining and consequently high-grade ore reserves were gradually depleted. Despite the energy-intensive nature of mining, high profitability motivated the mining companies to extract marginal-grade deposits with additional processing requirements, which increased energy consumption and ultimately increased the cost of iron ore production. This thesis sought to identify the energy efficiencies of open-cut iron ore mining operations, in terms of scale of operation as well as within individual mining processes, so that energy consumption could be reduced, and sustainability enhanced.

Efficiency indices were used to determine energy efficiency across different scales of operation. Overall energy consumption (per unit of processed ore) was directly related to the scale of operation, where large-scale mining operations are more energy efficient compared to medium and small scales requiring the lowest amount of energy to process a unit of ore. This suggests that an economy of scale based on energy efficiency can be observed in iron ore mining operations. Small-scale mining operations recorded the highest energy consumption to process a unit of ore, indicating the lowest energy efficiency among the three different scales of operation. However, the composite energy indicator indicated that the energy efficiency of a particular mining operation is also influenced by the geological and physical parameters of individual factors including the waste-ore ratio, grade of ore, average haulage distance and production capacity. The results of the regression analysis confirmed that it is the combined effect of all the aforementioned parameters that has a pronounced effect on the amount of energy consumed to process a unit of ore.

Energy consumption per unit of processed ore at different process stages revealed that the loading and hauling phase is the most energy intensive process stage in an iron ore mining operation regardless of the scale at which it is operating. The milling and stockpiling phase was the second highest energy consuming process stage, while the drilling and blasting phase was the subsequent energy demanding process stage in iron ore mining operations. Small-scale operations recorded a higher energy consumption in loading and hauling than the medium-scale operations, suggesting that the equipment with high load capacities and energy efficient technologies such as overland conveyor belts, and advanced technologies including

autonomous haulage trucks resulted lower energy consumption in medium scale mining operations. However, the energy consumed to mill and stockpile a unit of ore in medium-scale operations was high compared to the small-scale operations, suggesting that the energy consumption in milling and stockpiling is mainly influenced by the properties of the mill feed, such as moisture content. Further, the amount of processing needed to achieve sufficient final product quality can also influence energy consumption.

Findings from this study support the idea that an economy of scale can be observed across iron ore mining operations in Western Australia based on energy efficiency. The study also provided essential baseline information for future studies on the variations in energy efficiency across different iron ore mining operational scales in Western Australia.

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Chapter 1- General Introduction

1.1 Industry and Global Warming

The continued increase in concentrations of greenhouse gases (GHG) in the atmosphere is predicted to lead to significant changes in the global environment (Hughes, 2000; Cox, Betts, Jones, Spall and Totterdell, 2000). Of particular concern are four long-lived GHGs: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and halocarbons (CFCs, HCFCs), where CO_2 makes up 85% of the total global greenhouse gas emissions (Solomon et al., 2007). Owing to the heat-trapping nature of these gases, increased concentrations warm the earth and its atmosphere (Solomon et al., 2007), and these changes in the global temperatures have resulted in extreme weather events (Rosenzweig, Iglesias, Yang, Epstein, & Chivian, 2001; Schiermeier, 2011), sea level rises and coastal flooding (Wigley, & Raper, 1987; Meehl, Washington, Collins, Arblaster, Hu, Buja, Strand, & Teng, 2005; Raper & Braithwaite, 2006; Rahmstorf, 2007; Rahmstorf, 2010), longer wildfire seasons (Westerling, Hidalgo, Cayan & Swetnam, 2006; Giannakopoulos, Le Sager, Bindi, Moriondo, Kostopoulou, & Goodess, 2009), more frequent and intense heat waves (Rosenzweig, Iglesias, Yang, Epstein & Chivian, 2001), forest death (Jepsen, Hagen, Ims, & Yoccoz, 2008), pressure on groundwater resources (Kirshen, 2002), disruption to food supply (Rosenzweig & Parry, 1994; Parry, Rosenzweig, & Livermore, 2005; Memmott, Craze, Waser, & Price, 2007; Schmidhuber, & Tubiello, 2007), destruction of coral reefs (Glynn, 1991; Atwood, Hendee, & Mendez,1992; Hughes et al., 2003; Pandolfi, Connolly, Marshall & Cohen, 2011), changes in seasons (Solomon et al., 2007) and an increase in adverse health impacts (Martens, Jetten, & Focks, 1997; Kunkel, Pielke Jr, & Changnon, 1999; McMichael, Friel, Nyong, & Corvalan, 2008). These changes would be irreversible in the course of a human life-span and have serious consequences on all aspects of human life, including food, health, and habitat. Therefore, urgent action is needed to reduce the rapidly increasing global GHG emissions (International Energy Agency, 2014; IPCC, 2007 cited by Pellegrino and Lodhia, 2012).

Emissions of GHGs, mainly CO_2, arise from a number of sources, including fossil- fuel combustion in power generation, industrial, residential and transport sectors (Solomon et al., 2007), fossil fuels have been the main source of energy for the rapidly growing human population and their high rates of resource consumption (Vitousek, 1994). Among the many human activities that result in CO_2 emissions, the industrial sector is a key CO_2 emitting source (Figure 1.1) (Worrell, Bernstein, Roy, Price & Harnisch, 2009). Industry is responsible for

about 38% of the global carbon dioxide emissions, of which over 80% is a consequence of energy use (Worrell et al., 2009; International Energy Agency, 2014).
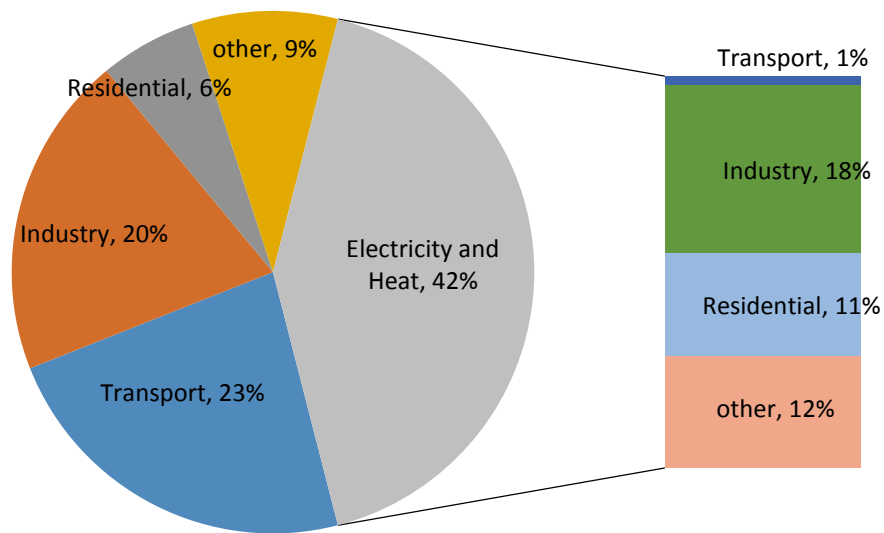
Figure 1.1: Global Carbon dioxide emissions by sector, 2012 (International Energy Agency, 2014)

Since the Industrial Revolution, atmospheric CO_2 concentration has risen exponentially, mainly due to demand-driven growth of the energy-intensive industries; including iron-ore mining, steel production, petroleum refining, chemical production (including fertilizers), mineral production (cement, glass, ceramics), pulp and paper production and non-ferrous metal production (Norgate & Rankin, 2002; Worrell et al., 2009; EIA, 2010; Norgate & Haque, 2010). Of particular concern is the fact that all of these industries rely on utilisation of natural resources (Durucan, Korre, and Munoz-Melendez, 2004), and also consume intensive amounts of fossil fuel to extract and process the resources (Dasgupta and Roy, 2000; Sinton and Fridley, 2000; International Energy Agency, 2007, 2008, 2014). These changes in industrial activity have led to increased concentrations of CO_2 in the atmosphere; wherein in 2013 the atmospheric CO_2 concentration (396 ppmv) was about 40% higher than the pre-industrial level (280 ppmv), with an average increase of 2 ppmv/year over the last ten years (IPCC, 2007).

Global demand for commodities from energy-intensive industries has risen continuously, and demand for primary metals and minerals has increased significantly since they are essential components of numerous products (IIED, 2002). Thus, the mining and mineral processing industry expanded globally, such that the resource consumption of the global mining industry has risen to 4-7% of global energy use (IIED, 2002). Consequently, the global mining and mineral processing sector is under pressure to reduce energy use so as to reduce mining costs, with the added benefit of a reduction in CO_2 emissions (Norgate and Haque, 2010). This pressure is mainly on countries with mineral-based economies, including the United States of America, Australia, Canada, Russia, Brazil, South Africa, China and the European Union, who are recognized as the principal global mineral producers (Azapagic, 2004). Despite the pressure to reduce CO_2 emissions, a rapid increase in commodity prices and the growing global demand encouraged the carbon-intensive economies, such as that of Australia, to expand mining operations. The resource-driven economies of countries like Australia are heavily dependent on the mining industry and export significant quantities of raw and semi-processed minerals and metals (Allardice and Young, 2000; Crowley, 2007).

1.2 Australian Mining and Mineral Processing Industry

Australia is one of the world's leading mining nations, with substantial resources of primary metals and major non-metallic minerals including iron ore, coal, bauxite, copper, gold, crude petroleum and natural gas (ABS, 2012). Australia is ranked in the top five producers and exporters worldwide (Energy Efficiency Opportunities, 2014; USGS, 2014; Connolly and Orsmond, 2011), and is one of the world's principal producers of iron ore, bauxite, ilmenite, rutile, and zircon; it is the second-largest producer of alumina, gold, lead, manganese ore, lithium and zinc; the third-largest producer of uranium; the fourth-largest producer of nickel, black coal and silver, and the fifth-largest producer of aluminium, copper and cobalt (Geoscience Australia and Bureau of Resources and Energy Economics, 2013).

Among the many Australian-produced mineral commodities, the iron-ore mining industry is the largest contributor (41%) to the total mining production of Australia, followed by coal mining and oil and gas extraction (both 26%), (ABS, 2012). Thus, minerals and fossil fuels play a vital role in Australia's economic success, especially iron ore and coal, where these two minerals represent more than half of Australia's export earnings (ABARE, 2009; Mineral Council Australia, 2014).

1.2.1 Australian Iron Ore Mining Industry

Australia has the world's largest iron ore reserves with 25% of known global reserves. Other significant reserves are found in Brazil (19%), Russia (14%), and China (13%) (Geoscience Australia, 2014a). Most of the identified iron ore resources occur in Western Australia (WA) (91%), of which 80% is in the Hamersley province (Geoscience Australia, 2014b). A few large economically viable deposits occur in South Australia, but they only account for 8% of the identified iron ore resources. Other small iron ore mines are found in Tasmania, New South Wales and the Northern Territory (Geoscience Australia and Bureau of Resources and Energy Economics, 2013) But they are insignificant (<1%) when compared to WA which produces (by volume) 30% of the world's output of iron ore (DMP, 2014a; Geoscience Australia, 2014b).

Iron ore reserves and resources in Australia are found as hematite and magnetite ores (Geoscience Australia, 2014b), where pure hematite contains 69.9% Fe, while magnetite ores contain 72.4% Fe (Geoscience Australia and Bureau of Resources and Energy Economics, 2013). However, the high incidence of impurities in magnetite ore make it expensive to produce since secondary processing stages are required which are very costly (Geoscience Australia and Bureau of Resources and Energy Economics, 2013). Hematite ores found in WA are rich in iron, and only need simple processing stages before the ore concentrate is ready for shipping to the plants around the world (Geoscience Australia and Bureau of Resources and Energy Economics, 2013). This type of ore is called direct shipping ore (DSO), since the mined ore only needs crushing and grinding before being exported (Geoscience Australia and Bureau of Resources and Energy Economics, 2013). Until the mid-1960s, iron ore production in WA was negligible with production of less than 10 million tons a year (DMP, 2013). However, once the profitability of the business became apparent due to these high-grade direct-shipping ores, the Australian iron ore industry became attractive to investors, and many new iron ore projects were initiated. Today WA produces 697 million tonnes, which is an approximately 700-fold increase on 1960s production volumes (Figure 1.2).
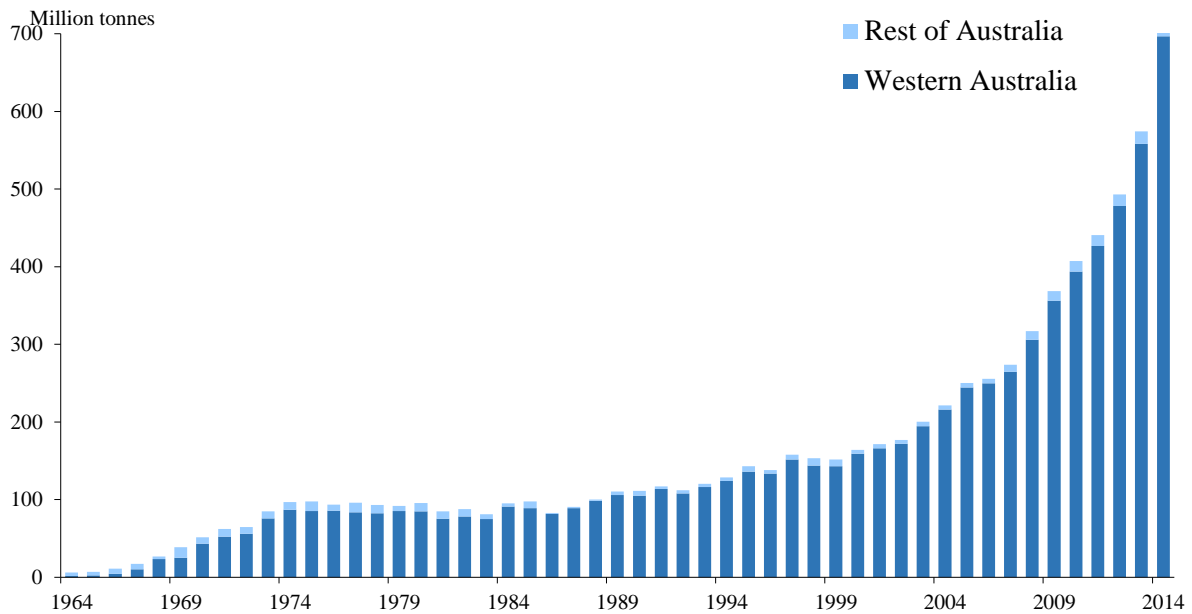
Figure 1.2: Iron ore production volumes of Western Australian and from rest of Australia from 1964 to 2014 (Source: Department of Mines and Petroleum, Western Australia. 2014)

Iron ore mining operations consist of three major operational stages, namely; extraction, beneficiation and processing of iron ore (US EPA, 1994), with each of these stages consisting of various process steps. The extraction of iron ore in WA generally involves surface/open-cut methods since underground/shaft mining is more energy-intensive because of extra process stages, such as ventilation, water pumping and other operational requirements (Norgate and Haque, 2010). In WA, the location of the ore, the size of the deposits, ore depths, and grades of ore are all suitable for surface mining methods (Yellishetty, Ranjith and Tharumarajah, 2010).

In open-cut mining operations, the ore is extracted after blasting agents placed in drilled cylindrical holes have been detonated. Drills for making the blasting holes are primarily operated by electricity and diesel, and different types of drills are used, including rotary drills and percussion drills, depending on the tasks that they have to perform (Kennedy, 1990; Norgate and Haque, 2010). Rotary drills are often used to drill and break the rock, whereas the percussion drills use a ploughing-scraping method in soft rocks, while a crushing-chipping method is used for hard rocks (Kennedy, 1990). However, depending on the hardness of the rocks, a combination of these drilling methods is employed. The production drilling of the percussion drills is limited to small mines, and in some instances these percussion drills are also used in secondary drilling and development work (Kennedy, 1990). After blasting, the fragmented ore is excavated using loaders, shovels or excavators then loaded into haul trucks for transport to the processing plant (Norgate and Haque, 2010). Most of the equipment used

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in haulage is powered by high energy-intensive diesel engines (USDE, 2007; Norgate and Haque, 2010). The fragmented ore is reduced to fine particles during the crushing and grinding processes, where efficiency is influenced by the drilling and blasting processes which are normally employed prior to the crushing and grinding (Norgate and Haque, 2010). The crushing and grinding plants are usually powered by electric motors, with the electricity often generated on-site using a diesel-fuel-based engine and generators (Norgate and Haque, 2010). The ground material then undergoes a screening process, where unwanted materials are separated from the ore which is then stacked prior to loading and transportation to dedicated ports for shipping to steel plants around the world (Norgate and Haque, 2010).

1.3 Global Demand and Australian Iron Ore Production

Since the Industrial Revolution, the use of steel has increased enormously, so that today steel is an essential component of most of all aspects of our day-to-day life. The wide use of steel has led to a massive worldwide demand for the production of iron ore (Yellishetty et.al, 2010). Over the past two decades, but mainly in the early years of the 2000s decade, the Australian iron ore mining industry, particularly in Western Australia, experienced a significant growth in its production as a result of the upturn in the global iron ore prices and significant increases in demand as a response to the rise of China's and other developing nations' requirement for steel and energy (Connolly and Orsmond, 2011; DMP, 2014a). In addition, low production costs, relatively low international shipping expenditure (Prior et.al, 2013), government policies, such as property rights related to native title, tax incentives and self-regulatory approaches towards environmental regulations (Goodman, 2008) attracted many investors to the Australian iron ore mining industry. As a result, in Australia, that industry grew with many new iron ore mining and mineral processing projects started, which ranged many-fold in terms of the scale of the operations. As a result, Australian resource exports increased by more than 300% from 2003 to 2011, due to rising commodity prices (Connolly and Orsmond, 2011). Consequently, the rate of iron ore production was significantly increased, while higher-grade reserves were progressively depleted, and the mined ore grades were gradually lessened.

The Western Australian resource boom of the first decade of the 21st century encouraged mining companies to develop projects based on marginal grade deposits and complex new deposits, all of which can be extracted profitably provided that the commodity prices remain high (Connolly and Orsmond, 2011; Norgate and Jahanshashi, 2011; Prior et. al, 2013). Many mining

companies also undertook capacity expansions in operating mines, thereby increasing the operational scale so that they could supply enough iron ore to meet demand (Crowson, 2003; Goodman, 2008). Because of the high energy-intensive nature of mining (Raab and Steinnes, 1993; Asafu-Adjaye and Mahadevan, 2003; Crowson, 2003; Crompton and Lesourd, 2008), extraction of low grade ore leads to many environmental and economic impacts, including increased amounts of mine wastes, increased energy and water consumption, and higher emissions of air pollutants (Prior et. al, 2013). With the increased use of lower grade ores, more ore needs to be mined and milled to produce the same amount of processed ore required for export. This results in the consumption of additional energy which is used to move and treat the additional gauge material (Norgate and Rankin, 2002; Norgate and Jahanshashi, 2006; Mudd, 2007; Sandy and Syed, 2008; Norgate and Haque, 2010). In parallel with the increased use of lower grade ores, many of the newly developed mines require significant amounts of energy since many of them are based on exploiting finer-grained ores that require more crushing and grinding to separate waste material (Norgate and Haque, 2009). Thus, iron ore mining and mineral processing operations were faced with additional processing requirements, which ultimately increased the cost of mineral processing, along with increased environmental and social costs (Prior et. al, 2013).

1.4 Global Commodity Price and Its Effect on Australian Iron Ore Mining Industry

The large investment in the iron ore mining industry over the last decade has boosted the national economy, and iron ore exports were the largest export earner in the Australian economy (ABARE, 2009; MCA, 2014). The rapid urbanization and industrialization of emerging Asian economies transformed global commodity demand which resulted in price increases in key steel-making commodities such as iron ore; without the enlargement of the Australian iron ore mining industry, the supply of iron ore might not have kept pace with demand (Connolly and Orsmond, 2011). Therefore, as explained in section 1.3, iron ore companies started to produce more iron ore to meet the global demand through extracting more marginal-grade deposits while expending a higher cost per unit on ore production. However, a global economic crisis began in 2007, which resulted in a depression in global commodity prices. Today the iron ore price (AUD) is 42% lower than that of the value it was as recently

as 2013 (DMP, 2014a). Thus, the value of the Australian iron ore industry has suffered as a consequence of the reduction in iron ore prices (Prior et. al., 2013).
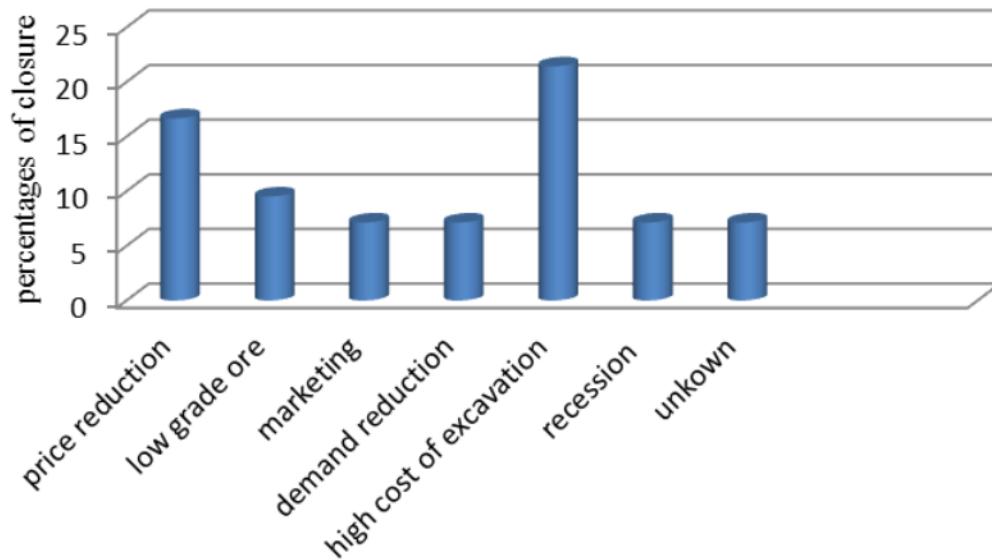
Figure 1.3: Major factors that cause economic uncertainty in mining operations (Source: Mobtaker and Osanloo, 2013)

Research has shown that 59% of the worldwide iron ore mine closures over the last century were premature, due to various reasons, including economic uncertainty, followed by geotechnical issues and other technical reasons (Mobtaker and Osanloo, 2013). These studies have also shown that the smaller mines are the most susceptible to become 'go bust' business when the ore prices fall (Crowson, 2003; Mobtaker and Osanloo, 2013). However, economic uncertainty of a mine is not only a consequence of ore prices but may involve other factors such as high costs of extraction, declining grades of ore and demand reduction (Figure 1.3) (Mobtaker and Osanloo, 2013). Among these factors, the high cost of extraction has been identified as the most influential reason (Figure 1.3) (Mobtaker and Osanloo, 2013). Research has shown the importance of identifying the economies of scale that exist in the iron ore mining industry (Raab and Steinnes, 1993; Truett and Truett, 1997; Asafu-Adjaye and Mahadevan, 2003; Crowson, 2003; Crompton and Lesourd, 2008). The scale of mining in relation to energy efficiency is critical, since energy accounts for up to 60% of the operating costs involved in the extraction of the ore (International Energy Agency, 2007). Therefore, knowing that the iron ore mining industry is an energy-intensive industry, identifying energy efficiency in the operations should be a key concern so as to reduce energy consumption, thereby ensuring the profitability of the operations.

1.5 Energy Efficiency for Sustainable Mining

Mining and mineral processing companies are currently experiencing tough economic challenges and urgently need to upgrade energy efficiency to maintain the profitability of their operations. Existing operations are faced with two main options, which are: to improve the energy efficiency of current operations; or to replace parts of the current processes with more energy-efficient technologies (Brooks and Subagyo, 2002). However, due to significant capital investment, the second option is unattractive (Brooks and Subagyo, 2002) especially when research can show where reducing energy use of the current processes can be obtained for little or no additional cost to the company. Therefore, while investments in new technology might be a long-term solution, more efficient energy use results in the highest economic benefits in the short run (Brooks and Subagyo, 2002; Irrek and Thomas, 2006 cited in Bunse et. al, 2011).

Economic Aspects:

Energy Costs
Resource Productivity
Resource Cost
Risk of Future Liability Cost
Cost Internalization (eg:
Emission Trading Systems)

Social Aspects:

Energy Awareness (Customers
and Workforce)
Ensure resource and Energy
security for future generation
Image in Society
Interaction with company and
political stakeholders

**Energy efficiency
in Sustainable
Mining**

Environmental Aspects:

CO2 Emissions
Other Emissions
Resource Scarcity (eg:
Fossil Fuel)

Figure 1.4: Central contribution of energy efficiency to triple bottom line outcomes in a sustainable mining operation (modified from Bunse et.al, 2011).

A study carried out by the United States Department of Energy showed that using best practices alone has the potential to reduce energy use by up to 27% (US Department of Energy, 2007). Therefore, it is apparent that the drivers of energy-use in mining and mineral processing operations should be identified, in order to find areas of improved energy efficiencies and for the setting of realistic and achievable reduction targets (Sterling, 2010). Reduced energy use is

not only beneficial economically, but it also has environmental and social benefits, with these benefits often referred to as the "triple bottom line" (Figure 1.4) (Kannan and Boie, 2003; Christoffersen, Larsen and Togeby, 2006; Laurence, 2011). For many companies, to meet their stated triple bottom line targets requires the identification of the major energy-consuming steps in their processes, be they manufacturing or resource extraction.

This study examines energy-use efficiency and carbon dioxide emissions across different scales of iron-ore mining operations in Western Australia. The study is divided into two stages, which include: i) an analysis of scales of mining operations to determine the most efficient scale of iron-ore production in Western Australia based on the patterns of energy consumption, and ii) an analysis of process stages in iron-ore mining operations to identify patterns of energy consumption and carbon dioxide emissions from each process stage. Knowing the location and the magnitude of the energy-intensive process stages allows for the identification of areas for possible energy-efficiency improvements, which will enhance the sustainability of iron ore mining operations in an economically challenging market.

1.6 Aims

Main Aim

The overall aim of this thesis is to calculate the energy efficiency and CO_2 emissions across different scales of operations in iron-ore mining in Western Australia so as to determine what influence the scale of operation has on the amount of energy consumed and carbon dioxide emissions produced per unit of ore produced.

The study was undertaken across three scales of operations based on production capacity, and calculated the energy efficiency and related carbon emissions of mining operations from eight mines.

Specific Aims

- To calculate the energy efficiency of all process stages at different scales of operations in iron-ore mining in Western Australia

- To calculate the related carbon dioxide emissions of all process stages at different scales of operations in iron-ore mining in Western Australia

- To compare the similarities and differences in the process stages in iron-ore mining operations at different scales

- To identify the most efficient scale of iron-ore mining in Western Australia based on energy efficiency

Chapter 2- Methodology

This study calculated energy efficiency and carbon dioxide emissions from iron ore mining operations in Western Australia. It was undertaken in two stages; an analysis of different scales of iron ore mining operations (Broad Scale) and a detail analysis of iron ore mining operation process stages (Fine Scale). The first stage involved a broad scale analysis, which identified the differences in energy efficiencies in various scales of operations. This stage of the study was carried out across three different-sized mines, which were classified based on the production capacity data from thirty-four currently operating iron ore mines in Western Australia.

The second stage involved a fine scale analysis, which was undertaken to calculate the energy efficiency and carbon emissions from each step in the mining process from drilling and blasting to the delivery of ore to the ports for shipping. This second stage of the study was conducted on data sourced from six iron ore mines operating in the Pilbara and Midwest regions of Western Australia. The mines ranged in size, based on production capacity from 3 to 60 million tons per annum. All data used in the analyses were from the 2014 financial year.

2.1 Iron Ore Composition in Western Australia

Iron ore is one of the most abundant minerals in the Earth's crust with more than 300 mineral formations (US EPA, 1994). However, only five formations are used as the primary sources of iron ore, these include magnetite (Fe_3CO_4), hematite (Fe_2O_3), goethite ($Fe_2O_3H_2O$), siderite ($FeCO_3$) and pyrite (FeS_2). The first three are the most important since they occur in large economically viable deposits (US EPA, 1994) with iron contents of at least $25 - 30\%$ which is the minimum required to make it economically viable to extract (US DOE, 2002; Yellishetty et.al, 2010; Yellishetty et.al, 2012). Western Australia is endowed with high grade iron ore, some of which have more than 60% iron content (Yellishetty et. al, 2012) and is comprised of major iron ore bearing minerals where several groups of ore can be identified according to the composition of the minerals, including Banded Iron Formation (BIF), Channel Iron Deposits (CID) and Detrital Iron Deposits (DID) (O'Brien, 2009; Yellishetty et.al, 2012). These iron ore groups can be classified into several ore types as following (based on Ramanaidou, 2009; Silva et al., 2002; Ramanaidou et al., 1996; Harmsworth et al., 1990; Morris and Fletcher, 1987; Morris, 1983, 1985, 2002; and Morris et al., 1980; cited by Yellishetty et.al, 2012) which are shown in Table 2.1 and their distribution in WA is illustrated in Figure 2.3. The geology and mineralogy of these major ore types is explained in detail below.

Table 2.1: Generic Ore Groups and Ore Types in Hamersley Province, Australia

Generic Ore Group	Generic Ore Type	Dominant Mineralogy
Banded Iron Formation (BIF) – derived iron deposits (BID)	Low Phosphorus Brockman (LPB)	Hematite – (goethite)
	High Phosphorus Brockman (HPB)	Hematite – goethite
	Marra Mamba (MM)	Hematite – goethite
Channel Iron Deposits	CID (Pisolite)	Goethite- hematite
Detrital Iron Deposits	DID (Detrital)	Hematite – (goethite)

2.1.1 Banded Iron Formations

Premium Brockman Ore (Low Phosphorous Brockman)

The Premium Brockman Ores contain high grade, low phosphorus, hard, microplaty hematitic ore (O'Brien, 2009). At present, there are only two deposits, Mount Whaleback and Mount Tom Price, which produce Premium Brockman ore (O'Brien, 2009). Typical composition of this ore is about 65% Fe, 0.05% P, 4.3% SiO_2 and 1.7% Al_2O_3 (O'Brien, 2009).

Brockman (High Phosphorous Brockman)

Brockman Ores contain high phosphorus and have a significant amount of goethite (O'Brien, 2009). They are not as hard as Premium Brockman Ores although they are quite similar (O'Brien, 2009). Mines such as Channar, Paraburdoo and Jimblebar produce significant amount of Brockman ore that have a composition of 63% Fe, 0.10% P, 3.4% SiO_2, 2.4% Al_2O_3 and 4.0% Loss on Ignition (LOI) (O'Brien, 2009).

Other hematite

Other hematite ores have a range of geological compositions and the only similarity they have is that the primary mineralogy is hematite (O'Brien, 2009). These types of ore are common in the Middleback Range and the Goldsworthy region (O'Brien, 2009). The composition of these ores vary from Pardoo where it contains 57% Fe, 0.09% P, 7.01 SiO_2, 2.4% Al_2O_3 and 4.0% LOI to Koolan Island, which contains 64% Fe, 0.02% P, 6.1% SiO_2, 1.0% Al_2O_3 and 0.5% LOI (O'Brien, 2009).

Marra Mamba

Marra Mamba iron ore is a hematite and goethite mix and occurs in the Marra Mamba Iron Formation in the Pilbara (O'Brien, 2009). Typically, it contains about 62% Fe, 0.06% P, 3.0% SiO_2, 1.5% Al_2O_3, and 5.0% LOI and is brown in colour due to goethite content. Nammuldi, West Angelas, Mining Area C, Marandoo, Hope Downs, Cloud Break and Christmas Creek are the major deposits containing Marra Mamba ore (O'Brien, 2009).

2.1.2 Channel Iron Deposits (CID)

CIDs are found in ancient paleochannels and are composed of concretionary iron oxides of hematite and hematite-goethite (Hall et al. 1990; cited by O'Brien, 2009). CDI is brown-yellow in colour containing 58% Fe, 0.05% P, 4.8% SiO_2, 1.4% Al_2O_3 and 10.0% LOI, and can be found in Yandicoogina and Robe River deposits (O'Brien, 2009; Yellishetty et.al, 2012).

2.1.3 Detrial Iron Deposits (DID)

DIDs are formed from weathered bedded iron formations and deposited as ore fragments in natural traps such as valleys (Yellishetty et.al, 2012). The quality of the iron ore of DID is dependent on the composition of the bedded iron ore deposits which are the source of the ore particles (Yellishetty et.al, 2012).
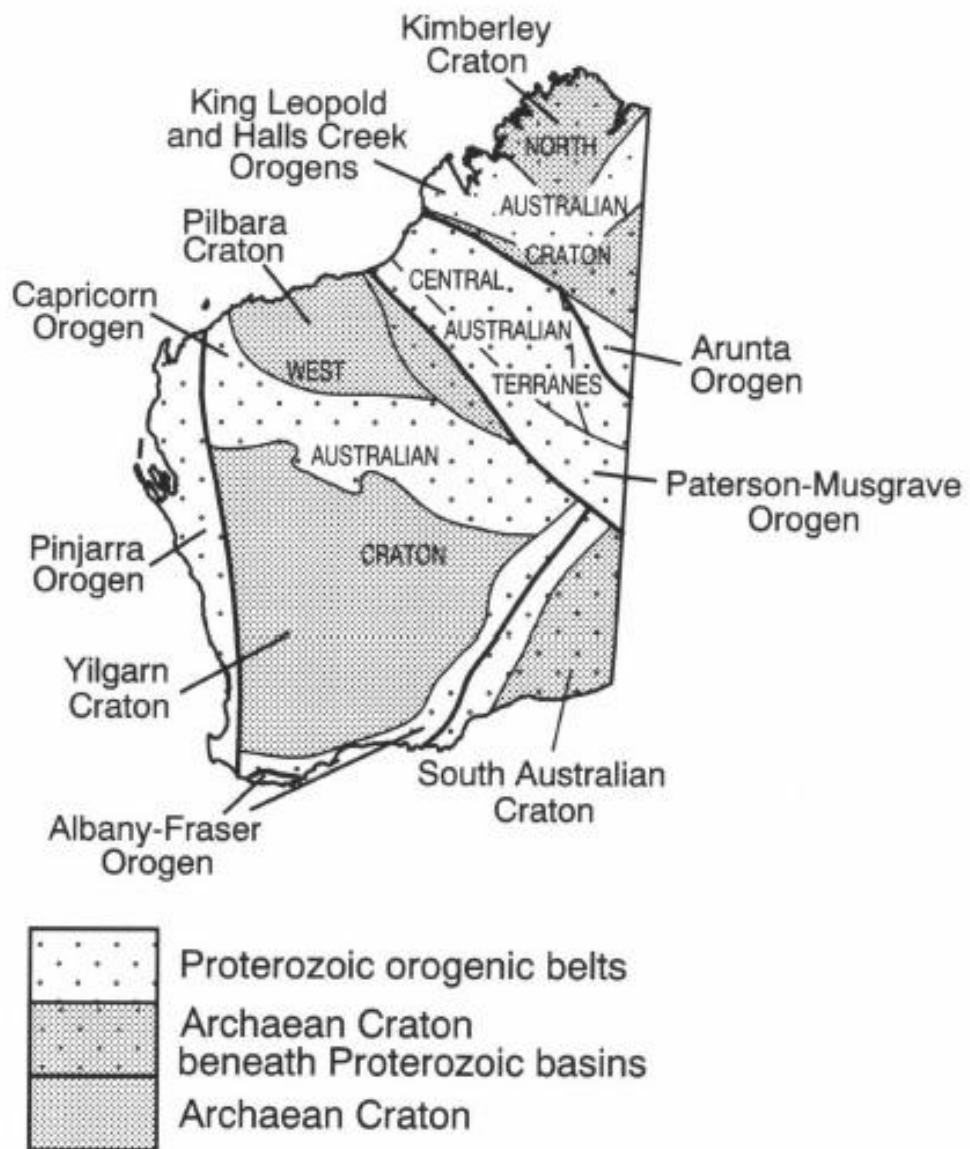
Figure 2.1: The major components of Western Australian craton recorded in Tyler et.al, 1998
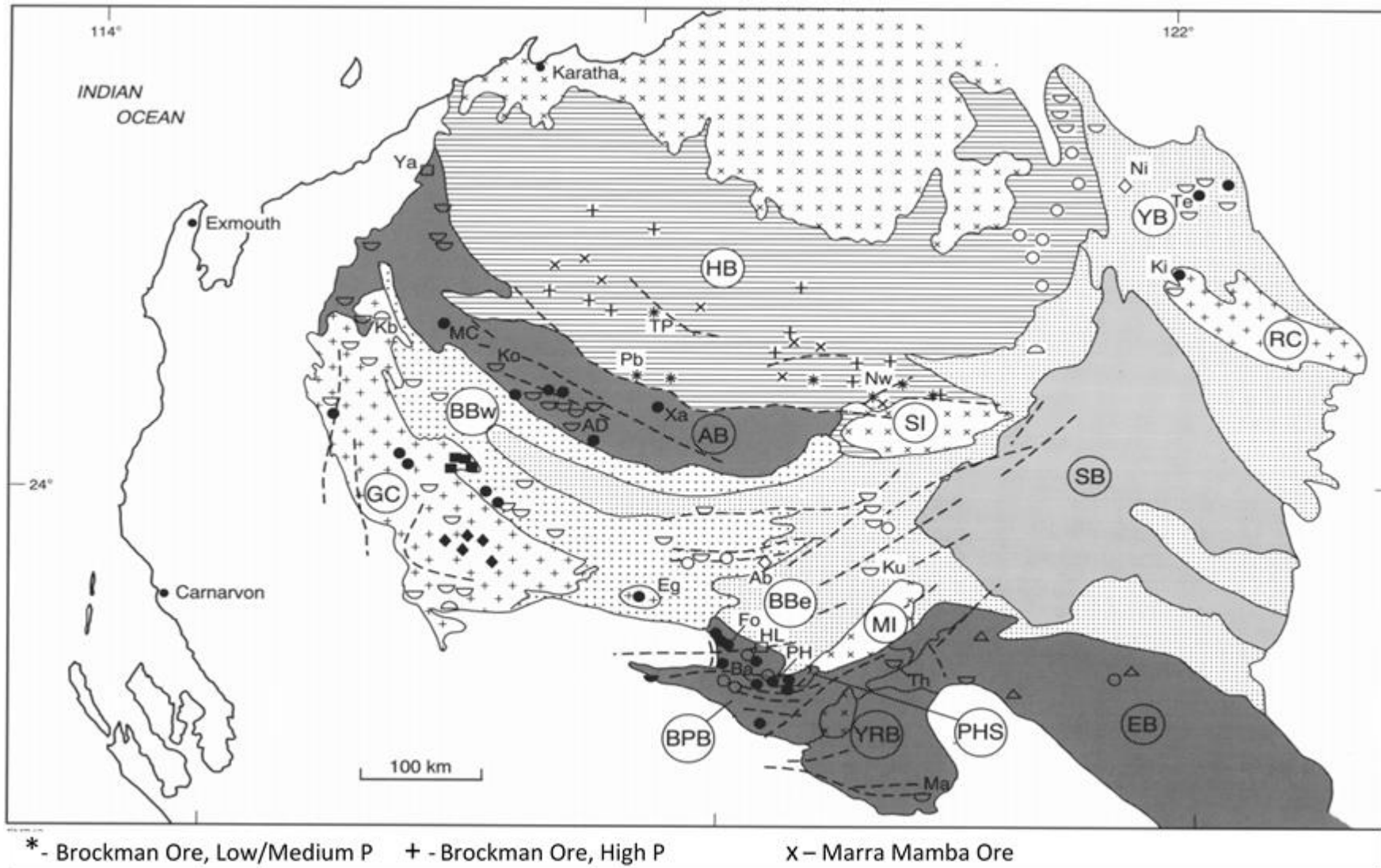
Figure 2.2: Metallogenic map of Proterozoic tectonic units between the Pilbara and Yilgarn Cratons (Tyler et al., 1998)

2.2 Study Area

Western Australia contains the largest share of Australia's iron ore deposits making up 89% of the total, with the majority of the resource found in the Pilbara district of the Hamersley province (Geoscience Australia, 2014b; 2014c). The Pilbara region covers an area of 507,896 km^2 from the north-west coastline of Western Australia to the border of the Northern Territory and it has three distinctive geographical formations; a vast coastal plain, inland ranges and an arid region (Bastin, 2008). The Pilbara Craton (Figure 2.1) found in the area is geologically one of the oldest regions in Australia, and hosts precious and base metal mineral deposits, and is overlaid by iron ore bearing sedimentary rocks (Western Australian Planning Commission (WAPC), 2013; Geoscience Australia, 2014b). Most of the iron ore deposits in the Pilbara consist of high grade ore with an average of 60% Fe due its BIF enrichments (Geoscience Australia, 2014b). The climate is arid to tropical, characterized by high temperatures and high evaporation where $40^{o}C$ plus days are frequent in summer with extreme conditions above $50^{o}C$ experienced in inland areas. Average temperatures in winter are more moderate at $25^{o}C$ (Regional Development Australia (RDA), 2010). Rainfall across the region is low and is highly variable due to occasional cyclones with a median rainfall (for the years 1890 – 2005) of 298mm, most of which falls from April to March (Department of Environment, 2008; Regional Development Australia, 2010).

The Midwest region lies south of the Pilbara region and is approximately one fifth of the land area of WA comprising some 468,712 km^2. It extends along the west coast from Green Head to Kalbarri and over 800km inland to Wiluna in the Gibson Desert (Midwest Development Commission (MDC), 2013a). The Yilgarn Craton (Figure 2.1), characteristic of the region, is one of the largest masses of Archean crust on Earth and it contains many different mineral deposits including gold, nickel, iron ore, bauxite, tantalum and uranium (Monroe, 2013). The Coastal area of the Midwest region experiences a Mediterranean climate with an average temperature of $30^{o}C$, while the inland areas are more arid with average temperatures of $38^{o}C$ (Midwest Development Commission, 2013b). The average annual rainfall in the coastal area of the Midwest is 400-500mm, while the inland area is more variable and has an annual average of less than 250mm (Mid-west Development Commission, 2013b).
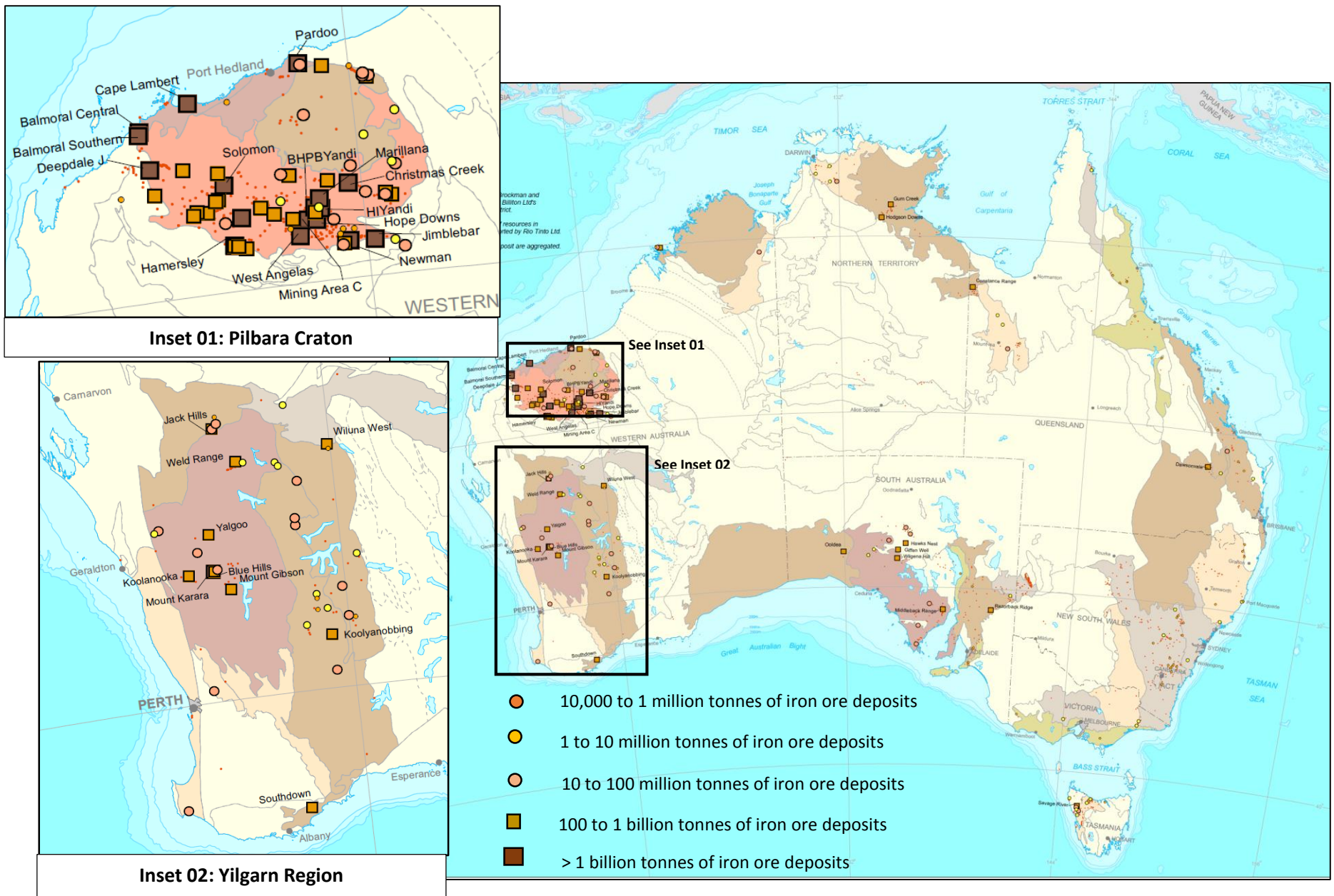
Figure 2.3: Australian iron ore resource map with currently operating iron ore mines as recorded on the Australian Iron Ore Resource Map, 2010 (Geoscience Australia, 2014a)

2.3 Selection and Classification of Mines into Different Scales

The selection and the classification of the mines into different scales required data collection from various sources. Although the mining industry consists of a range of operational scales, there are no defined criteria to categorize Australian iron ore mining operations into different scales. To define the scale of operations for this study, a list of currently operating mines was obtained from the Department of Mines and Petroleum, Western Australia website (DMP, 2014b), of which a total of thirty-eight operating mines were recorded. The production capacity information of thirty-four mines out of the total operating mines was obtained from company websites and annual reports, in order to categorize the mines into different scales of operation. Based on production volumes, the mines were classified as small, medium and large scale operations. Large-scale operations were mines which produced > 50 Mt per annum, medium-scale mines were those with production volumes of 25 - 50 Mt per annum, and small-scale mines were those which produced < 25 Mt per annum (Table 2.2).

A total of 59% of these iron ore mines were classified as small-scale mines, while 21% were medium-scale mining operations and 20% of mines were categorized as large-scale mines. Twenty-seven of the thirty eight mines are operated by just three major iron ore mining companies including almost all of the large-scale; medium scale mines are operated by other much smaller companies. A letter was sent to all identified mining companies, providing background information on the study and requesting their participation in the study. From the five companies who operate three or more iron ore mines in WA, two companies expressed their willingness to participate in this study.

Table 2.2: Iron ore mines currently operating in Western Australia, classified by the scale of operation

Small Scale Mines (<25 Mt a^{-1})		Medium Scale Mines (25 - 50 Mt a^{-1})	Large Scale Mines (>50 Mt a^{-1})
Abydos	Mt. Webber	Area C	Newman
Brockman 2	Nammuldi	Cloudbreak	Yandi
Brockman 4	Nullagine Mine	Kings Valley	Jimblebar
Extension Hill	Paraburdoo	Karra Project	Wheelara
Firetail	Pardoo	Mesa A	Christmas Creek
Hopes Down 4	Ridges Iron Ore Project	West Angelas	Yandicoogina
Koolan Island	Tallering Peak	Tom Price	
Marandoo	Weld Range	Hopes Down	
Mesa J	Wodgina		
Mt. Dove	Yarrie		

However, due to commercial-in-confidence considerations, an agreement was entered into with the companies to maintain their anonymity and individual mines are not identified in the study. Six mines from the two companies were considered in order to carry out the detailed analysis of the process stages to perform the energy efficiency and carbon dioxide emissions calculations; of which, three were small-scale and the other three medium-scale mines. Small-scale mines were identified as Mine A, B and C, and medium-scale mines were named as Mine D, E and F. To perform the analysis across the different scales of operation, data from two large-scale mines, Mines G and H, were obtained from publicly available literature.

2.4 Identifying Major Iron Ore Mining and Mineral Processing Stages

Iron ore mining and mineral processing operations consist of two major operations, which are extraction and beneficiation stages (US EPA, 1994). Extraction is the removal of ore from the deposit and includes all other process stages prior to beneficiation (US EPA, 1994). Beneficiation is the process of concentrating the ore by removing the gangue material (US EPA, 1994; US Department of Energy, 2002). Concentrated iron ore is then shipped to steel makers around the world, with many located in Asia and Europe (Yellishetty et.al, 2010), for processing into iron or steel using pyro-metallurgical techniques (U.S. Department of the Interior, Bureau of Mines 1968; United States Steel 1973 cited by US EPA, 1994). Beneficiation is required since many iron ore processing technologies have specific requirements, such as the size of the ore pellets and chemical composition, to obtain suitable concentrate (Weiss, 1985 cited by US EPA, 1994). The two main stages consist of a number of process stages which are shown in Figure 2.4 and discussed below.

2.4.1 Extraction

Extraction of iron ore involves two basic methods, these are surface or open-cut mining; which the most common method worldwide, and underground or shaft mining with one operating mine (Figure 2.4) (US EPA 1994; US DOE, 2002; Norgate and Haque, 2010; Yellishetty et.al, 2010). The latter is more energy-intensive, due to hauling, ventilation, water pumping and other operations (Norgate and haque, 2010). The mining method selected is dependent on the proximity of the ore to the surface (U.S. DOI, Bureau of Mines 1983 cited by US EPA 1994). Surface mining is used to expose the ore deposits, which lie close to the surface, by removing the overburden, whereas deep iron ore deposits are extracted using underground mining. This involves a shaft dug from the surface to transport people, machinery and ore (US EPA 1994; US DOE, 2002). Surface mining methods are the predominant methods used to extract iron ore in Australia and around the world (US EPA 1994; US DOE, 2002; Norgate and Haque, 2010; Yellishetty et.al, 2010), and all mines used in this study use the open-cut mining method. During the extraction operation in open-cut mining, a number of mining and mineral processing stages, such as drilling, blasting and hauling, are undertaken prior to beneficiation (Figure 2.4) (US EPA 1994; US DOE, 2002; Norgate and Haque, 2010; Yellishetty et.al, 2010).

Drilling

Drilling operations are conducted using mechanized drills such as diamond drills, rotary drills and percussion drills, which are specific for each drilling method, to generate a hole with an appropriate depth, diameter and direction in the ore deposit for explosives to be placed for blasting preparation (US EPA 1994; Norgate and Haque, 2010). Diesel fuel, electricity and to a lesser extent, compressed air, are used to run the drills to perform tasks such as rotation and hammering (Norgate and Haque, 2010).

Blasting

Blasting is used to expose the ore body and to fracture the ore to muck piles for extraction (US EPA 1994). This process is very different from the other process steps that use traditional sources of energy such as diesel fuel and electricity (Norgate and Haque, 2010). Explosives come in many forms and in the past nitroglycerine was extensively used in mining operations, whereas today a mixture of ammonium nitrate and fuel oil (ANFO) are commonly used (US EPA 1994; Norgate and Haque, 2010). The characteristics of the ore are critical in determining the amount of explosives needed to blast a unit of ore (referred to as the Powder Factor) to get the required degree of fragmentation (Nielsen & Kristiansen, 1996; (Kanchibotla, Morrell, Valery, & O'Loughlin, 1998) Kanchibotla, Valery, & Morrell, 1999; Norgate & Haque, 2010).

Loading and Hauling

Loading and hauling is the process of loading the excavated ore into haul trucks and transporting them to the processing plants for beneficiation. Loading and hauling fleets are comprised of several types of earth-moving equipment such as wheel loaders, shovel units, excavators and off-road dump trucks with a range of capacities, and the numbers of each type used vary depending on the size of the mine (Norgate and Haque, 2010). The number of earth moving machinery deployed will depend on daily production rates and the capacities of the selected equipment (Lashgari, Yazdani & Sayadi, 2010). The size of the equipment will be determined by the planning parameters of the mine, such as drill-hole diameters and loading heights, fractured ore, waste rock and overburden (US EPA 1994). The products are excavated using either front-end loaders, excavators or shovels and are transported to the beneficiation plant by dump trucks (Norgate and Haque, 2010). Much of the loading and hauling equipment is powered by diesel engines which are highly energy intensive (Norgate and Haque, 2010).

Open cut Mining

Clear and level area

Topsoil Removal

Drilling

Blasting

Overburden Removal

Loading

Underground Mining

Vertical Shaft

Drilling

Blasting

Loading

Hauling

Crushing

Screening

Grinding

Concentration

Stock Pilling
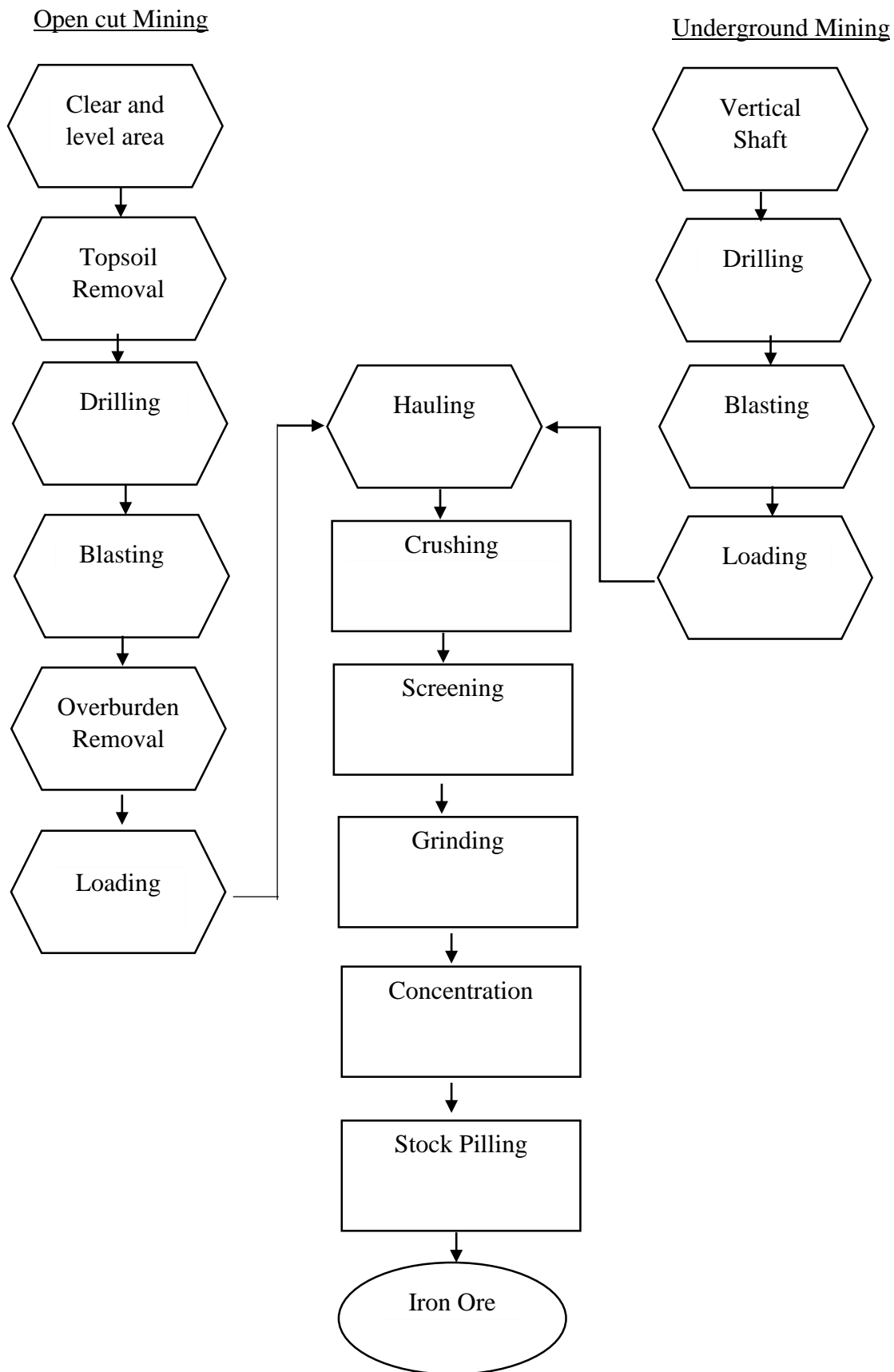
Iron Ore

Figure 2.4: Iron ore mining and mineral processing flow diagram modified from United States' Department of Energy, 2002

2.4.2 Beneficiation

Iron ore seldom occurs in a pure form, because crude ore is often mixed with other gangue minerals (US EPA, 1994; US DOE, 2002; Norgate and Haque, 2010) such as phosphorus, sulphur, sodium, potassium, alumina, silica, and sometimes titanium. These minerals reduce the iron content of the ore, and as a result many ores require some form of beneficiation (US DOE, 2002). Crude ores are often classified into one of three categories based on the amount of processing required prior to shipping, namely direct shipping, concentrates and agglomerated ore (US DOE, 2002). The processing of iron ore in the beneficiation plants usually involves techniques such as milling (crushing and grinding), washing, filtration, sorting, sizing, gravity concentration, magnetic separation, and flotation (US EPA, 1994). However, Australia is endowed with high grade ore deposits, some of which have more than 60% iron content (Yellishetty et. al, 2012), therefore only milling and concentration techniques are required (Norgate and Haque, 2010).

Milling

Milling is a multistage process where crushing and grinding processes are used to produce uniform-sized particles in the run-of-mine material (US EPA, 1994; US DOE, 2002; Norgate and Haque, 2010). Crushing of the ore may undergo primary, secondary or tertiary crushing stages where the size of the ore can be reduced from a meter diameter to coarse particles, typically of around 5 mm (US DOE, 2002; Norgate and Haque, 2010). In the final stage, the product is ground into finer particles, often less than 100 μm in size (US EPA, 1994; US DOE, 2002; Norgate and Haque, 2010). The type of milling plant used is based on the hardness and the density of the ore and range between rod mills, ball mills, autogenous mills or semi-autogenous mills (US EPA, 1994; US DOE, 2002; Norgate and Haque, 2010). The milled product is then blended with products from several operations (that contain different grades, sizes and iron compositions), to obtain a uniform final product (US EPA, 1994). Crushing and milling plants are generally powered by electricity which is often generated by onsite diesel generators (Norgate and Haque, 2010).

Concentration

A concentration process is carried out to separate the valuable mineral from the worthless gangue material based on the physical properties of the ore material (US DOE, 2002; Norgate and Haque, 2010). Several concentration methods are used, including magnetic separation, flotation and gravity separation (US EPA, 1994; US DOE, 2002; Norgate and Haque, 2010). Magnetic separation is the preferred method used to separate magnetite ore from the less or non-magnetic gangue material (US EPA, 1994; US DOE, 2002; Norgate and Haque, 2010). Flotation is used to concentrate hematite ores (US DOE, 2002) where the ore is treated with chemical reagents (US DOE, 2002; Norgate and Haque, 2010) that facilitate adherence of minerals to air bubbles. The reagent used in flotation is dependent on the minerals mixed in with the ore (US EPA, 1994; US DOE, 2002).

In iron ore mining operations, screening is the principal concentration method used to separate the ore into two products, namely lumps and fines (Norgate and Haque, 2010). The size of lumps ranges from 10 to 80 mm and the fines ranges from 150µm to 10 mm (Das, Kumar, Ramachandrarao, 2000; Norgate and Haque, 2010). After the mining and mineral processing stages (Figure 2.4), the processed iron ore is stockpiled before being transported to dedicated ports to be shipped to steel plants worldwide (Norgate and Haque, 2010). Some mining operations have facilities to load the processed ore directly into the beneficiation plants, whereas other operations have to transport the ore to an intermediate transfer station using trucks, before it can be transported long distance.

2.5 Data Acquisition

Two main data sources, publicly available data, and data from the companies' databases, were used to undertake analyses in this study. The first stage of this study, comparing the different scales of operation, was performed using both company data and publicly available data, whereas the second stage of investigation energy use at each process stage, was carried out using the data from the companies' databases only. The companies, who expressed their willingness to take part in this study, provided access to their energy consumption databases which are maintained by a third party company for the purpose of reporting to the National Greenhouse Gas and Energy Reporting (NGER) System. These energy consumption data were pre-processed to ensure that there was no incomplete data for each type of equipment. In the case of incomplete data in the databases, the vehicle usage summaries, which contain the hours of operation of particular equipment, and average fuel consumption per hour of the equipment, could have been used to calculate the amount of diesel consumed by each type of equipment.

Publicly available energy consumption data were obtained from the companies' annual reports, performance reports, sustainability reports and websites. Where there were no records of energy consumption, Scope 1 (direct GHG emissions from combustion of fossil fuels) (WRI and WBCSD, 2004) and, Scope 2 (indirect GHG emissions from purchased electricity, heat or steam) (WRI and WBCSD, 2004) were collected to back-calculate energy consumption. All data used for the analyses were from the 2014 financial year.

2.5.1 Analysis of Scales of Operation

The analysis of scales of operation was carried out to determine the most efficient scale of mining based on the patterns of energy consumption across the three different scales of operation (small, medium and large). For each operation type, the total energy consumed and the total ore produced for 2014FY were used to calculate the energy consumption per unit of processed ore. For small and medium-scale operations, datasets were downloaded from the third party company's database. For large-scale operations, ore production data were obtained from the 2014 annual report of the respective company. The energy consumption data and the Scope 1 and Scope 2 emission data were obtained from the 2014 performance report of the company. In the absence of energy consumption data, carbon emissions data were used to derive the energy data and vice versa (Equation 2.1). However, large companies have multiple iron ore mining business units in their operations which are dispersed in Australia as well as various countries across the world. Therefore, they have reported their total energy

consumption and/or emissions data based on their operations in different countries. Thus, co-production allocation was done in order to determine the energy consumption and carbon emissions statistics for individual mines which are considered in this study.

2.5.2 Analysis of Process Stages

The analysis of process stages was undertaken to identify the highest energy-demanding and carbon dioxide-emitting process stages in iron ore mining operations. This required a detailed calculation of energy consumption and carbon dioxide emissions in each process stage. Variables measured as part of the analysis included grade of ore, annual production, total material mined, waste amount mined during the production, equipment used in mining and mineral processing, equipment numbers, annual diesel consumption, average haulage distances and production capacity. These data were obtained from the various sources mentioned above (Section 2.5). Further information required for this analysis was provided by the environmental officers of the companies, since the databases did not contain some important variables such as total material mined and the amount of waste generated. Due to incomplete data, this analysis was only carried out for small and medium-scale operations, since the aforementioned data were accessible only for these two scales of operation.

2.6 Data Analysis

2.6.1 Analysis of Scales of Operation

A comparison of energy consumption across three different scales of iron ore mining operations (small, medium and large), was undertaken using three different energy efficiency indices, i.e., specific energy consumption, an energy efficiency index, and composite indicator, to identify the most energy-efficient scale of operation. Energy consumption values to calculate aforementioned indices for small and medium-scale operations were calculated using the diesel consumption figures from the company databases and the energy content factors given in the National Greenhouse Account Factors published by the Australian Department of Environment (DoE, 2014). Energy consumption values for large-scale operations were obtained from the publicly available data sources, and in the absence of the above-mentioned data for large-scale operations, the values were derived from the available data using the following equations as mentioned in section 2.5.

Carbon dioxide emissions were calculated to understand the relationship between energy consumption and the carbon dioxide emissions across scales of operation. As with the energy consumption values, emission values for all three operational scales were calculated using the

diesel consumption values and carbon dioxide emission factors from the National Greenhouse Account Factors published by the Australian Department of Environment (DoE, 2014), and publicly available sources. A regression line was used to understand the relationship between calculated energy consumption and gaseous emissions. The factors and equations used in the analyses to calculate energy efficiency indices and carbon dioxide emission values included the following:

The energy content of a 1 litre of diesel is considered 11.1 kWh or 38.6 $GJkL^{-1}$ and 1 GJ of energy emits 69.2 CO_2-e kg.

69.2 CO_2-e kg	= 1 GJ
Therefore, 1 CO_2-e kg	= (1/69.2) GJ
1 GJ	= 1,000 MJ
Therefore, 1 CO_2-e kg	= (1000/69.2) MJ
1 CO_2-e kg	= 14.45 MJ -------------- Equation 2.1

1 kL of diesel	= 38.6 GJ
1 kL of diesel	= 38.6 x 69.2 CO_2-e Kg
Therefore;	
CO_2 emissions from 1 litre of diesel	= (38.6 x 69.2)/1000 CO_2-e Kg
1 litre of diesel	= 2.67 CO_2-e Kg -------------- Equation 2.2

Energy Efficiency Indices

Specific Energy Consumption (SEC)

Specific energy consumption can be defined as the ratio of the amount of energy consumed to unit of product output in a particular process (Phylipsen et. al, 1997, González, Díaz, Caamano and Wilby, 2011), and the reduced specific energy consumption values reflect the increased energy efficiency (Mukherjee, 2008). SEC is a widely used energy efficiency indicator where the current study calculated the energy consumption per unit of processed iron ore to identify the efficient use of energy across three different scales of iron ore mining operations (Equation

2.3). The SEC value was calculated for all eight mines considered in this study, using the energy per unit output ratio formula. Finally, an independent sample t-test was performed to compare the mean energy consumption of small and medium scales of operation (n=3 in each scale) to identify whether there is a statistically significant difference in the mean energy consumption between the two scales.

Specific Energy Consumption = Ei / Qi   -------------- Equation 2.3

Where Ei is the total energy consumed (kWh) by ith iron ore mine, and Qi is the total amount of iron ore processed (tonnes) in ith mine in a particular time period

Energy Efficiency Index (EEI)

The energy efficiency index is a widely used efficiency indicator, which is used to compare the energy demand in different levels of aggregations such as regions, sectors, technology or processes (Price et. al, 1999; Ang, 2006; González et. al, 2011). EEI is measured as the ratio of actual energy consumption to the best practice energy consumption, considering the best practice equals to 100 (Price et. al, 1999). However, due to lack of published literature related to the energy consumption in iron ore mining operations in Australia, a best practice energy consumption value could not be found for Australian iron ore mining operations. Therefore, it was assumed that the energy consumption value of Mine H, as the best practice consumption since it is the lowest recorded value among the mines in the sample.

Energy Efficiency Index = (E_i / E_b) x 100   -------------- Equation 2.4

Where E_i is the energy consumed to process a unit of ore $(kWht^{-1})$ by i^{th} iron ore mine, and E_b is the energy consumed to process a unit of ore $(kWht^{-1})$ by the best practice mine

Composite Energy Indicator

Another energy efficiency indicator is the calculation of a composite energy indicator, based on the specific energy consumption and a portion of the total mining industry's energy use (Nyboer and Bennett, 2014). This method has been widely used in the Canadian mining sector, which considers that the composite indicator is a good reflection of the extraction efficiency of a mine, which is influenced by the physical characteristics of an individual mine including richness of the ore, ore hardness, and dimensions of the mine, and other factors that are within

the control of individual facilities such as types of technology used (Nyboer and Bennett, 2014). The Composite indicator can be given by the following equation:

Composite Indicator = SECij x ESij   -------------- Equation 2.5

Where   SECi = Specific energy consumption of Mine i in year j

ESi = Energy share of Mine i, which is the ratio of the total energy consumed by Mine i to the total energy consumed by the Australian mining sector in year j

Effect of Geological and Physical variables on Energy Efficiency

Energy use and CO_2 emissions for each mine were standardised based on one or more factors, including the ore grade, average haulage distance and the waste-to-ore ratio to identify the most persuasive factor on energy consumption and carbon dioxide emissions from the operation. Ore grade and the waste-to-ore ratio data were obtained from the downloaded data sets, and the missing data were obtained by contacting the environmental officer of the respective company. The average haulage distances for a few mines were obtained from the environmental officers of the respective companies. Additionally, the GEOVIEW interactive map available in the Department of Mines and Petroleum, Western Australia was used to obtain the coordinates of the different infrastructure in mining operations, and Google Earth (https://earth.google.com/) applications were used to calculate the haulage distances of the rest of the mines and also to verify the haulage distances supplied by the environmental officers. The coordinates of the processing plants in each mine and each operating pit were obtained through the GEOVIEW interactive map. Then, using those coordinates, various pits of each operation were identified using Google maps and the Euclidean distances were measured from each pit to the processing plant and the average distances were calculated based on the number of pits operating in each mine. Then, a multiple linear regression analysis was performed to find the relationship between the energy consumption and the aforementioned factors, and also to find the relative importance of each parameter on energy consumption using the p value of each parameter ($p < 0.05$). All the statistical analyses were performed in IBM SPSS Statistics 22.0 software (IBM Corp., 2013).

2.6.2 Analysis of Process Stages

This stage of the study was performed using energy consumption databases of the companies, of which the energy consumption was recorded as the litres of diesel consumed by each equipment type for the 2014 financial year. However, not all the equipment was used in mining and mineral processing, since these data sets recorded all the machineries used in mine operations including; mining infrastructure equipment such as power generators and lighting equipment, mining and processing equipment, maintenance equipment, transportation vehicles and ancillary equipment. Thus, reviewing literature and in consultation with environmental officers of the respective companies, equipment used in mining and processing was filtered from the database. Then, equipment was sorted according to the process stage that being used, and a process flow diagram was constructed to show the operational stages (Figure 2.5) and equipment used in particular stages, from drilling the ore to the delivery of ore to ports for shipping, for the mines that participated in this study. This was used as a basis to identify the energy usage at each stage, and for calculating fuel consumption. The diesel energy content and CO_2 emission factors do not differ between stationary, transport and non-transport modes (DoE, 2014). Therefore, the energy consumption and carbon dioxide emission outputs from the different diesel powered equipment types were calculated using the equations given in Section 2.6.1.

After that, an analysis of variance (ANOVA) test was performed to identify whether there are any statistically significant differences ($P<0.05$) in energy consumption in various process stages of small-scale and medium-scale iron ore mining operations. The ANOVA test was performed using IBM SPSS Statistics 22.0 software (IBM Corp., 2013), and the graphical representations of energy consumption and carbon dioxide emissions from different process stages were generated using SigmaPlot 13 (Systat Software Inc., 2012). Finally, the mean energy consumption values in small and medium scales of operations were compared with a similar study carried out by Norgate and Haques (2010), to identify the similarities and the differences in the energy consumption of each process stage over the time.

```
                    Drilling and Blasting                          ┌─────────────────────┐
                             │                                     │ Drills              │
                             │                                     │ Service Trucks      │
                             ▼                                     │ Loader (wheeled)    │
                    Loading and Hauling                            └─────────────────────┘

                             │                                     ┌─────────────────────┐
                             │                                     │ Haul/Dump           │
                             ▼                                     │ Trucks              │
                       Stockpiling                                 │ Excavator           │
        ┌ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─│─ ─ ─ ─ ─ ─ ─ ─ ─ ┐                │ Dozer (Wheeled)     │
                             ▼                                     └─────────────────────┘
        │             Crushing and Grinding        │
                                                                   ┌─────────────────────┐
        │                    │                     │               │ Mine Generators     │
                             ▼                                     │ Loader (wheeled)    │
        │                Screening                 │               │                     │
                             │                                     │ Mobile Crusher      │
        │                    ▼                     │               │ Mobile Screen       │
                        Stockpiling                                │ Mobile Conveyor     │
        └ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─│─ ─ ─ ─ ─ ─ ─ ─ ─ ┘                └─────────────────────┘
         ┌───────────────────┴───────────────────┐
         ▼                                        ▼
    Conveying to      ┌──────────────────┐     Haulage        ┌──────────────────┐
    Trains/Ships      │ Loader (wheeled) │                    │ Road Trains      │
                      └──────────────────┘        │           └──────────────────┘
                                                  ▼
                                           Loading to Trains  ┌──────────────────┐
                                                              │ Loader (wheeled) │
                                                  │           └──────────────────┘
                                                  ▼
                                          Transporting to Port ┌──────────┐
                                                               │ Trains   │
                                                               └──────────┘
```

Figure 2.5: Process stages of participating iron ore mining operations

3.1 Analysis of Scales of Operation

3.1.1 Energy efficiency across different scales of operation and energy efficiency indices

Specific Energy Consumption

Specific Energy Consumption values for three different scales of iron ore mining operations in Western Australia are shown in Figure 3.1. The mean energy consumption values show a variation in energy consumption to process a single unit of ore in small, medium and large scale operations (Figure 3.1). The highest mean energy consumption per unit of processed ore was recorded in the small-scale iron ore mining operations, which was 47.5 kWht^{-1}, while the lowest value of 11.34 kWht^{-1} was recorded in the large-scale mining operations (Figure 3.1). The specific energy consumption recorded for an average iron ore mining operation (the mean energy consumption of the eight mines considered in this study) in WA was 35.64 kWht^{-1}, which was lower than the mean energy consumptions recorded in small and medium-scale operations considered in this study (Figure 3.1). Statistical significance of the energy consumption values between small and medium-scale operations were observed based on the independent sample t-test statistics, where the specific energy consumption values in small and medium operational scales did not show any statistical difference (Figure 3.1).
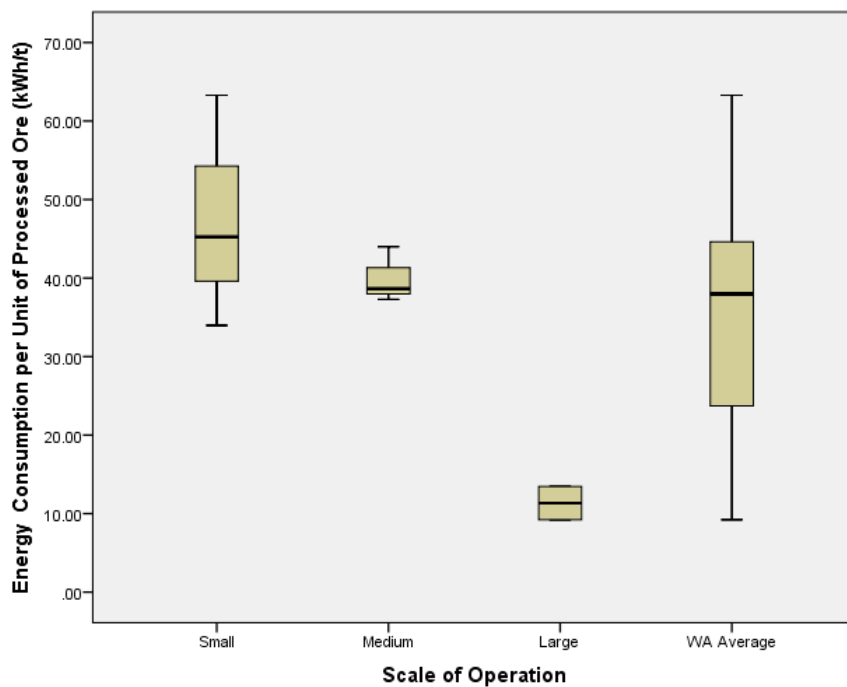
Figure 3.1: Box plot showing the mean energy consumption to process a unit of ore across three different scales of iron ore mining operations in WA; n=8 (small =3, medium=3, large=2); boxes indicate lower quartile, median and upper quartile ranges; lines indicate minimum and maximum energy consumption values; t (4) = 0.86, P = 0.44

Energy Efficiency Index

In order to compare the energy consumption pattern across small, medium and large scales of iron ore mining operations, the EEI was calculated and is shown in Figure 3.2. The EEI returned similar results for energy consumption with the small-scale having the highest values and the large-scale with the lowest EEI value (Figure 3.2). The EEI shows that the large-scale mining operations are the most energy-efficient operational scale since the energy efficiency index of large-scale mines was closest to the best practice benchmark of 100, while the small and medium-scale mining operations were considerably different (higher) than the best practice benchmark (Figure 3.2). The average EEI values of the three scales clearly show that the small-scale iron ore mining operations were the least energy-efficient scale of operation among the three operational scales considered in this study, and the energy efficiency increases in medium and large-scale mining operations respectively (Figure 3.2).

Figure 3.2: Energy efficiency index for iron ore mines and the average energy efficiency index for small, medium and large iron ore mining operations in Western Australia

Composite Energy Indicator

The composite indicator, which reflects the influence of physical characteristics such as ore grade, depth and hardness of individual mines, indicates the real improvements in energy efficiency in a particular mine. The composite indicator based on the amount of processed ore shows a dynamic behaviour across the mines; however, it shows a decline in the energy intensity of the specific energy consumption indicator in Mine A, B and C, suggesting an improvement in energy consumption in small-scale iron ore mining operations (Figure 3.3). However, medium-scale operations (Mines D, E and F) and large-scale mining operations (Mine G and H) show a rise in the composite indicator reflecting a worsening energy efficiency (Figure 3.3), and these results suggest a potential influence of the physical factors on energy efficiency.
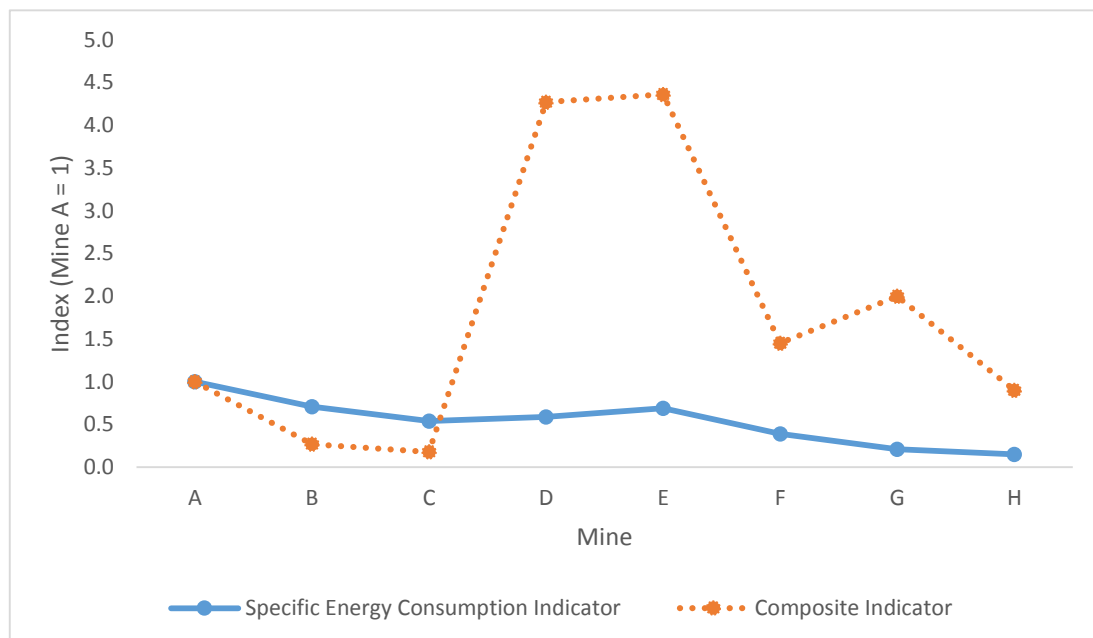
Figure 3.3: Composite and specific energy consumption indicators for iron ore mines in Western Australia

Table 3.1: Energy indices, specific CO_2 emissions, and geological and physical factors for 8 iron ore mines in Western Australia

Parameter	Small Scale			Medium Scale			Large Scale	
	Mine A	Mine B	Mine C	Mine D	Mine E	Mine F	Mine G	Mine H
Specific Energy Consumption (kWh^{-t})	63.28	45.25	33.97	37.29	44	38.65	13.46	9.22
Energy Efficiency Index (EEI)	686	490	368	404	477	419	146	100
Composite Indicator	1	0.27	0.18	4.27	4.36	1.45	2	0.9
Specific CO_2 emissions (Kg CO_2^{-t})	15.22	10.88	8.17	8.97	10.58	9.30	4.05	2.80
Grade of Ore (Fe%)	64%	61%	57%	57.3%	57.6%	57.2%	56.1	61
Average Haul Distance (Km)	1.9	1.0	1.4	5.9	5.4	4.0	4.2	4.7
Waste:ore Ratio	6.73:1	2.48:1	1.66:1	4.62:1	5.53:1	2.84:1	1.3:1	1.3:1
Production Capacity (Mtpa)	3	3	4	50	40	60	78	55
Ore Type	Hematite	Hematite	Hematite	Hematite	Hematite	Hematite	Hematite	Hematite
Mine Design	M	M	S	M	M	M	S	M

Mine design: S = single pit; M = multi pits

3.1.2 Effect of geological and physical factors on energy consumption

A Pearson's correlation analysis was performed to determine whether the geological and physical factors such as grade of ore, average haulage distance, waste-ore ratio and production capacity have an influence on the energy consumed to process a single unit of iron ore. A significant and a strong correlation was observed between waste-ore ratio and the specific energy consumption (Figure 3.4), suggesting that energy consumption to process a unit of ore increases as the waste-ore ratio in a particular mine increases. Unexpectedly, the correlation between the grade of ore and the energy consumption indicates that, as the grade of ore increases so does energy consumption (Figure 3.4), and energy consumption decreases as the average haulage distance increases (Figure 3.4). A fairly strong but non-significant relationship was observed between the energy consumption and the production capacity of a mine, suggesting the possibility of observing economies of scales in terms of energy consumption patterns (Figure 3.4). However, these relationships cannot be used to draw any strong conclusion about the influence of these factors on energy consumption.

A multiple linear regression analysis was performed to determine whether the grade of ore, average haulage distance, waste-ore ratio and the production capacity had any influence on energy consumed by the iron ore mining and mineral processing operations, and to determine the relative importance of these parameters on energy consumption. The R^2 value of this analysis showed that, 93.9% of total variability of energy consumption is explained by the predictor variables (Table 3.3). The analysis of variance results indicates that the synergetic influence of the grade of ore, average haulage distance, waste-ore ratio and the production capacity were statistically significant in predicting energy consumption, $F_{(4,3)}=11.55$, $P=0.036$.

Table 3.2: Model summary table of the multiple linear regression model

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.969[a]	0.939	0.858	6.58119

a. Predictors: (Constant), Production Capacity, Waste-ore Ratio, Grade of Ore, Average Haulage Distance
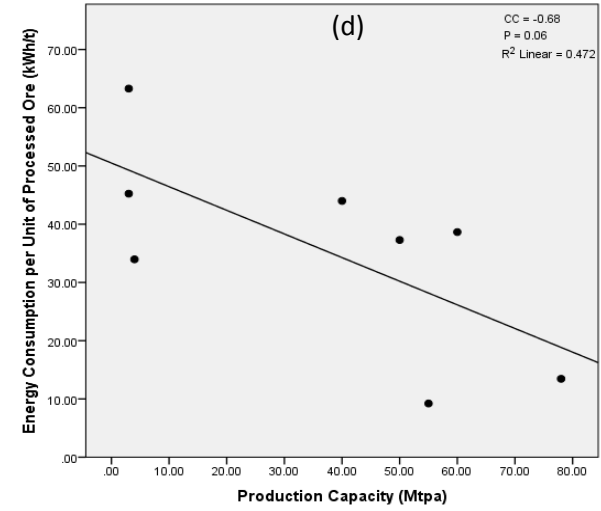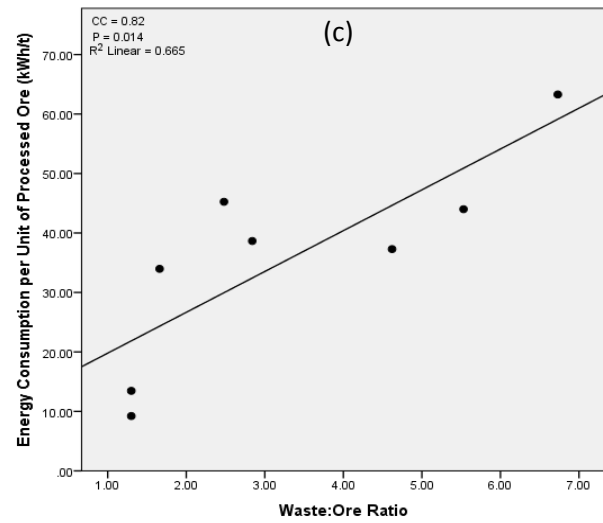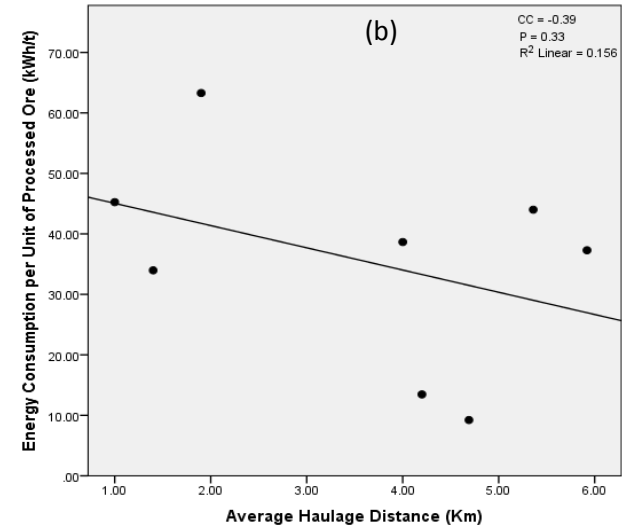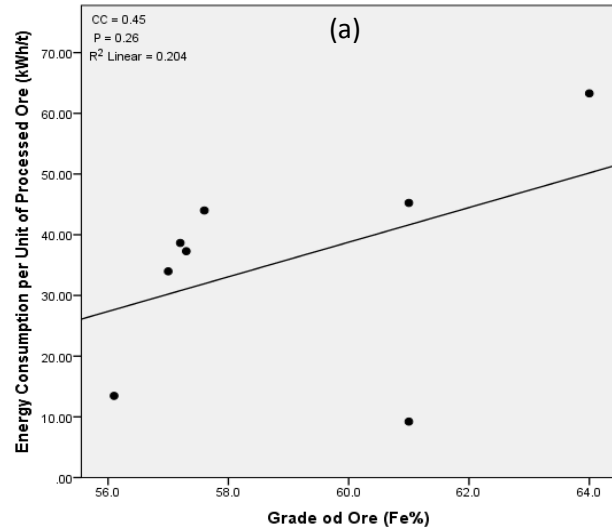
Figure 3.4: Relationship between the geological and physical factors and energy consumption per unit of processed ore (n=8; CC = Pearson's correlation coefficient, P = 0.05)

The relative importance of each variable is shown in Table 3.4 and the waste-ore ratio can be identified as the variable which has a significant influence ($P<0.05$) on the amount of energy consumed to process a unit of iron ore. The unstandardized coefficient of the waste-ore ratio recorded in Table 3.4 reflects that the energy consumption will be increased by eight units as a result of changing one unit in the waste-ore ratio, when all the other parameters remain constant. The upper and lower bound 95% confidence interval indicates that the waste-ore ratio in iron ore mines in WA ranges from 2.28 to 13.78. Not unexpectedly, the grade of ore and the production capacity show a negative influence on the amount of energy consumption in mining operations, where the increases in grade of ore and production capacity results decreases in energy requirement, although the Pearson's correlation between energy consumption and the grade of ore showed a positive correlation. Surprisingly, in both correlation analysis and regression analysis, average haul distances show a different pattern to the energy consumption than what was expected. The outcomes of these analyses indicates that as the average haul distance increases, the energy requirement decreases. However, it can be proposed that the estimated energy consumption of an open-cut iron ore mine can be obtained using the model as follows.

$$E_{estimated} = 105.58 + 8.03W_R - (1.30G_R + 5.29A_H + 0.025P_C)$$

Where,

$E_{estimated}$ = Estimated energy consumption to process a unit of iron ore

W_R = Waste to ore ratio (Stripping ratio) G_R =   Grade of ore

A_H = Average haul distance P_C = Production capacity of the mine

Table 3.3: The relative importance of each physical and geological parameter on estimated energy requirement to process a unit of iron ore. Significant values (P<0.05) are shown in bold.

Model	Unstandardized Coefficients		Standardized Coefficients			95.0% Confidence Interval for B	
	B	Std. Error	Beta	t	Sig.	Lower Bound	Upper Bound
1 (Constant)	105.579	69.960		1.509	.228	-117.065	328.223
Grade of ore	-1.303	1.169	-.206	-1.114	.346	-5.024	2.418
Average Haul Distance	-5.290	2.968	-.569	-1.783	.173	-14.735	4.155
Waste:ore ratio	8.030	1.807	.954	4.445	**.021**	2.280	13.779
Production Capacity	-.025	.193	-.043	-.132	.903	-.638	.588

a. Dependent Variable: Energy

3.1.3 Carbon dioxide emissions across different scales of iron ore mining operations

This study noted the expected strong positive relationship between energy consumption and carbon dioxide emission, where high energy consumption per unit of ore processed released the highest amounts of carbon dioxide emissions (Figure 3.5). The mean CO_2 emissions per unit of processed ore were calculated in eight iron ore mines in WA and are given in Table 3.2. The mean emissions values show a variation in the CO_2 emissions across three different scales of iron ore mining operations and follow a trend similar to the specific energy consumption values across different operational scales (Figure 3.1, Table 3.2); the lowest carbon dioxide emissions were calculated to be from the large-scale mining operations with a mean value for carbon dioxide emissions at 3.42 kg CO_2^{-t} (Table 3.2). The medium-scale operations emitted the second highest amount of carbon dioxide emissions at 9.62 kg CO_2^{-t} ore, while the emissions per unit of processed ore highest from the small scale iron ore mining operations was 11.42 kg CO_2^{-t}.
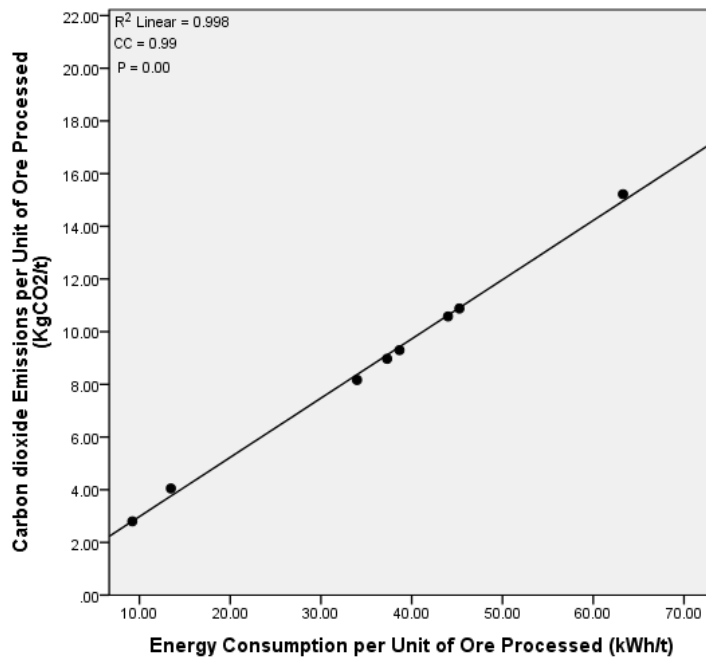
Figure 3.5: Relationship between energy consumption and carbon dioxide emissions in iron ore mining operations (n=8; CC = Pearson's correlation coefficient; P < 0.01)

Table 3.4: Mean CO_2 emissions per unit of ore processed (kg CO_2^{-t}) for small, medium and large scales of iron ore mining operations in WA; n=8; t (4) = 0.86, P = 0.44

Scale	Mine	Carbon dioxide Emissions (kg CO_2^{-t})	Mean (kg CO_2^{-t}) (Min, Max)	Standard Deviation
Small	A	15.22		
	B	10.88	11.42 (8.17,15.22)	3.55
	C	8.17		
Medium	D	8.97		
	E	10.58	9.62 (8.97, 10.58)	0.85
	F	9.30		
Large	G	4.05	3.42 (2.80, 4.05)	0.88
	H	2.80		

3.2 Analysis of iron ore mining process stages

3.2.1 Energy consumption and carbon dioxide emissions from small scale mining operations

Energy consumption per unit of ore processed (kWh^{-t}) in iron ore mining process stages in small scale mine are shown in Figure 3.6. These results show that loading and hauling had the highest energy consumption in Mine A and B, while Mine C recorded transporting milled ore to the rail siding areas as the largest energy consumption process stage. In Mine A, 47.18 kWh^{-t} was required to haul and load one tonne of iron ore, which is 75% of the total energy consumed (Figure 3.6). In Mine B loading and hauling accounted for only 36% of the energy used while in Mine C it was <5% (Figure 3.6). Transporting ore to the rail siding was another energy demanding process accounting for 26% and 14% of the energy used in Mine B and C respectively (Figure 3.6). In Mine A, this process is a negligible user of energy since the ore is loaded directly into ships from the mine. Energy required for loading ships at Mine A was also very low and only accounted for 3% of total energy used by the mine. Energy consumption for the drilling and blasting, and milling stages was <10% at all three mines and patterns of use were similar across all mines.

Figure 3.6: Energy consumption per unit of ore processed in iron ore mining process stages in small scale mines, where Mine A does not have process stages including transporting to rail siding, loading to trains and transporting to port

Since, there is a strong relationship between energy use and carbon dioxide emissions (Figure 3.5), it is not unexpected that the energy-demanding process stages were those that emitted the most carbon dioxide emissions. As with the energy consumption results, loading and hauling was recorded as the highest carbon dioxide-emitting process step except at Mine C (Figure 3.7). In this mine, transportation of processed ore to the rail siding site was identified as the process stage which emitted the highest amount of carbon dioxide and this process was second highest in Mine B (Figure 3.7). Across all three mines, it is evident that the common processes of loading and hauling, milling and stockpiling, and drilling and blasting are significant carbon dioxide-emitting process stages within iron ore mining and mineral processing operations (Figure 3.7) with transportation to port being more variable and dependent on distance to the harbour.

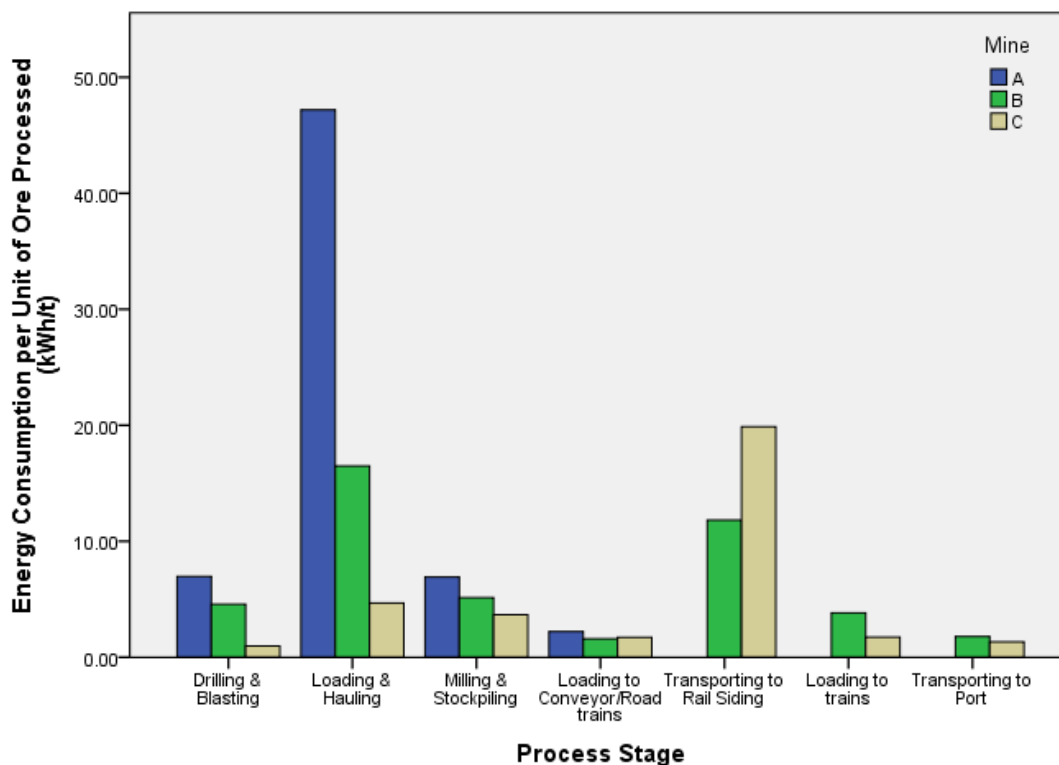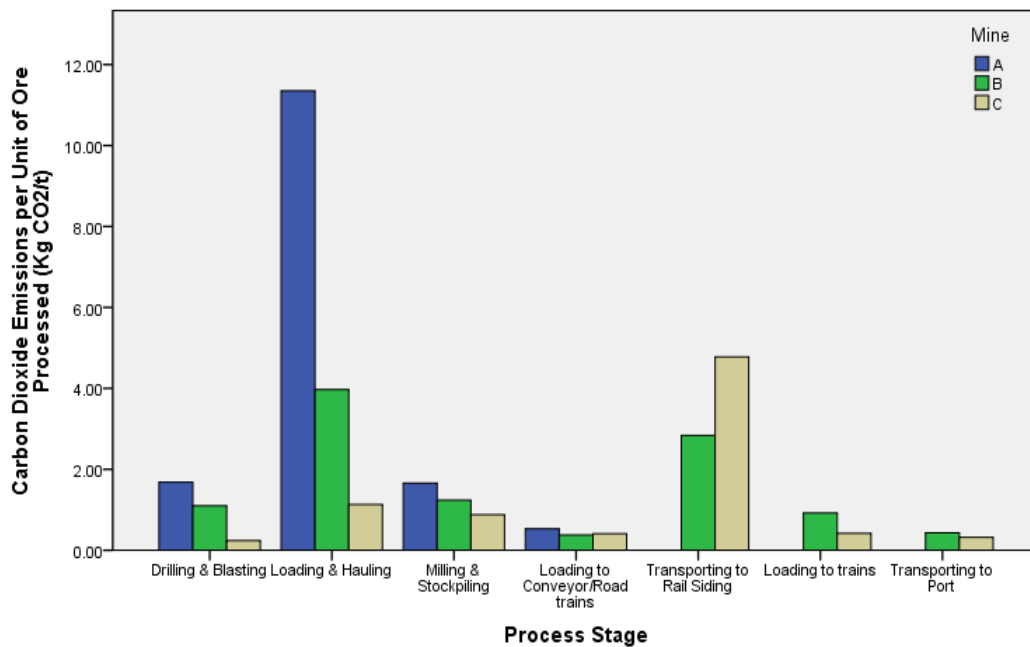Figure 3.7: Carbon dioxide emissions per unit of ore processed in iron ore mining process stages in small scale mines, where Mine A does not have process stages including transporting to rail siding, loading to trains and transporting to port

A detailed analysis was carried across three medium-scale mining operations (Section 2.4) to identify the major energy-demanding and carbon dioxide-emitting process stages in iron ore mining and mineral processing operations and whether these differ from the process stages identified previously as being important. In Mine D, 18.4 kWht^{-1} was required to load and haul one tonne of blasted iron ore, which is 49% of the total energy consumed (Figure 3.8). Loading and hauling in Mine E accounted for 58.8% of the total energy consumed, which was 25.9 kWht^{-1}, and in Mine F it accounted for 77.3% of total energy consumed (Figure 3.8). Crushing and grinding, screening, and stockpiling (milling and stockpiling) was the second highest energy-consuming process stage in medium mining operations (Figure 3.8). Mine D and E were recorded 29.2% and 24.9% of total energy used to mine and process one tonne of iron ore (Figure 3.8). In Mine F, 0.8 kWht^{-1} of energy was required to perform this process, which was 3.2% of the total energy consumed (Figure 3.8). Drilling and blasting was also identified as a high energy demanding process stage where in Mine D it accounted 21.4% of total energy consumption (Figure 3.8). Mine E and F recorded energy consumption of 7.1 and 4.6 kWht^{-1} respectively for this stage (Figure 3.8). Energy consumption for rail transportation was negligible in Mines E and F, while in Mine D there was no data available for energy used in rail transportation (Figure 3.8).
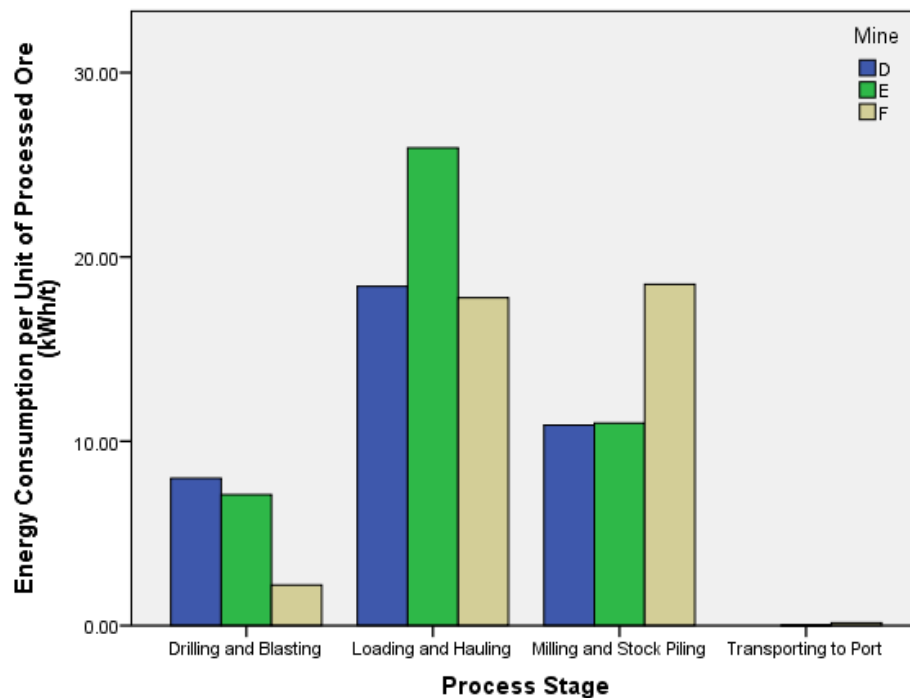
Figure 3.8: Energy consumption per unit of ore processed in iron ore mining process stages in medium scale mines

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The strong correlation between energy consumption and carbon dioxide emissions (Figure 3.5) resulted in the highest carbon dioxide emissions from the same process stages identified as the highest energy demanding process stages (Figure 3.8 and 3.9), with the highest amount of carbon dioxide emissions recorded from the loading and hauling process stage in all three medium-scale mines (Figure 3.9). Milling and stockpiling was the second most carbon dioxide-emitting process stage with the exception of Mine F, where drilling and blasting was identified as the second most carbon dioxide-releasing process stage (Figure 3.9). The drilling and blasting process stage in Mines D and E was also identified as a significant source of carbon dioxide emissions (Figure 3.9), while like patterns for energy consumption, the emissions from rail transportation were negligible (Figure 3.9).
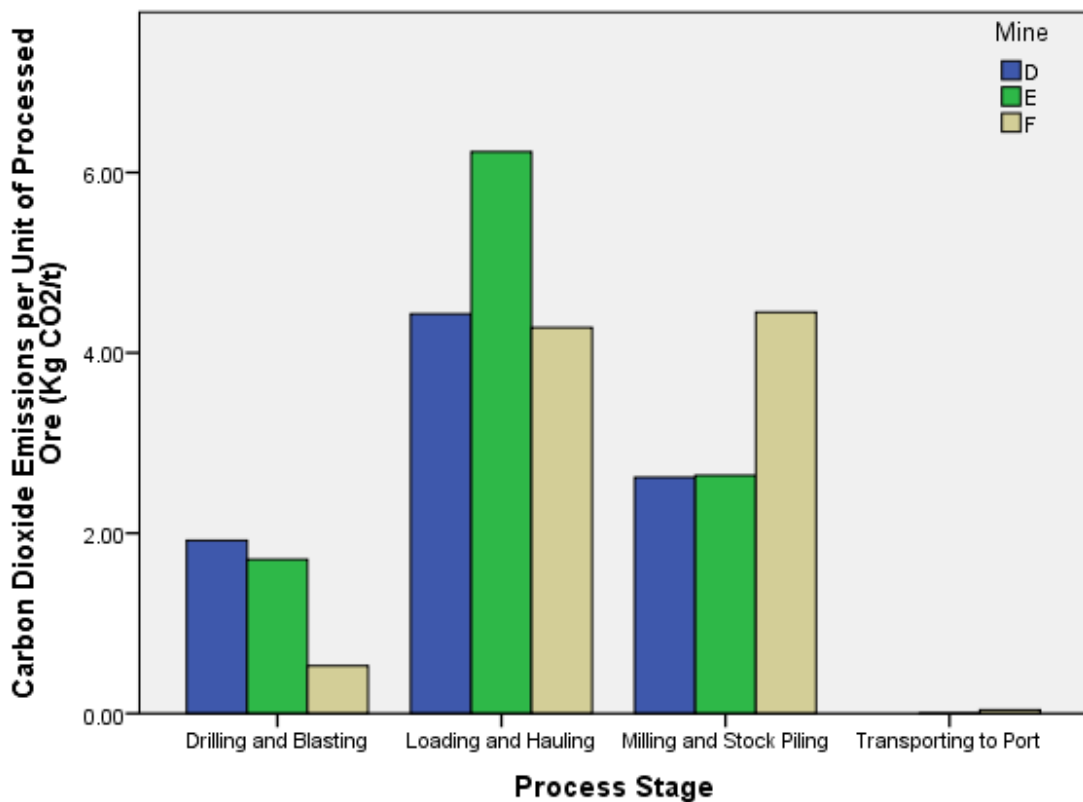
Figure 3.9: Carbon dioxide emissions per unit of ore processed in iron ore mining process stages in medium scale mines

3.2.3 Comparison of energy consumption and carbon dioxide emissions results of small and medium scales of operation

The highest energy-consuming and carbon dioxide-emitting process stages in small and medium scale mining operations are shown in Figure 3.10 and Table 3.6. The mean energy consumption results were compared with each other to identify the similarities and the differences in each process stage at different operational scales. The current study identifies loading and hauling, milling and stockpiling, and drilling and blasting as the top three energy-intensive process stages in the iron ore mining and mineral processing operations, regardless of the scale of operating (Figure 3.10). Loading and hauling, as the most energy-intensive process stage in the iron ore mining and mineral processing operations, consumes more than 60% of the total energy for the operation, regardless of the operational scale (Figure 3.10). Milling and stockpiling was the next highest consumer of energy, accounting for around 20% of the total energy consumed (Figure 3.10). Small mining operations recorded a low energy consumption for the milling and stockpiling stage (9.7%), which is almost half that recorded for the medium-scale operations (21.4%) (Figure 3.10). This current study identified the drilling and blasting process stage as the third highest energy consuming process stage, where small scale operations consumed 8.8% of the total energy, while medium scale operations accounted for 18.6% of the total energy consumed, which is nearly threefold higher than the small scale operations (Figure 3.10). However, because of a lack of data, the present study does not identify the rail transport process stage as a substantial energy consumer, although the processed ore is transported for long distances by rail.

Statistically significant energy consumption variation in process stages in small and medium-scale operations was observed based on the two-way ANOVA results ($P<0.05$) (Table 3.7). At the mining scale there were no significant differences between different-sized operations ($P<0.05$), but there were very clear significant differences ($P<0.05$) in energy consumption at each process stage (Table 3.7). Two-way ANOVA Tukey's *post hoc* test statistics results show that the loading and hauling process stage has a significant difference in energy consumption compared to the other process stages (Table 3.7).

Table 3.5: Mean carbon dioxide emissions values and standard deviations for different process stages in iron ore mining operations at different scales of operations (n=6)

Process Step	Small Mines		Medium Mines		Overall Mean CO2 Emissions (Kg CO_2/t)
	Mean CO2 Emissions (Kg CO_2/t)	SD	Mean CO2 Emissions (Kg CO_2/t)	SD	
Drilling and Blasting	1.16	0.49	1.38	0.42	1.29
Loading and Hauling	8.50	2.57	4.98	1.00	6.78
Milling and Stockpiling	1.25	0.39	3.23	1.41	1.54
Rail Transport	0.37	0.07	0.20	0.03	0.20
Total	**11.28**		**9.79**		**10.53**
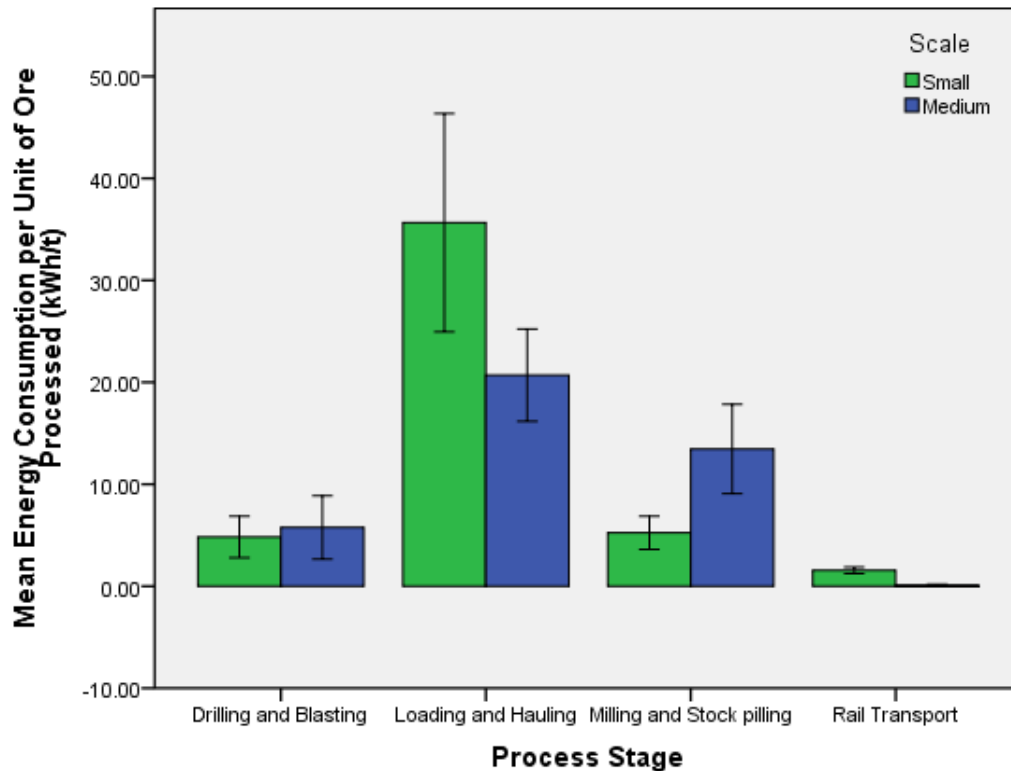
Figure 3.10: Bar graphs showing the variations in mean energy consumption in different process stages at small and medium scales of operation; n=6; lower case letters indicate the statistically significant differences ($P< 0.05$) in energy consumption between small and medium scales based on Tukey's post hoc test in factorial ANOVA statistics

Table 3.6: Tests of Between-Subjects effects

Dependent Variable: Energy

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	2822.367[a]	7	403.195	16.545	.000
Intercept	2539.219	1	2539.219	104.194	.000
Scale	17.670	1	17.670	.725	.409
Process	2381.860	3	793.953	32.579	.000
Scale * Process	421.667	3	140.556	5.768	**.009**
Error	341.180	14	24.370		
Total	6241.043	22			
Corrected Total	3163.547	21			

a. R Squared = .892 (Adjusted R Squared = .838)

4.1 Analysis of Scales of Operations

Results from this stage of study show that energy efficiency in an iron ore mining operation in Western Australia is affected by its scale of mining operation, since a higher energy consumption to process a unit of iron ore was recorded in the small-scale iron ore mining operations, while the least energy consumption was recorded from the large operational sites. However, the composite energy indicator shows that the small scale operations are achieving energy efficiency compared to the medium and large operational scales, suggesting that the physical factors in individual mines have a potential influence on the amount of energy consumed by a particular operation to process a unit of ore. Among the physical and geological variables considered in the study, the waste-ore ratio showed a significant influence on the energy consumption of a mine, while grade of ore, average haulage distance and production capacity appear to have a weak relationship with the energy consumption patterns that were observed across three different scales. However, it was observed that, it is the combined effects of these parameters, that have the highest influence on the amount of energy consumption in mining operations. This is the first study that has assessed the economies of scales based on energy efficiency in iron ore mining operations and that has considered the influence of multiple physical and geological factors in predicting the estimated energy consumption of a particular iron ore mine.

4.1.1 Energy efficiency across scales of operation

In this study, large-scale iron ore mining operations were found to be the operational scale with the highest energy efficiency, due to the lowest amount of energy consumed to process a unit of iron ore, while the small-scale iron ore operations recorded the lowest energy efficiency based on the specific energy consumption and energy efficiency index values. Although, the energy consumption values of small and medium scale of operations did not show any significant difference, the mean specific energy consumption as well as the average EEI increases approximately four-fold as the scale of operation decreases from large to small scale of operation, suggesting a strong economy of scale based on the energy efficiency in iron ore mining operations. A study in the North American iron ore industry (Raab and Steinnes, 1993) revealed that it is the small scale iron ore operations which have the lowest efficiency in terms of cost of production, and nearly 30% reduction in operating costs can be achieved when the production scale increases from small into large-scale mining. Similarly, the existence of the economy of scale in the global iron making industry revealed by Crompton and Lesourd (2008),

confirming the economic axiom that the cost of production decreases with the increasing scale of operation (Crowson, 2003). Since the mining industry is an energy-intensive industry (Raab and Steinnes, 1993; Asafu-Adjaye and Mahadevan, 2003; Crowson, 2003; Crompton and Lesourd, 2008), the energy cost can account for up to 60% of the total cost of the mining operation (Bunse et al, 2010). It is therefore expected that, as with the cost of production, the energy consumption to process a unit of iron ore in mining operations will decrease as the scale of operations increases, as such resulted in the current study. Similar to the results of the current study, a study in India (Sahoo, Bandyopadhyay and Banerjee, 2013), looking at the energy efficiency in opencast mining, reported that the specific energy consumption of smaller sized mines with lower production rates are higher than the larger sized mines with higher production rates. Thus, these comparisons suggest that the large scale iron ore mining operations are more energy-efficient than the small-scale mining operations and these differences in energy consumption across the scale of operations suggest that the economy of scale based on energy efficiency in iron ore mining operations could be expected.

In contrast to the specific energy consumption and energy efficiency index results, the composite energy indicator per unit of processed ore generated in the current study showed the small scale mines (Mines A, B and C) which have a composite energy indicator that is lower than the SEC are more efficient than the medium (Mines D, E and F) and large (Mines G and H) operational scale mines, which have a higher composite indicator than the SEC of each mine. These results suggest that factors such as the type of technology used in individual facilities and physical parameters including grade of ore, hardness of the ore, and depth of the mine, etc. have an influence on the energy requirement of a mine. This hypothesis is supported by the findings of a study in the USA open cut copper mining (Pitt and Wadsworth, 1981); looking at the mining energy requirements in the copper industry, reporting that the energy required by a mining process is largely attributable by the physical characteristics in the individual mines. These parameters include the nature of the mineralization such as the cut-off grade and the properties of the mill feed which will be going through milling, stripping ratio and the dimensions and the depth of the pit (Pitt and Wadsworth, 1981). When the composite indicators of the mines generated in this study were analysed, based on the physical parameters according to the information suggested in the international literature, an interesting trend was observed, which indicated that the mines (Mines D and E), which have a higher waste-ore ratio, higher average haulage distance and comparatively lower ore grade, recorded a high value in the composite indicator, which reflects a worsening of the efficiency, although these mines are operated on a higher production scale (Table 3.1). However, there was no clear fallout pattern

between the composite indicator values and the aforementioned parameters. Thus, the composite indicator values of the mines in the current study suggest that the energy consumption of a mine is possibly being affected by the combined effect of these physical and geological parameters; that is, the grade of ore, waste-ore ratio, average haulage distance and the production capacity of the mine.

The distinct behaviour of the energy consumption of small, medium, and large scale operations in the three energy efficiency indicators provides the information on the most efficient scale of iron ore mining operations in Western Australia, and allows the reasons for the identification of the dissimilarities in energy consumption across different scales of iron ore mining operations. Specific energy consumption was used to calculate the ratio of the energy consumption per tonnes of ore processed, where the reduced values for specific energy consumption reflect the increased energy efficiency (Mukherjee, 2008; Bunse et.al, 2011). It is therefore calculating the energy consumption per unit of work done and thus does not account for any influence from the variables that affect the energy efficiency. As with specific energy consumption, the energy efficiency index is also used to compare the energy consumption of an operation, while accounting for the differences in processes used (Price, Worrell and Phylipsen, 1997). The EEI often calculates the ratio of the actual energy consumption to the best practice benchmark (Price, Worrell and Phylipsen, 1997), and therefore allows the quantifying influence of the variables which affect the energy efficiency of the particular process. The Composite Energy Indicator measures the changes in the energy consumption by its proportion of the total mining industry's energy use (Natural Resources Canada, 2005). Calculation of the energy share of each mine, therefore accounts for the real efficiency changes in individual facilities and the effect of physical variables that influence energy efficiency. Thus, comparison of the results of specific energy consumption, energy efficiency index and the composite indicator suggest that the economy of scale in terms of energy efficiency can be identified in iron ore mining operations, where large-scale iron ore mining operations recorded the highest energy efficiency while small-scale operations recorded the least energy efficiency. And the amount of energy consumed to process a unit of ore is possibly affected by the cumulative effect of the waste-ore ratio, grade of ore, average haulage distance and production capacity of a particular mine.

4.1.2 Effect of geological and physical parameters on energy efficiency

The correlations between specific energy consumption of the iron ore mines' waste-ore ratio showed a strong, significant correlation, while a non-significant, but a moderately strong correlation showed between energy consumption and the remaining parameters. However, these observations did not allow any strong conclusion between the relationship of energy consumption and the geological and physical variables. The results from the regression analysis clearly reflect the effect of all the aforementioned parameters and their relative importance in estimating the energy consumption of a mining operation, where the generated energy estimation model showed that these variables are capable of explaining 85% of variance in energy consumption of an iron ore mining process. This study identifies the waste-ore ratio as the most significant parameter in predicting the energy requirement of an iron ore mining operation. Waste-ore ratio or the stripping ratio can be explained as the unit of overburden or waste that has to be removed to extract a unit of crude ore mined (US EPA, 1994; Rafiee and Ashghari, 2008), where higher values of waste-ore ratios in mining facilities require a substantial fraction of energy in the excavation and transporting of the overburden (Hancock, 1984), which ultimately increases the amount of energy required to process a unit of ore, such as that found in the current study (Table 3.1). Similar to the current study, a study in South Africa (Thompson, 2005), looking at surface strip coal mining, also reported that the waste-ore ratio is the most significant component of the energy use and the cost of mining operations, since the variations in waste-ore ratio affect the scale of equipment use and the efficiency of the operation.

Of the remaining parameters, grade of ore can be identified as another prominent factor that has an influence in variations in energy consumption in different mining operations, where the current study indicates that the higher grade ore results in low energy consumption (Table 3.4). This is to be expected, since lower grades contain higher amounts of gangue materials, such as phosphorus, sulphur, sodium, potassium, aluminium and silica, that need to be removed (DOE, 2002; Norgate and Rankin, 2002; Norgate and Jahanshashi, 2006; Mudd, 2007; Norgate and Haque, 2010). This fallout of the current study is confirmed by a study carried out in Australian copper and gold mines that observed a higher energy intensity per unit metal produced in low grade mines than in high grade ore mines (Ballantyne and Powell, 2014). Additionally, Sandu and Syed (2008) also reported that the average grade of ore in Australian ore bodies has halved over the past three decades, and has led to a 70% increase in energy consumption across mining operations, suggesting that the grade of ore in a particular ore deposit has a pronounced effect

on energy consumption. However, the correlation graph between ore grade and the specific energy consumption (Figure 3.4) did not show any clear relationship as recorded in the regression analysis and also in the other studies. This probably could be that a high grade ore deposit with high waste-ore ratio requires more energy than a low grade ore deposit a low waste-ore ratio (Hancock, 1984), such as recorded in Mines A, B and H (Table 3.1). Mine A recorded the highest ore grade and also the highest energy consumption to process a unit of iron ore as it has the highest waste-ore ratio (Table 3.1). On the other hand, Mines B and H recorded the same grade of ore, where Mine B has a high waste-ore ratio which resulted in a higher energy requirement than Mine H which has a low waste-ore ratio (Table 3.1). Thus, it is suggested that there is no simple relationship with the grade of ore and energy consumed in mining (Hancock, 1984), which reflects that the synergetic effect of these geological variables has a pronounced effect on the amount of expended energy in mining as reported in the current study (Table 3.4).

Other variables, which have an influence on the amount of energy required to process a unit of ore were: the average haulage distance and the production capacity of the mines, and the latter recorded a negative association with energy consumption (Figure 3.4 and Table 3.4), suggesting that as the production capacity increases the amount of expended energy in mining operation decreases, resulting in an economy of scale in iron ore mining operations based on energy efficiency (Section 4.1.1). Surprisingly, this study indicated that as the average haulage distance increases so does the energy consumption (Figure 3.4 and Table 3.4). This was unexpected, since it is apparent that longer distances to processing plants, waste dumping sites, and tailing dumping sites cause significant increases in fuel consumption in dump trucks; for the reason that fuel efficiency decreases with increasing haulage distances (Awuah-Offei, Osei, & Askari-Nasab, 2011). A study in India (Sahoo, Bandyopadhyay and Banerjee, 2013), however, found that the dump-truck operations in larger mines with longer haul distances is more energy-efficient than in smaller mines with shorter haul distances, which was also identified in the current study (Figure 3.4 and Table 3.4). This was probably because of a reduction in queuing or truck waiting gained from increasing haulage distances, mainly in the waiting time at the loading point (Awuah-Offei, Osei, & Askari-Nasab, 2011). Within a mine, a typical haulage cycle is comprised of four major actions, which are unloaded travel, loading, loaded travel and dumping (Smets, Eger, and Grenier, 2010; Carmichael et. al, 2014), and is repeated between the loading and dumping points. A truck experiences two waiting times in a cycle, where one is at the loading point, which is the manoeuvre time of the truck at excavator, and has been identified as a considerable amount, while the second waiting time is at the

dumping point for the truck to dump the ore, which is assumed to be very small (Carmichael et. al, 2014). Thus, decreases in manoeuvre time of a truck results in reduction in inefficient diesel combustion and ultimately improves the energy efficiency of the operation.

Another reason for high-energy efficiency in larger mines with longer haulage distances could be that the larger mines are using overland conveyor belts in addition to dump trucks to transport the blasted ore to processing plants, as in some of the medium-scale mines considered in this study. However, in the small-scale mines, dump trucks are being used to transport the blasted ore to processing plants, since the haulage distances are comparatively lower than medium and large-scale operations. Dump trucks are powered by diesel engines and are highly energy-intensive (US DoE, 2007; Norgate and Haque, 2010). Pitt and Wadsworth (1981) reported that a 30% savings in the haulage energy requirement could be obtained in mining operations by installing conveyor belts to transport the ore. Thus, implementation of such energy-efficient technologies in larger mines could possibly have a great influence on energy consumption at different mining operations. Thus, for these reasons, it is suggested that the larger mines such as Mines G and H with longer distances are more energy-efficient than the smaller mines such as Mines A, B and C with shorter haulage distances (Table 3.1). The analysis of the abovementioned geological and physical variables upon the amount of energy consumed show that the waste-ore ratio is the most influential variable, and suggests that it is the symbiotic effect of grade of ore, waste-ore ratio, average haulage distance and the production capacity that are being affected on the energy consumption of a mining operation.

4.1.3 Effect of mine planning and mining equipment on energy efficiency

In addition to the effect of geological and physical factors on energy consumption in mining operations, mine planning could be another factor affecting the energy requirements of the mining process. In the iron ore mines considered in this study, most of the mines were multi-pit mines except Mines C and G, which are single pit mines (Table 3.1). Results show that Mine G, a large-scale mine, recorded a lower amount of energy consumed per unit of ore processed, while Mine C recorded the lowest energy consumption among the small-scale mines. Operating multiple pits is a common practice undertaken to obtain processed ore to meet the grade requirements of the client. This is often achieved through blending ore from different pits (Caccetta and Hill, 2003; Rafiee and Asghari, 2008; Askari-Nasab, Pourrahimian, Ben-Awuah and Kalantari, 2011). Such operations demand more labour, equipment and capital to operate several pits simultaneously, and may also need more onsite electricity production and

use more diesel in ore and waste haulage. Thus, it can be argued that operating a large single pit is more energy-efficient than operating several small pits.

Another reason that can be proposed to explain the difference in energy efficiencies in mining operations may be the number of pieces of equipment used in the mining operations, since the number does not increase proportionately. Other studies of iron ore mining operations (US DoE, 2007; Norgate and Haque, 2010) suggest that, the number of drilling machines could vary from two up to six, and the number of haul trucks could vary from 10 up to 22 as the mines increase from medium to large-scale operations. Therefore, in large-scale operations, the energy consumption of the higher number of machines and trucks, possibly larger load capacities and efficient fleet management would allow for a greater output, resulting in a lower amount of energy consumption in large mines to process a unit of output. In small-scale operations, the number and possibly the sizes of pieces of equipment will be less resulting in smaller output and hence a higher energy consumption per unit of output.

4.1.4 Carbon dioxide emissions across scales of operation

The carbon dioxide emissions from each scale of iron ore mining operations in the current study show that, like energy consumption the small-scale mining operations are responsible for the highest amount of emissions per unit of processed ore. Large-scale mines recorded the highest total carbon dioxide emissions largely as a consequence of their size. Carbon dioxide emissions occur as a result of the direct use of fossil fuel and indirectly from the purchase of energy and both contribute to the amount of energy consumed (Worrell, Bernstein, Roy, Price and Harnisch, 2009; De La Torre, 2011; Prior, Daly, Mason and Giurco, 2013). The highest carbon dioxide emissions are thus expected from mining operations which are energy-intensive, since the energy consumption and the carbon dioxide emissions values recorded in this study show a strong positive linear relationship with each other.

4.2 Analysis of Process Stages

4.2.1 Comparison of Energy Intensive Process Stages in Small and Medium Iron Ore Mining Scales in Western Australia

The results of the detailed analysis of iron ore mining process stages of small and medium-scale operations identify that loading and hauling is the highest energy-demanding process stage in Western Australian iron ore mining operations regardless of the scale at which it is operating. And the mean specific energy consumption for loading and hauling in small scale operations is higher than that of medium-scale operations. This suggests that the resulting economy of scale (section 4.1.1), based on energy efficiency across scales of operation, can be observed at the process stage level since a lower amount of energy resulted in loading and hauling a unit of ore at the higher scale of operation. Although the geological and physical variables explain the differences in energy efficiencies across scales, the variables recorded in this study do not show any clear relationship with the loading and hauling energy consumption in the two operational scales as expected. Thus, longer haulage distances and comparatively higher waste-ore ratio recorded in medium-scale operations resulted in lower energy consumption in the loading and hauling process stage. Therefore, this suggests that the loading and hauling energy is more likely to be associated with the equipment used at each scale of operation (Table 4.1), because loading and hauling energy consumption in medium-scale operations would be much higher than the small-scale operations if associated with geological and physical parameters (Table 3.1). This hypothesis is supported by a study carried out by Awuah-Offei (2016), looking at the energy efficiency in mining operations, which reported that the efficiency of the loading and hauling variation mainly depends on the efficiency of the equipment units used to load and transport the ore.

When the haulage equipment use in small and medium scale operations was analysed, it indicated that 75% of the haul trucks used in the medium-scale operations are with larger load capacities (>150 t), compared with the small-scale operations (Table 4.1). Since loading and hauling equipment is generally powered by diesel technologies which are highly energy intensive (US DOE, 2007), increases in load capacities would possibly be expected to increase amounts of fuel consumption due to the high power requirement. However, a study in India (Sahoo et. al, 2014) reported that the fuel consumption decreases with increasing load capacities, suggesting that the productivity is increasing with equipment with larger capacities since the payload per unit of fuel consumption is high. Confirming the same fact, Motlogelwa

Table 4.1: Comparison of haulage equipment used in small and medium scale operations recorded in the databases and the published literature the mines used in this study

Scale	Equipment	Model	Engine Capacity (KW)	Gross Weight (t)	Empty Weight (t)	Pay Load (t)
Small Scale	Haul Trucks	CAT 777F	758.0	163.3	74.0	89.3
		CAT 785C	1082.0	249.5	95.7	153.8
		CAT 785D	1082.0	249.5	117.6	131.9
		CAT 789B	1342.3	317.5	121.9	195.5
		CAT 789D	1566.0	324.3	99.1	225.2
		KOMATSU 730E - 7	1491.0	324.3	140.6	183.7
		KOMATSU HD785-7	895.0	166.0	72.0	94.0
		Volvo A40D	313.0	68.3	31.3	37.0
Medium Scale	Haul Trucks	CAT 777F	758.0	163.3	74.0	89.3
		CAT 777D	746.0	163.4	64.7	98.7
		CAT 785C	1082.0	249.5	95.7	153.8
		CAT 789C	1417.0	317.5	140.5	177.0
		CAT 789D	1566.0	324.3	99.1	225.2
		CAT 793C	1715.0	376.5	113.5	263.0
		CAT 793F	1976.0	390.0	163.2	226.8
		KOMATSU 930E	2014.0	502.0	210.2	291.8
		Terex 3700	1510.0	335.7	149.7	186.0

and Minnitt (2013) observed that the fuel consumption of a haul truck declined from 1.68 litres per tonne to 1.57 litres per tonne when the load capacity increased from 18 t to 21.5 t. Thus, in the current study it is also evident that the equipment with larger load capacities in the medium operational scale would allow for a greater output, resulting in a lower amount of energy consumption to load and haul a unit of ore, whereas equipment with smaller load capacities in small-scale operations results in a higher amount of energy consumption in loading and hauling.

Another explanation for the low energy consumption in loading and hauling in medium-scale operations could be related to the method of transportation of ore. The small-scale iron ore mining operations are using haul trucks for transportation of blasted ore to the processing plants which are usually powered by the energy-intensive diesel technologies. The efficiency of these diesel equipment varies from 30% - 45% (US DOE, 2007), therefore results in high amounts of diesel consumption to transport a unit of ore. In contrast, medium-scale operations considered in this study are using overland conveyor belts to transport ore to the processing facilities in addition to the energy-intensive haul trucks. Conveyor belts are higher in energy efficiency and therefore significantly reduce the energy consumption in material handling due to their efficient transportation (Zhang and Xia, 2011), resulting in lower energy consumption to transport a unit of ore. A study carried out by the United States Department of Energy (2007) reported that the average efficiency of a conveyor belt is assumed to be 85%, which is the efficiency of a typical electric motor and approximately two times higher in efficiency than a diesel engine. Thus, the operations with the energy-efficient conveyor belts would result in lower amounts of energy in loading and hauling operations, as recorded in the medium-scale operations of this study.

Advancements in technology have also resulted in higher energy efficiencies in the machinery (Sullivan, 1990; Gajogo and Dhaou, 2015), and implementation of these advanced machineries at the mining and mineral processing operations could possibly have a great influence on energy efficiency. One such implementation is the computer-assisted autonomous haul trucks which are being used in the medium-scale operations considered in this study. Autonomous haul trucks are considered to be more energy-efficient since they remove the human operators completely from the haulage operations whose performance may vary on the operating shift (Parreira and Meech, 2012) as well as the behaviour of the driver. A study in Canada (Parreira, 2013) reported that the autonomous haulage systems resulted in an improvement in fuel consumption by 6.1% L/t and also had the potential to increase the productivity by 21.3%. This

could be mainly because, compared to the human operators, an autonomous haul truck can be considered to be operating optimally almost all the time, which results in optimal gear shifting and leads to significant fuel savings since the computer assisted control algorithms can design acceleration set points more precisely (Parreira and Meech, 2012). Early research has shown that switching to the right gear in haul trucks results in a 15% reduction in fuel consumption (Parreira and Meech, 2012). Furthermore, optimal speed setups in autonomous haul trucks may also result in reduction in delays and idle time in a truck cycle and will lead to reduction in inefficient diesel usage, which ultimately improves the fuel consumption efficiency. Thus, implementation of autonomous haul trucks appears to have contributed significantly to lower energy consumption in loading and hauling in medium-scale operations due to the high fuel efficiency in these driverless trucks.

The subsequent high energy-demanding process stage which was identified in this study is milling and stockpiling of iron ore, of which the energy efficiency of milling varies widely (Fuerstenau and Abouzeid, 2002). It would be expected that with the increasing scale of operation, the energy consumption in milling and stockpiling in medium-scale operations would be lower than the small-scale mining operations. Surprisingly, this was not the case in milling and stockpiling, since the medium-scale operations recorded approximately 2.5-fold higher energy consumption to mill and stockpile a unit of ore compared to the small-scale operations. Both medium and small-scale operations produce direct shipping ore (DSO), where this ore undergoes simple crushing and grinding processes to obtain the size requirement. However, characteristics of mill feed undergone in each milling operation could be identified as a possible explanation, since parameters including moisture content and grain characteristics of a specific ore-type play a vital role in determining the effectiveness of the milling process (Fuerstenau and Abouzeid, 1998; Kanchibotla, Valery, and Morrell, 1999; Fuerstenau and Abouzeid, 2007; Saramak 2011). Medium mining operations considered in the current study are conducting their mining below the water-table which resulted in considerably higher moisture content, 7-9%, compared to the small-scale mining operations which have an average moisture content of ~3%, thus resulting in a higher amount of energy to mill a unit of ore. Crushing and grinding process stages in mining operations are often operating in dry conditions (Lu, 2015), and it is hard to handle the wet ore in these dry operations. As a result, the wet ore needs to undergo some additional energy-intensive process stages including wet scrubbing and screening (Lu,2015). This results in a higher amount of energy to mill a unit of ore, as resulted in the medium scale mining operations in the current study. These results agree with observations in Saramak and Kleiv (2013), and Fuerstenau and Abouzeid (1998) which suggest

that the moisture content has a negative influence on the specific energy consumption in milling operations.

In addition to the moisture content of the mill feed, the amount of beneficiation needed to obtain the required quality of final product could also be by influenced the amount of energy consumed at the milling and stockpiling process stage in iron ore mining operations. Although, the medium and small-scale operations process ore from similar geological origins, the composition of iron content and the impurities vary according to the lithological formation of the particular ore (O'Brien, 2009; Yellishetty et.al, 2012). The ore feed in medium mining operations are marra mamba ore, and a mixture of brockman, channel iron deposits and detrial iron deposits and often contain an average ore grade of 57% Fe, whereas the majority of the iron ore processed at the small-scale processing plants are high grade hematite and consist of an average iron content of 61% Fe (Table 3.1). Since the comparatively low grade ore needs a number of stages of crushing and grinding to upgrade the ore to the required quality, the energy consumption to process a unit of ore in medium-scale operations would be much higher than that recorded in the small-scale operations.

Drilling and blasting is another energy-intensive process in iron ore mining operations in Western Australia, and the medium-scale operations recorded a higher energy consumption in the drilling and blasting process, while small-scale operations recorded low energy consumption. There could be a number of explanations to this variation, since drill and blast energy consumption vary considerably upon the variations in geological conditions of the ore including bedding structure and material properties such as porosity and density (Kennedy, 1990; Kanchibotla, Valery, and Morrell, 1999). However, the current study does not possess the information related to the mines considered in this study to be able to identify the major reasons for the energy consumption variations in drilling and blasting in small and medium operational scales. It is therefore important to investigate the relationship between these factors and the variation in drilling and blasting energy, since this process stage is one of the key energy-intensive process stage in iron ore mining operations where significant energy-saving potential could be expected.

Results from this stage of study were compared with the results of similar studies carried out worldwide to identify the similarities and the differences in energy intensive and highest carbon dioxide-emitting process stages (Figure 4.1). This comparison includes the current study and another study carried out in Western Australian iron ore mines (Norgate and Haque, 2010), one study that was undertaken in the United States (US DOE, 2007) and another study carried out in Canadian iron ore mines which has data only for milling and stockpiling (Natural Resources Canada, 2005). All three studies in this comparison have identified that the loading and hauling operations are the most energy intensive process stage in mining operations, while milling and stockpiling, and drilling and blasting consume lesser amounts of energy respectively.
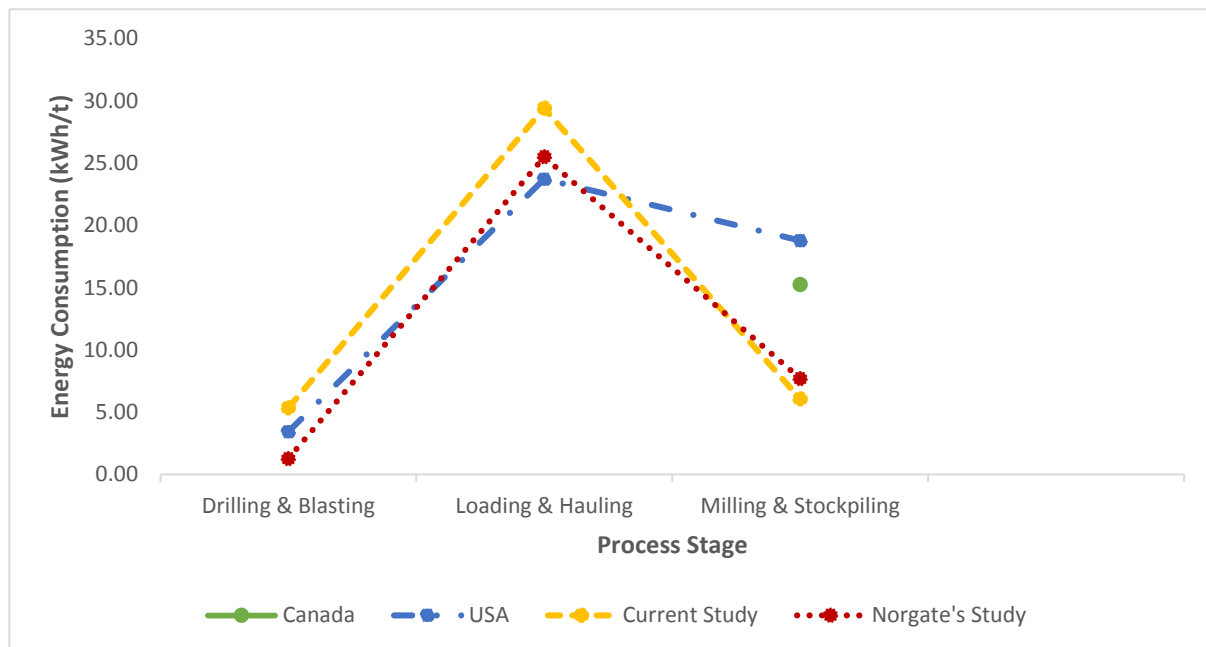
Figure 4.1: Comparison of the energy consumption in energy intensive process stages in iron ore mining operations in Western Australia, United States' and Canada

The amount of energy consumed to load and haul a unit of ore varies among the three studies where the Western Australian iron ore mining operation recorded higher amount of energy compared to the USA mining operations. There may be several reasons for variations in energy consumption; one reason can be where the high demand for Western Australian iron ore led the mining companies to extract iron ore from complex new mines including mines with thick overburden. Thus, these mines have generated more waste material during excavation, resulting in more energy consumption to handle and transport the higher amounts of overburden material. Another reason for low energy consumption in loading and hauling in USA mining operations could be the extensive use of energy-efficient technologies such as

conveyor belt systems (US DOE, 2007). As discussed in section 4.2.1, the electric motor systems used in the conveyor belt systems are more energy-efficient than the diesel technologies which are used in the haul trucks, resulting in a lower amount of energy to transport a unit of ore. The majority of the mines considered in both the current study and the Norgate and Haque study (2010) are small-scale and medium-scale mines where small-scale mines use only haul trucks for transporting the blasted ore to the processing plants, while some of the medium-scale mines use conveyor belts as well. Thus, extensive use of diesel equipment in Western Australian mines possibly resulted in high energy consumption to load and haul a unit of ore compared to the mines in United States, due to low fuel efficiency.

Milling and stockpiling is the second highest energy consuming process stage identified in all these studies, where the energy consumption in milling and stockpiling in USA and Canadian mines is much higher than that of the Western Australian mines. The low energy requirement in milling operations for Western Australian iron ore may be influenced by several factors. Western Australian iron ore is high-grade hematite ore (62-63% Fe), which traditionally produces direct shipping ore (DSO) (Geoscience Australia, 2014a; Lu, 2015). Therefore, this ore generally requires minimum processing and undergoes stages of simple crushing and grinding to produce lumps and fines, which results in low energy consumption in milling and stockpiling. In contrast, the iron ore mined in USA is low in iron content (25-30% Fe), largely hard taconite-type ore and contains varying proportions of hematite and magnetite, where magnetite is the main iron mineral that is recovered in the mining process (Lu, 2015). Thus, compared to the WA iron ore processing, USA iron ore requires some additional processing stages other than crushing and grinding and includes magnetic separation and in some instances flotation to produce a magnetite concentrate and finally requires pelletizing before use (Lu, 2015). Therefore, these processing stages demand significant amounts of additional energy in milling operations, resulting in greater amounts of energy in USA iron ore milling operations.

Despite the iron mineral recovered from milling operations, the iron content of the ore may also have influenced the high milling and stockpiling energy in USA mining operations, since the iron content is significantly lower in USA ore (25-30% Fe) compared to WA ore (62-63% Fe). Lower grade ore contains higher amounts of gangue material, thus requiring additional energy to remove these impurities (DOE, 2002; Norgate and Rankin, 2002; Norgate and Jahanshashi, 2006; Mudd, 2007; Norgate and Haque, 2010). The magnetite taconites found in USA iron ore mines are hard, fine-grained, compact and dense rocks which contain 40-55% of silica (Poveromo, 1999). Therefore, these high impurity levels in USA iron ore possibly result

in higher energy consumption in milling operations than the WA iron ore, of which the SiO_2 levels range from 3-7% (O'Brien, 2009). In addition to the impurities, the structure of the rocks could also contribute to the increased amounts of milling energy in USA iron ore operations. The complex structures of finer-grained, hard, compacted rocks found in USA mines may consist of strong bonds and therefore possibly require greater energy to fracture these bonds, since the energy required in milling operations increases with the fineness and the hardness of the ore (Jankovic, Valery, Maloney and Markovic, 2006). Similar to the USA iron ore, Canadian iron ore also contains hematite-magnetite ore and the iron content ranges from 30-40% Fe (Lu, 2015). Fine-grained to coarse-grained structures can be found in Canadian iron ore, and beneficiation requires gravity separation and magnetic separation as required and undergoes agglomeration to form pellets before use (Poveromo, 1999; Lu, 2015). Thus, compared to the WA iron ore, Canadian iron ore demands significant amounts of energy in milling operations due to the complex beneficiation process stages that are undergone before obtaining the final product, and processing of low grade iron ore may also claim greater energy resulting in higher amounts of energy per unit of processed ore.

Drilling and blasting is another key energy-intensive process stage in iron ore mining operations, where the USA mining operations record lower amounts of drilling and blasting energy per unit of ore compared to the current study and a higher value than to the previous study carried out in WA iron ore mines. This was unexpected as USA mining operations extract magnetite-taconite which is more abrasive with an average hardness of >6.5 in Mohs scale (Hagenbuch, 2015) compared to the hematite ore extracted in WA of which the hardness ranges from 5.5-6 (Hagenbuch, 2015). Thus, it would be anticipated that the taconite ore results in higher amounts of energy in drilling and blasting than the amount of energy consumed in WA mines, since taconite ore often requires additional drilling and blasting to extract the ore because of its hardness (US EPA, 2002). However, the current study records higher energy consumption than USA mines; again, this may be due to complex structures of newly explored mines and increased thickness of the overburden which results in deeper drilling and higher amounts of blasting material to uncover the orebody. The mineral boom experienced in the WA iron ore industry over the last decade exploited all the rich iron ore deposits and encouraged the mining companies to extract more complex deposits with reasonable geological probability and these deposits require more drilling and blasting energy to extract the valuable ore. When comparing the drilling and blasting energy of the current study with the energy consumption in drilling and blasting in the Norgate and Haque study, the low energy requirement in the previous study confirms this hypothesis that present iron ore mining

operations may be influenced by thick overburdens and complex structures as a result of extensive mining over time. These reasons could possibly explain the higher energy consumption in drilling and blasting in the current study compared with the other studies.

4.3 Energy Efficiency Improvement Recommendations for WA Iron Ore Operations

Studying energy consumption in iron ore mining process stages provides information on the high energy intensive process stages in WA iron ore operations, and it is these stages where the major benefits in energy efficiency and reductions in carbon dioxide emissions may be realised, which will ultimately improve the environmental and economic performance of the overall mining operation. Implementation of energy efficiency programs can be identified as an important approach which will allow companies to achieve improvements in energy savings at no or low additional costs. Since this study provides the preliminary identifications of energy-intensive process stages specific to each mining operation, energy managers, with the help of an energy management team consisting of representatives from each of the major component of the operations, can choose an appropriate energy-efficiency plan which will improve the efficiency of mining operations by setting key performance indicators and targets. The successful implementation of energy-efficiency programmes will benefit the companies with significant cost savings, reduction in greenhouse gas emissions, improvement in productivity and, in addition, adapting of management system certification such as ISO50001:2011- Energy Management Systems (EnMS).

Looking at the energy-intensive process stages, shifting to larger capacity haul trucks could be another practical recommendation that will significantly improve the overall energy efficiency especially in small-scale operations, where in some instances, loading and hauling has accounted for 75% of the total energy consumed. In order to ensure efficiency improvement and the achievable savings, it is imperative to analyse the payback period of the particular equipment and the fuel cost, which will clearly show the expected savings. Mine planning and design can be identified as another energy efficiency improvement approach, that will result in a reduction in energy consumption mainly in loading and hauling, and will ultimately improve overall energy efficiency. Effective mine planning will result in the optimum haulage roads with reduced distances and favourable road conditions, therefore these condition will result in a reduction in truck cycle time and fuel consumption, which could possibly improve the productivity of loading and hauling operations.

Chapter 5 - Concluding Remarks

The aims of the first stage of this study were to determine the most efficient scale of iron ore mining operations in Western Australia, and to identify the parameters that influence the differences in energy consumption across different scales of operation. The iron ore mining operations resulted in a strong economy of scale in terms of energy efficiency, where large-scale iron ore mining was identified as the most efficient scale of operation, while the small-scale operations were identified as the least efficient scale according to the results of the Specific Energy Consumption and the Energy Efficiency Indicator. The distinct behaviour of the three operational scales displayed in the composite indicator suggests that the energy consumption of a mining process is significantly influenced by the physical parameters and geological parameters which include: grade of ore, average haulage distance, waste-ore ratio and production capacity of an individual operation. Although waste-ore ratio was identified as the significant parameter that affects the differences in energy consumption in iron ore mining operations, the regression analysis results show, it is the combined effect of the aforementioned parameters that influence the most on energy consumption variations in different iron ore mining operations.

The aims of the second stage of the present study were to identify the energy-intensive process stages in iron ore mining operations; and to identify the similarities and the differences in the iron ore mining process stages across different scales. These results show that there is no significant difference between small and medium-scale operations process stages, but a significant difference was observed in energy consumption at each process stage. Loading and hauling was identified as the most energy-intensive process stage in WA iron ore mining operations, while milling and stockpiling is identified as the second highest and the drilling and blasting as the third highest energy consuming process stage. Characteristics of the equipment fleet were identified as the prominent factors that influence the loading and hauling energy consumption at different scales of operations, where the larger load capacities, energy efficient technologies and advanced mechanisms in equipment result in lower energy consumption in loading and hauling in higher operational scales. It was observed that the energy consumption in milling and stockpiling is mainly dependent on the properties of the mill feed, where the results of this study show that the high moisture content in ore results in increased amounts of energy in milling operations.

Limitations and Future Recommendations

The major limitation of this study was the access to the data. This was mainly due to different mining companies undertaking different levels of data reporting, as experienced in this study. As recorded in the process stage analysis, energy consumption of small-scale mining operations was analysed into seven major process stages, as a result of detailed data reporting in diesel consumption by mining equipment, while energy consumption in medium scale mining operations was analysed only into four process stages. Thus, these results allow the small-scale mining operations to identify additional energy-intensive process stages, where more energy savings potential may be realized. However, the comparison of the energy-intensive process stages may be more comprehensive, and could possibly identify additional variables which influence the energy consumption differences in process stages at different-sized mines in Western Australia.

Furthermore, this study considered various media, which iron ore mining and mineral processing companies used to disclose their sustainability performance, to carry out the broad scale analysis of the operations. Of particular concern, were annual reports, stand-alone sustainability reports and corporate websites. However, significant inconsistencies were observed in the level of disclosure in the reporting media of different companies. There may be various reasons for these differences in sustainable reporting. Confidentiality policies of the respective companies can be identified as one explanation, since most of the companies are self-laudatory (Frost, Jones, Loftus and Van Der Laan, 2005). For instance, some companies have reported the direct and indirect energy separately with Scope 1 and Scope 2 emissions, while some others reported only the total energy consumed and greenhouse gas emitted. Facility level data reporting was observed for some companies, while some reported corporate level emissions. Since many companies operate several operations, some of them may have negative impacts, while reporting as a group will not show any undesirable impacts and therefore, companies may be interested in reporting at corporative level consumption and emissions. For these reasons, mining companies may be unable to report their sustainability performance in a detailed manner. This has implications for how serious the mining companies, and possibly the government are, concerning the true sustainability performance of the industry. This means that a new standard reporting system, that would contain the necessary parameters, should be introduced to the mining and mineral processing industry in Australia.

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