

# Strategic investment decisions in Zambia's mining sector under a constrained energy system



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degree of

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To my loving parents (both deceased) and their grandchildren.



## Declaration

I, Bernard Tembo, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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Bernard Tembo

January 2018



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## Abstract

This thesis studies the challenge of balancing between economic growth and social development that many developing countries are facing. The study sought to understand the impacts that these goals have on each other and how these impacts could be minimised. It looked at how clean energy access is modelled in developing countries and also how growth in Zambia's mining sector would be impacted by meeting the government's clean energy access targets in the residential sector. On one hand, increasing access to clean energy would lead to increase in energy demand, which would, in turn, imply increased capital investment in the energy supply system. This augmented investment means increase in energy prices which in turn would limit the growth of the mining sector (the backbone of the economy). Limited growth implicitly means reduced funding for clean energy projects. Thus, in order to adequately capture these complex interactions, three bottom-up models were developed: energy demand, energy supply and mining models. The energy models sought to understand how energy demand would evolve by 2050 and how much capital investment would be required to meet this demand. The mining model focused on understanding how developments in the energy sector would impact strategic investment decisions in the mining sector. It was found that approaches used to study how households transition from one energy fuel to another in developing countries had significant conceptual errors. However, these errors could be minimised by using a bottom-up approach. Furthermore, it was found that while profit margins would reduce as a result of increase in energy prices, the impact of these prices on the firm's production output was negligible - except if a firm is a marginal mine operation. The output was not impacted because mining firms make decisions based on thresholds and not marginal

decrease in profits. Thus, even though reliable energy supply is critical in mining operations, the influence of energy price in investment decision making in Zambia's mining sector is limited. The key decision variables in the sector were found to be copper price, grade and type of ore.

## Publications

1. Spalding-Fecher et al. 2017. Electricity supply and demand scenarios for the Southern African power pool, Energy Policy, DOI <http://dx.doi.org/10.1016/j.enpol.2016.10.033>.
2. Tembo, B., 2016. Modelling of capital investment decisions. System Dynamics Conference, Delft, The Netherlands. <https://www.systemdynamics.org/assets/conferences/2016/index.html>
3. Tembo, B., 2016. Modelling of energy efficiency in Copper mining industry. IAEE Conference, Bergen, Norway. <http://www.iaee.org/proceedings/article/13683>
4. Spalding-Fecher et al. 2016. The vulnerability of hydropower production in the Zambezi River Basin to the impacts of climate change and irrigation developments, Mitig. Adapt. Strateg. Glob. Change, DOI 10.1007/s11027-014-9619-7.
5. Tembo, B., 2015. Trade-offs in Zambia's Energy System: Identifying key drivers. WholeSEM Conference, Cambridge, UK. <http://www.wholesem.ac.uk/wholesem-events-repository/annual-conf-15>
6. Milligan, BM et. al., 2014. (as an academic contributor). 2nd GLOBE Natural Capital Accounting Study: Legal and policy developments in twenty-one countries. GLOBE International, UCL Institute for Sustainable Resources. <http://discovery.ucl.ac.uk/1432359/>

7. Spalding-Fecher, R., et al., 2014. Climate Change and Upstream Development Impacts on New Hydropower Projects in the Zambezi Project: Report for Climate and Development Knowledge Network, January 2014.  
<http://www.erc.uct.ac.za/groups/esap/current/esap-zambezi1>
8. Tembo, B. and Merven, B., 2013. Policy options for the sustainable development of Zambia's electricity sector. *Journal of Energy in Southern Africa*, 24(2), pp.16–27.  
<http://www.scielo.org.za/pdf/jesa/v24n2/02.pdf>

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“Ambition never comes to an end.”

KENNETH KAUNDA

Zambia's First Republican President



# Glossary

**CEC** Copperbelt Energy Corporation Plc [163](#), [290](#), [292](#)

**clean energy** Energy that causes minimal pollution to the atmosphere and environment when used. Examples of clean energy on the supply side are solar, wind and hydro technologies. On the demand side, electricity and gas (bio-gas included) are examples of clean energy. In this thesis, the discussion on clean energy focuses on the demand side. As such, a clean energy form is that which leads to minimal indoor air pollution (in the residential sector). Electricity and gas are considered clean while charcoal, wood, coal and other crop residuals are dirty and unsafe fuels. [29](#), [30](#), [32](#), [33](#), [76](#), [79–82](#), [130](#), [139](#), [147](#), [149–151](#), [153](#), [155](#), [186](#), [187](#), [194](#), [197](#), [203](#), [218](#), [239](#), [240](#), [244](#), [252–255](#), [259–262](#), [264–268](#)

**COMEX** New York Commodity Exchange [46](#)

**CSO** Central Statistics Office [30](#), [33](#), [136](#), [137](#), [142](#), [143](#), [155](#), [299](#)

**DoE** Department of Energy [331](#)

**DoM** Department of Mines [332](#)

**energy efficiency gap** The energy use difference that exists between the current or expected future use and the optimal current or future use. This helps in quantifying the energy saving opportunity available the stakeholder. [53](#), [99](#), [127](#), [174](#), [178](#), [180](#)

**energy intensity** A measure of energy consumed per unit of activity or output. This measure includes, but is not limited to, *kWh/tonne*,

*GJ/HH, Btu/US\$ or MJ/Kwacha.* 58, 61, 70, 78, 130, 131, 133, 140, 143, 145, 188, 242

**ERB** Energy Regulation Board of Zambia 32, 163, 164, 224, 290

**HFO** Heavy Fuel Oil 49, 301

**IEA** International Energy Agency 62, 63, 142, 163, 186

**KCM** Konkola Copper Mines Plc 49–51, 91, 164, 336

**LEAP** Long-Range Energy Alternative Planning System 33, 56, 77, 129, 146, 155, 185, 188

**LHPL** Lunsemfwa Hydro Power Limited 290, 292

**LME** London Metal Exchange 46

**LPG** Liquefied Petroleum Gas 30, 149, 187, 194, 252, 255

**MARKAL** MARket ALlocation 56, 62, 145

**MoE** Ministry of Energy 32

**OAT** one-at-a-time 59, 151

**ore grade** The share of the metal in the ore reserve. This is expressed as total content of the metal (in tonnes) divided by the total ore size (in tonnes). 39, 40, 43, 47, 51, 68, 70, 84, 86, 90, 91, 97, 127, 134, 160, 162, 164, 166, 171, 172, 178, 183, 189, 218, 220, 225, 230, 233, 235, 237, 239, 240, 250, 251, 257, 263, 265, 266, 333, 334, 341, 342, 354, 373

**OSeMOSYS** Open Source Energy Modeling System 33, 129, 145, 147, 185, 188, 198, 219, 222

**REDD+** Reducing emissions from deforestation and degradation and enhancement of carbon stocks 148, 210, 254

**SAPP** Southern Africa Power Pool [146](#), [198](#), [216](#)

**SNL** SNL Metals and Mining [164](#)

**suppressed energy demand** The energy demand that is not met. It is a situation where required energy is not adequately supply to the end-user: this could be due to limited supply infrastructure or poverty. [131](#)

**TAZAMA** Tanzania Zambia Mafuta Pipeline Limited [149](#)

**tonCath** tonnes of copper cathodes [171](#), [173](#), [174](#)

**tonConc** tonnes of copper concentrate [171](#), [173](#)

**tonContCu** tonnes of contained copper [171–173](#), [177](#), [178](#)

**tonOre** tonnes of ore [168](#), [169](#), [171–173](#), [177](#), [181](#)

**World Bank** The World Bank Group [164](#), [369](#)

**ZESCO** ZESCO Limited [146](#), [148](#), [163](#), [224](#), [291](#), [292](#)



# Chapter 1

## Introduction

Policy makers in developing countries are confronted with the challenge of balancing between social development, economic growth and investing in infrastructure to support this growth. This is a similar dilemma that Zambia's government faces; it hopes to increase access to [clean energy](#)<sup>1,2</sup> and at the same time hopes that the economy continues growth at a fast rate (GRZ, 2006). On one hand, increase in access to clean energy leads to increase in energy demand. This, in turn, implies more capital investment in the energy supply infrastructure.<sup>3</sup> On the other hand, increased investments in the energy sector mean increase in energy prices which in turn could limit the growth of energy-intensive economic sectors, such as the mining sector.

However, these complex interactions between the social goals (such as increasing access to [clean energy](#)), economic growth (such as growth of the mining sector) and development of the energy system are under-researched for many African countries. Further, there is limited understanding of how investment decisions that lead to growth in key economic sectors (such as

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<sup>1</sup>See the Glossary for the definition of [clean energy](#).

<sup>2</sup>While a complete discussion of [clean energy](#) should include both the demand and the supply of energy, the discussion of [clean energy](#) in this thesis is limited to the demand side only.

<sup>3</sup>This thesis takes into account that there is a supply shortage. Thus, to meet any additional energy demand, there would be need to invest in new supply infrastructure which have a higher levelised cost (LCoE) than the current stock.

mining sector) are made. Thus, there is need to research and understand how changes in the economic and energy sectors impact each other and how this would affect the governments' development targets.

Zambia is one of the fast-growing economies in Africa, with an annual average growth rate of 6% between 2005 and 2010<sup>4</sup>. This growth was largely driven by the mining sector<sup>5</sup> which grew by almost 100% between 2002 and 2011 (to 700, 000 tonnes of copper cathodes). This growth coincided with a copper price increase (in real terms) of almost 300% (from US\$1, 850 per tonne in 2002). The mining sector is and has been the backbone of the Zambia's economy (GRZ, 2006; IMF, 2008). For instance, in 2010, the sector accounted for over 80% of the foreign exchange earnings (BoZ, 2011). Thus, the sector is projected to continue playing a critical role in Zambia's social and economic development through to 2030 and beyond (GRZ, 2006; MOF, 2016).

Furthermore, between 2002 and 2010, while electricity demand in the mining sector only increased by 4%, demand in the residential sector grew by over 110%. Despite the growth in residential sector's demand, access to clean energy<sup>6</sup> only increased by 20% (from 18.4% in 2002 to 22% in 2010) (CSO, 2005; 2012). It is for this reason that the Zambian government has increasing access to clean energy as one of its top development priorities (GRZ, 2006; 2011).

The government plans to use income realised from the mining sector (through copper exports) to re-invest into different developmental projects and sectors of the country (GRZ, 2006; MOF, 2016). It is expected that as the mining sector grows, more financial resources could be generated which would enable more investments into clean energy supply infrastructure. This, Zambian government's logic, therefore makes a good case study to

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<sup>4</sup>Complete statistics from Central Statistics Office (CSO) and ZRA only go up to 2010.

<sup>5</sup>The phrases "mining sector" and "copper industry" (in Zambia's context) will be used interchangeably throughout this thesis because mining sector is almost only made up of the copper industry.

<sup>6</sup>The phrases "access to electricity" and "access to clean energy" will be used interchangeably through out this thesis. This is because of the three available energy options (wood, charcoal and electricity), only electricity is clean. Gasses (Liquefied Petroleum Gas (LPG), biogas and natural gas) are other possible future options.



analyse whether such interactions would lead to intended outcomes and what their impacts would be. This is because the interactions between the mining sector and these developmental plans are not straightforward as the above might imply; as there are several feedback loops that would act as barriers to realising these development aspirations.

This chapter gives the rationale for the study and highlights the main challenges that Zambia's energy and mining sectors face. Section 1.1 gives the context of the research. This section also presents research questions and gives the contributions that this study makes. Finally, section 1.2 gives the overview and outline of the thesis.

## 1.1 Research context

In 2010, Zambia had a population of 13 million with per capita annual income of \$748<sup>7</sup> (CSO, 2012; World Bank, 2013). Of the total population, 60% were based in rural areas, of which only 3.1% had access to electricity while 49.8% of the urban population had access to electricity. Further, all households that did not have access to electricity used kerosene, candles or went without lighting service. These households also used traditional fuels (wood and charcoal) for their cooking and heating needs. Traditional fuels, however, are neither safe nor clean and do not provide high quality energy services (Ekholm et al., 2010; Javadi et al., 2013).

As shown in Figure 1.1 below, final energy consumption in Zambia<sup>8</sup> is dominated by traditional fuels and the residential sector. In 2010, the total final energy consumption was 230 PJ and traditional fuels accounted for 71%. This 71% was largely consumed in the residential sector by 82% of the households, for their cooking and heating service (CSO, 2012; IEA, 2012). This means that a large portion (82%) of Zambia's population<sup>9</sup> is using unsafe and unclean fuel for their energy needs, which also has wider environmental impacts such as deforestation.

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<sup>7</sup>In 2005 US\$ constant price.

<sup>8</sup>See Figure A.1 for Zambia's historical total final electricity consumption.

<sup>9</sup>The population in 2010 was 13 million and it is projected to increase to 25 million and 45 million by 2030 and 2050 respectively.

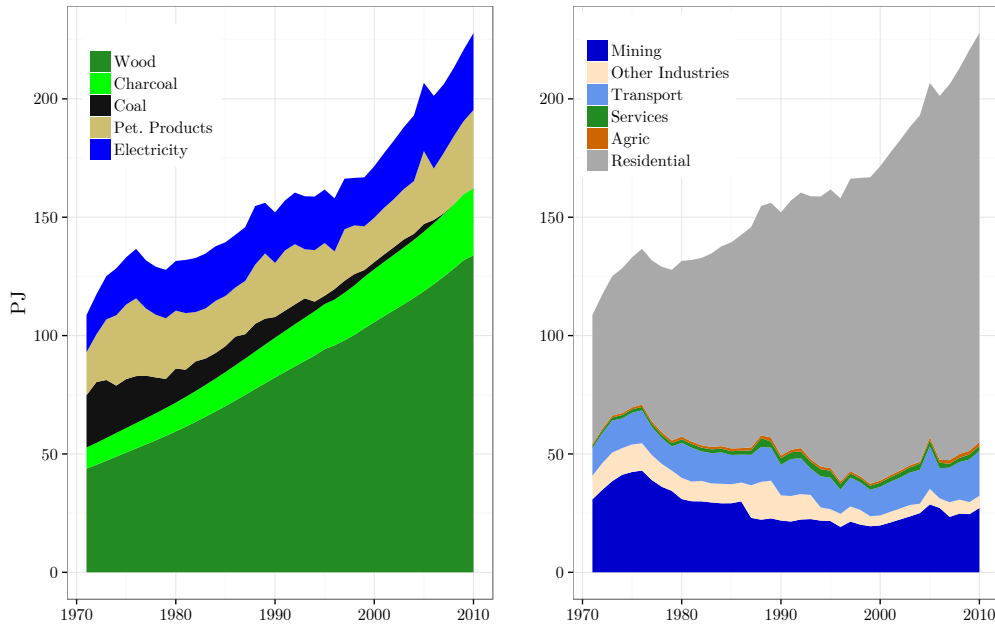


Figure 1.1: Zambia's historical total final energy consumption (ERB, 2013; IEA, 2012; ZESCO, 2013)

These concerns, among others, led to the development of Vision 2030 (GRZ, 2006) and the Sixth National Development Plan (GRZ, 2011)<sup>10</sup> that spelt out the plans of how to increase access to [clean energy](#). Central to these plans is the mining sector, which is private sector led and the largest electricity consumer (over 50%). The sector's value addition is projected to grow at an annual rate of 7.3% (GRZ, 2006). This growth is expected to contribute to the country's social and economic development (GRZ, 2006; MOF, 2016). With increasing access to [clean energy](#) as one of the main development targets, the government targets to reduce consumption of traditional fuels from 73% (in 2006) to 40% by 2030<sup>11,12</sup>. However, there still remain significant challenges to achieving these aspirational targets. The two main challenges are limited energy supply infrastructure and lack of knowledge of how the mining sector would grow over time due to uncertainty in the global market.

<sup>10</sup>The Seventh National Development Plan was recently launched, in July 2017.

<sup>11</sup>The share of urban household is projected to increase from 40% (in 2010) to 47% (in 2030) and 55% (in 2050).

<sup>12</sup>Note: Apart from this work, there are no energy projections that go beyond 2030 in Zambia. This was confirmed by sources from both [Ministry of Energy \(MoE\)](#) and [Energy Regulation Board of Zambia \(ERB\)](#).

### 1.1.1 Research questions

This research, therefore, answers three questions:

1. How would Zambia's energy sector evolve by 2050?
2. How do mining organisations make strategic investment decisions and what are the key decision variables in the mining sector?
3. What impact does increasing access to [clean energy](#) in Zambia have on mining sector's profitability?

The research is thus divided into two themes: development of the energy system and decision making in the mining sector. The first theme sought to understand how energy demand would evolve in Zambia and also how much capital investment would be required to develop the supply system.<sup>13</sup> This theme paid particular attention to how changes in energy use patterns (such as increasing access to [clean energy](#)) in the residential sector<sup>14</sup> would impact the energy price. To achieve this, a review of journal articles (given in Chapter 3) and analyses of statistics from Zambia's CSO and other government agencies and departments were done and the findings were integrated into an energy system model (using [Long-Range Energy Alternative Planning System \(LEAP\)](#) for energy demand and [Open Source Energy Modeling System \(OSeMOSYS\)](#) for energy supply)<sup>15</sup>.

The second theme focused on understanding how mining firms make strategic investment decisions<sup>16</sup> and applying this knowledge to Zambia's mining sector using a system dynamics (SD) model (built on Vensim platform). Development of the SD model is critical in analysing how the mining sector would evolve in Zambia. This is necessary because there is limited knowledge (in Zambia) of how local mining firms make strategic investment decisions yet the sector is vital and is projected to continue playing a critical role in the country's economy ([GRZ, 2006](#); [MOF, 2016](#)). Therefore,

<sup>13</sup>See section [A.1](#) of Appendix [A](#) for a brief description of the electricity sub-sector market in Zambia.

<sup>14</sup>The residential sector is the largest final energy consumer in Zambia.

<sup>15</sup>A detailed description of these two models is given in Chapter [5](#).

<sup>16</sup>Strategic investments are investments that require firms to commit significant resources in order to achieve their desired outcome. See Chapter [4](#) for more details.

understanding the decision processes would help Zambia's policy makers to develop policies and regulations that would create a conducive investment environment.

To achieve the objectives of the second theme, interviews (see Chapter 6 for more details) with local mining firms and industry experts were conducted. The interviews focused on understanding the decision processes of local mining firms, what their main production costs components were and the policy environment that would enhance local firms to invest more were done. Also, a review of industry reports and journal articles (given in Chapters 3 and 4) which helped in identifying the key exogenous factors in the sector's decision making processes as well as the production cost structures and production processes for different mining operations was carried out.

### **1.1.2 Contribution to knowledge**

From the reviewed literature, opportunities to contribute to knowledge have been identified. This research contributes to:

1. Energy system modelling of a small developing country, as most energy systems studies of developing countries focus on big economies such as China, India and Brazil.
2. Literature of firms' strategic investment behaviour under uncertainty, by considering a key economic sector that is energy intensive in a country that has limited energy supply infrastructure.
3. Literature that focuses on the interdependence and trade-offs between developments in the energy sector and growth of key economic sectors. This study captures the feedbacks between these sectors and the impact they have on each other.

## 1.2 Thesis outline

The thesis consists of 8 chapters and accompanying appendices.

After this introductory chapter, Chapter 2 gives a brief industry context and introduces some technical terms used in the industry.

Chapters 3 and 4 are literature review chapters. Chapter 3 reviews literature on energy systems modelling in developing countries and industrial energy uses. It also looks at the structure and key components of the copper industry. It then concludes by explaining the linkage between the copper industry and the energy sector. Chapter 4 reviews literature on strategic decision making in firms. It highlights the influence that environments in which firms operate have on their decision making behaviour and how best this behaviour could be modelled.

Chapters 5 and 6 explain and describe the methods used in modelling and analysing Zambia's energy and mining sectors. Chapter 5 describes the methods used to model energy demand and also identifies key energy drivers. The chapter also describes how energy supply options were evaluated in the supply model. The methods used in modelling decision making in the copper industry are described and explained in Chapter 6. This chapter also identifies key production cost drivers and linkages.

Chapter 7 presents and discusses the results of the research, from the reviews, interviews and models.

Chapter 8 gives the main conclusions and recommendations, and also discusses the limitations of the study and possible future work.



# Chapter 2

## Industry context

This chapter gives a brief industry context of copper. It is divided into two sections: Section 2.1 defines and introduces some technical concepts and terminologies of the industry; while section 2.2 highlights the state of the global copper industry: production and consumption patterns. It also gives the role that the industry plays in Zambia's energy sector.

Copper is an important mineral resource; by weight, it is the third most used metal after iron and aluminium (Radetzki, 2009). It is an important input in our modern day technology and infrastructure development. Thus, copper plays a critical role in today's economies and life-style. In 2010, the industry's gross income was US\$ 146 billion with a net income of US\$ 80 billion<sup>1</sup>: considering total consumption of 19.332 million tonnes, average copper price of US\$ 7, 535 per tonne and average production cost of US\$ 3, 391 per tonne (Cochilco, 2012; World Bank, 2015).

Copper is a mineral found in the earth's crust. It is mainly present in form of sulphide and oxide minerals (see Table 2.1 below). About 80% of the world's primary copper comes from sulphide minerals, with oxide minerals accounting for the balance. Of the total copper global production, 10-15% is produced from recycled material (Davenport et al., 2002; Norgate and Jahanshahi, 2010).

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<sup>1</sup>In nominal price value.

## 2.1 Resources and reserves

**Resource:** A copper resource “is a concentration or occurrence of solid material of economic interest in or on the Earth’s crust in such form, grade (or quality), and quantity that there are reasonable prospects for eventual economic extraction.” (JORC, 2012; pg. 11). Depending on the level of confidence, a mineral resource can be categorised into three: Inferred, Indicated and Measured.

The Inferred resource category includes all the resource that has sufficient geological evidence of the mineral presence but require further exploration and evaluation to upgrade it into the Indicated resource category. When there is sufficient confidence and details to support feasibility evaluation and mine planning, the resource is referred to as Indicated resource. To use the word reserve, part of this resource that can be economically mined could be referred to as probable ore reserve. The final category is Measured resource, which has detailed and reliable information in order to support detailed economic analysis and mine planning. When the confidence is high, economically minable Measured resource can be referred to as proved or proven ore reserve.

**Reserve:** As described above, part of the mineral resource that can be economically feasible to extract is referred to as a reserve. A copper ore reserve is made up of copper, by-products and waste minerals. The size of the reserve varies depending on the price of copper and the unit production cost. Low price and high unit production cost reduce the size of the reserve via raising the ore cut-off grade and vice versa is true. Further, similar to a resource, a reserve could be sterilised by economic, political, social and environmental factors (see Crowson (2011) for a further discussion).

**Cut-off grade:** This is the lowest grade at which mineral extraction or mining is economically feasible. In other words, it is a threshold below which a firm chooses not to produce from the ore. Grade is the share of ore that contains the metal (in this case, copper). On average, the cut-off grade for copper from open pit mines is 0.5% while from the underground mines it is 1% (Davenport et al., 2002). Generally, if the ore only con-



tains one mineral say copper, its cut-off grade will be higher than the ore that contains by-product minerals such as cobalt, gold and silver. This is because these by-products help reduce the unit production cost (at firm level). Further, because there is variance in the manner in which [ore grade](#) is distributed in its ore resource, mining firms usually mine different grades of ore throughout its operational life. For instance, a firm could currently be producing copper from low grade ore because it is the more accessible and also because of the ore distribution (ore production does not move from high [ore grade](#) to low [ore grade](#)).

There are two main types of ore: sulphide and oxide. Majority of the global reserves are sulphide and in particular the chalcopyrite ore ([Dav-enport et al., 2002](#); [Riekkola-Vanhanen, 1999](#)). Table 2.1 below gives a list of the main types of ore. In addition, the type of ore determines the processing facility that a mining firm should develop, see below.

Table 2.1: Main types of copper ore minerals

Mineral	Type of ore	Formula
Chalcopyrite	Sulphide	$CuFeS_2$
Covellite	Sulphide	$CuS$
Bornite	Sulphide	$Cu_5FeS_4$
Anilite	Sulphide	$Cu_7S_4$
Digenite	Sulphide	$Cu_9S_5$
Djurleite	Sulphide	$Cu_{31}S_{16}$
Chalcocite	Sulphide	$Cu_2S$
Carrollite	Sulphide	$Cu(Co, Ni)_2S_4$
Copper	Native	$Cu^o$
Cuprite	Oxide	$Cu_2O$
Malachite	Oxide	$Cu_2(CO_3)(OH)_2$
Azurite	Oxide	$Cu_3(CO_3)_2$
Chrysocolla	Oxide	$(Cu, Al)_2H_2Si_2O_5(OH)4nH_2O$
Planchéite	Oxide	$Cu_8Si_8O_{22}$
Tenorite	Oxide	$CuO$
Brochantite	Oxide	$Cu_4(SO_4)(OH)_6$

**Mining methods:** Mining method is the process by which ore is extracted from the earth to the surface, where the metal can be liberated from the ore. There are two mining methods used in primary copper production: open pit (also known as open cast or surface) and underground methods. The choice of which method to use depends on the [ore grade](#), ore body size, topography and ground condition ([Davenport et al., 2002](#)). Generally, development of an underground mine requires higher investment costs than an open pit mine, per tonne of mined ore. Further, underground mines are deeper and are electricity intensive whereas open pit mines are diesel intensive.

**Processing methods:** To liberate copper metal from the ore, the ore is processed either by pyro-metallurgy or hydro-metallurgy processes. Pyro-metallurgy process involves concentration and smelting steps while

hydro-metallurgy process involves leaching and solvent extraction stages, as shown in Figure 2.1 below. All sulphide ore is processed using pyro-metallurgy while hydro-metallurgy is used for oxide ore, with the exception of Chalcocite ore which can be processed using both processes. Electro-refining and electro-winning processes are the last steps in the production process of copper cathodes in pyro-metallurgy and hydro-metallurgy routes respectively. These two processes are electrolytic processes.

While all the ore that is processed using hydro-metallurgy is processed on-site or at a facility near the mining site, ore that takes the pyro-metallurgy route (after the concentration stage) can be processed in facilities far away from the mining site. After adding value to the ore (at concentration stage), a mining firm can decide to process the resulting concentrates (30% copper content) at its facility, sell it to another firm or export it. If the firm decides to process the concentrates at one of its facility, the resulting blister copper (99.5% copper content) can be sent to its electro-refinery, sell it to another firm or export it. Countries like Zambia incentivise firms to process their sulphide ore at least up to blister copper before exporting it.<sup>2</sup>

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<sup>2</sup>In order to incentivise firms to add significant value before exporting copper products, firms in Zambia have to pay a relatively high export duty for all their ore and concentrate exports.

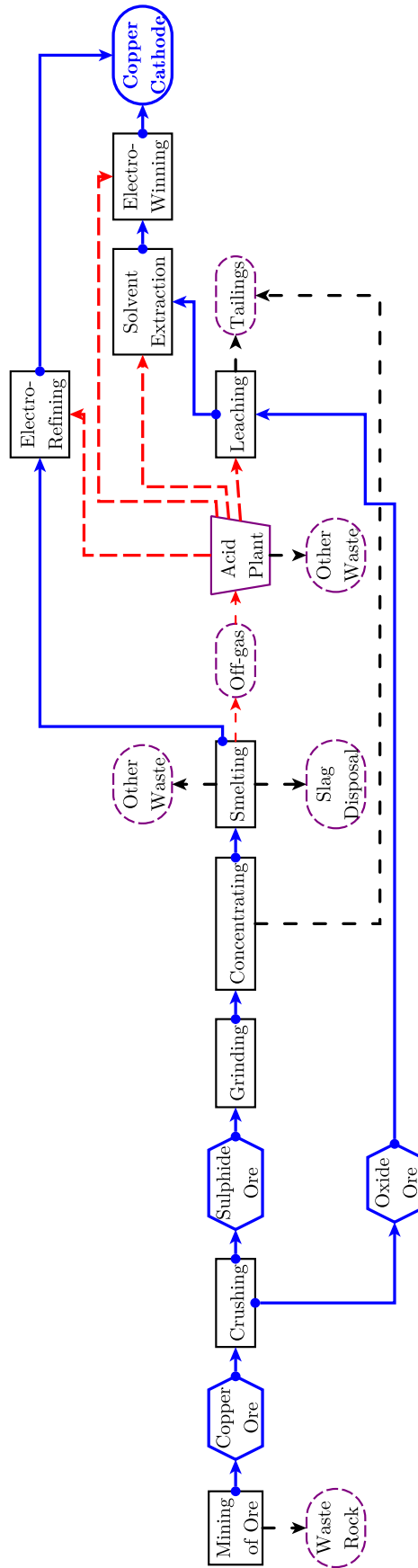


Figure 2.1: Generic process flow in primary copper

## 2.2 State of global copper industry

Historically (from 1800 to 2010), primary copper production has been dominated by 5 countries: Chile, USA, Russia, Canada, and Zambia (Mudd et al., 2013)<sup>3</sup>. These countries account for over 63% of the total cumulative production (a total of 567 million tonnes of contained copper). Until the early 1980s, the USA was the largest copper producer but now it is Chile; which accounted for at least 33% of global production in 2010 (Cochilco, 2012; Mudd et al., 2013; Radetzki, 2009). Using a distinction of developing and developed countries, between 1997 and 2011, developing countries accounted for at least 62%<sup>4</sup> of primary copper production (Cochilco, 2012).

Similarly, as of 2014, developing countries accounted for at least 65% of the total mineral resource (SNL, 2015). However, the consumption of copper is and has always been dominated by developed countries. Between 1997 and 2011, developed countries have consumed at least 83%<sup>5</sup> of the total annual production (Cochilco, 2012). The top producing companies (that account for at least 75% of total production) in the industry are based in developed countries, using headquarters location (SNL, 2015). This means that even though copper resources are located in developing countries, the resources are controlled by companies in developed countries. Tables 2.2 and 2.3 below show the list of top 20 locations of mineral resources and primary copper production (by country)<sup>6</sup> and top 20 copper producing companies respectively.<sup>7</sup>

<sup>3</sup>See Table 3 in Mudd et al. (2013).

<sup>4</sup>If China is classified as a developed country, otherwise, the share would increase to 67%.

<sup>5</sup>If China is classified as a developed country, otherwise, the share would reduce to 60%.

<sup>6</sup>Profitability of the resource is not dependent on the size but on many other resource characteristics such as ore grade and by-products.

<sup>7</sup>See Table B.1 of Appendix B for top 20 copper consuming countries.

Table 2.2: Copper Resource (SNL, 2015) and Production (Cochilco, 2012)

Mineral Resource		Copper Production	
Country	Share (%)	Country	Share (%)
Chile	34.7	Chile	32.4
USA	8.1	China	7.8
Peru	7.7	Peru	7.6
Russia	5.7	USA	7.0
Australia	5.4	Australia	5.9
Canada	3.8	Zambia	4.8
DR Congo	3.7	Russia	4.5
China	3.4	Canada	3.5
Mexico	2.8	Indonesia	3.2
Argentina	2.5	Mexico	2.7
Zambia	2.4	DR Congo	2.7
Kazakhstan	2.3	Kazakhstan	2.7
Poland	2.1	Poland	2.6
Indonesia	2.1	Iran	1.9
Mongolia	1.8	Brazil	1.3
Philippines	1.5	Laos	0.9
Panama	1.2	Papua New Guinea	0.8
Papua New Guinea	1.1	Mongolia	0.8
Ecuador	0.9	Argentina	0.7
Iran	0.9	Bulgaria	0.7
Other	6.2	Other	5.5

Table 2.3: Copper Production by company as for 2014 (SNL, 2015)

Company	Share (%)	Location of Headquarters
Codelco	11.7	Chile
Freeport-McMoRan Inc.	8.4	USA
Glencore Plc	7.7	Switzerland
BHP Billiton Group	7.7	Australia/UK
Southern Copper Corp.	4.0	USA
KGHM Polska Miedz S.A.	3.8	Poland
Antofagasta Plc	3.6	UK
Rio Tinto	3.5	UK
Anglo American Plc	3.3	UK
Kansanshi Holdings Ltd.	2.4	Ireland
OJSC MMC Norilsk Nickel	2.2	Russia
Vale S.A.	2.2	Brazil
Teck Resources Ltd.	2.0	Canada
Lundin Mining Corp.	1.5	Canada
Mitsubishi Corp.	1.4	Japan
Barrick Gold Corp.	1.3	Canada
National Iranian Copper	1.3	Iran
Cuprum Holding Ltd.	1.2	Mauritius
ZCCM Investments Holdings Plc	1.2	Zambia
MMG Ltd	1.1	Australia
Other	25.7	various

While consumption (demand) drives and is also affected by price, production participation of each mining site in a country varies, depending on its production cost. Further, the difference between the copper price and production cost is what influences a firm to invest in its production capacity. Besides, because of the mismatch between the rate at which demand and supply grows, the price of copper will fluctuate over time. This behaviour has long been observed in the industry. As [Stevens \(1903\)](#) aptly put it,

“There will be seasons when demand will follow so closely on the heels of supply that prices will go skyward, and the fool will say in his heart that the markets must forever advance. There will also be periods when the supply will exceed demand, and the faint of heart will say that copper mining is overdone, and never more can be profitable, but in the aggregate the great law of averages, immutable as the law of gravitation, will give to the world the copper for its imperative requirement, at prices not prohibitory to the consumer, yet sufficiently high to provide for the well-managed mines profits beyond the dreams of avarice.” (as cited in [Prain, 1975](#); pg. 50)

Figure 2.2 below gives the average global unit cost of production and copper price<sup>8</sup>, while figure 2.3 gives the total copper cathode production and consumption.

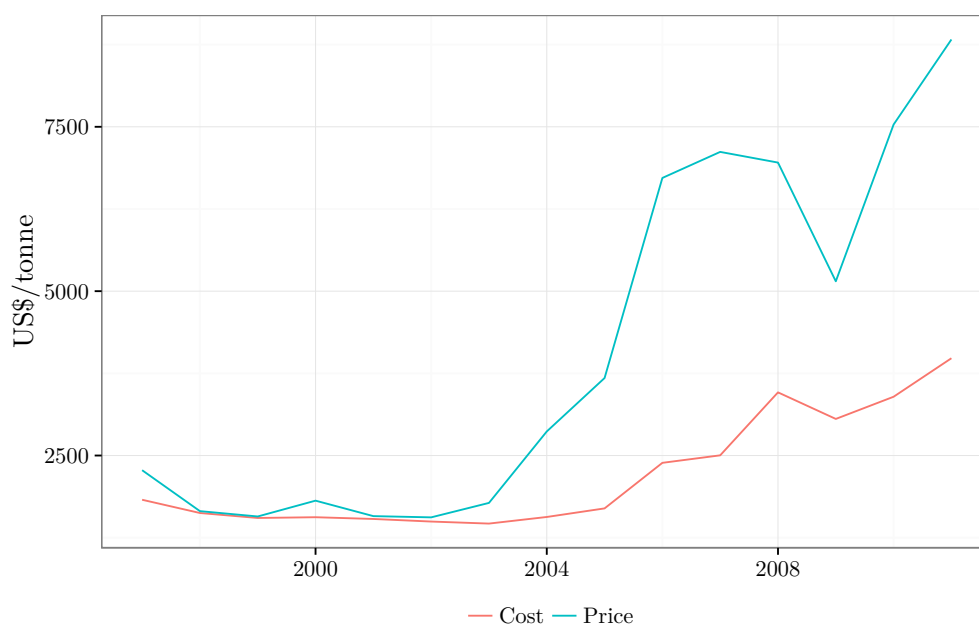


Figure 2.2: Average nominal copper price and unit cost ([Cochilco, 2012](#); [World Bank, 2015](#))

<sup>8</sup>The two main markets that determine the copper price are [London Metal Exchange \(LME\)](#) and [New York Commodity Exchange \(COMEX\)](#).



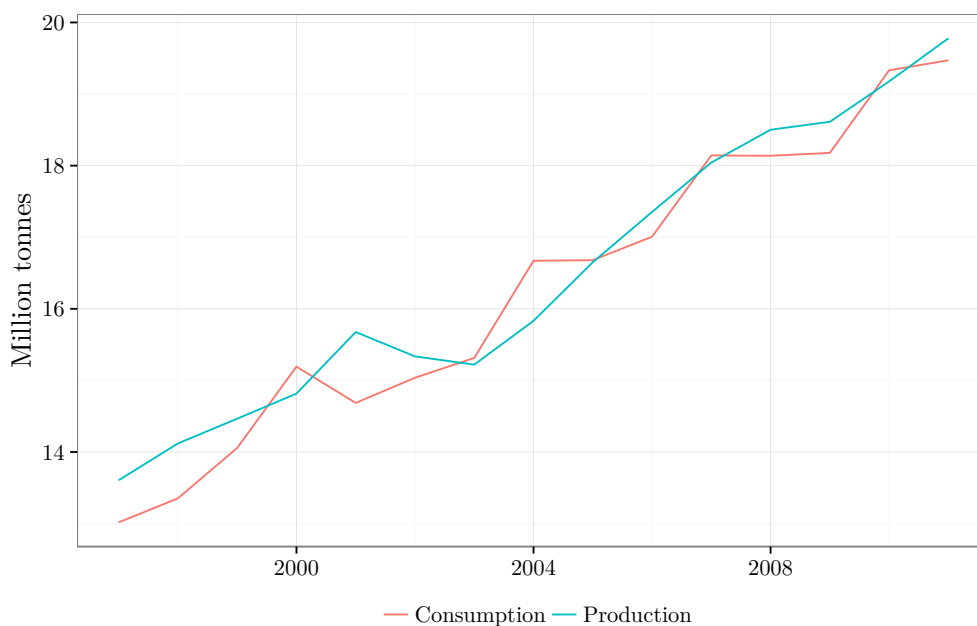


Figure 2.3: Global copper cathode production and consumption (Cochilco, 2012)

### 2.2.1 State of the Zambian copper industry

Having given the global context of the industry in the above sections, this sub-section focuses on the state of Zambia’s copper industry: the mining sites, their resources and the state of energy use. The sub-section also provides context and information that forms part of the mining model that is developed in Chapter 6.

Zambia has an estimated mineral resource of 69 million tonnes of contained copper of an average ore grade of 1.34%, with reported reserves of cobalt, gold, uranium and nickel (SNL, 2015).<sup>9</sup> According to USGS (2013), in 2011, Zambia had a total maximum refining capacity of 1 million tonnes (575, 000 of electro-refining<sup>10</sup> and 463, 000 of electro-winning), and a total of 69 million tonnes of ore processing capacity (53.5 and 15.6 million tones for sulphide and oxide ore capacity respectively).

There are 10 main mining firms<sup>11</sup> in Zambia’s industry, which in total

<sup>9</sup>This is significantly higher than the 47 million tonnes at 1.03% grade reported in Mudd et al. (2013).

<sup>10</sup>Smelting capacity of 661, 000 tonnes.

<sup>11</sup>These are Albidon Ltd, Chambishi Copper Smelter, Chambishi Metals PLC, Chibuluma Mines PLC, Kansanshi Mining PLC, Konkola Copper Mines, Lubambe Copper Mines, Lumwana Mining Copper Mines, Mopani Copper Mines PLC and NFC Africa

employed 63, 300 people and produced 720, 000 tonnes of copper cathodes in 2012 (CoM, 2014; CSO, 2013). Based on the production statistics and industry reports, it was estimated that Copperbelt Open Pit, Copperbelt Underground and North-Western Open Pit accounted for 10.0%, 40.2% and 49.8% of the total production in 2010 respectively. Of the total resources, it is estimated that sulphide ore accounts for 88% with the remainder as oxide ore. In addition, North-Western Open Pit resources also contain cobalt, gold, uranium and nickel, while both Copperbelt Open Pit and Underground only contain cobalt as their by-product. Table 2.4 shows the reported<sup>12</sup> mineral resources at mining site level.<sup>13</sup>

Table 2.4: Zambia's mineral resources at mining site level (SNL, 2015)

Site	Resources (tonnes)	Ore grade (%)	Grouping
Chibuluma South	5,700,000	3.55	C-OP
Chibuluma West	9,795,000	3.49	C-OP
Ndola	2,100,000	0.65	C-OP
Chingola Tailings	98,900,000	1.46	C-OP
Luanshya	54,820,000	1.34	C-UG
Muliashi North	77,930,000	1.09	C-UG
Lubambe	210,300,000	3.49	C-UG
Trident	1,450,000,000	0.76	NW-OP
Nchanga	314,000,000	1.28	C-OP
Konkola	752,900,000	2.16	C-UG
Konkola Deep	215,000,000	3.80	C-UG
Chambishi	213,981,000	1.95	C-OP
Mifulira	335,800,000	2.05	C-UG
Lumwana	527,345,000	0.56	NW-OP
Kansanshi	1,091,200,000	0.86	NW-OP

C-OP – Copperbelt Open Pit; C-UG – Copperbelt Underground; NW-OP – North-Western Open Pit

Mining; see Table B.2 of Appendix B for a complete list.

<sup>12</sup>Reporting dates ranging from 2003 to 2014.

<sup>13</sup>See Table B.4 of Appendix B for a complete summary of the mineral resources by mine grouping level.

In 2010, the Zambian copper industry accounted for approximately 54% and 32% of the total final electricity and petroleum consumption of the country's supply respectively (IEA, 2012); with electricity, diesel and Heavy Fuel Oil (HFO) as the main energy carriers, and small quantities of petrol and kerosene. The main electricity end-use services include ore conveyance, ore milling, water pumping, mine ventilation, air compression, general mining and mineral processing uses. Diesel is mostly used for ore hauling and transportation services, with HFO used as a heating fuel in the smelting process (under pyro-metallurgy route). Petrol and kerosene are mainly used in other transportation and general operations.<sup>14</sup> Figure 2.4 below show the consumption of total final energy at industry level. From the Figure, it can be seen that electricity<sup>15</sup> is by far the most consumed energy carrier.

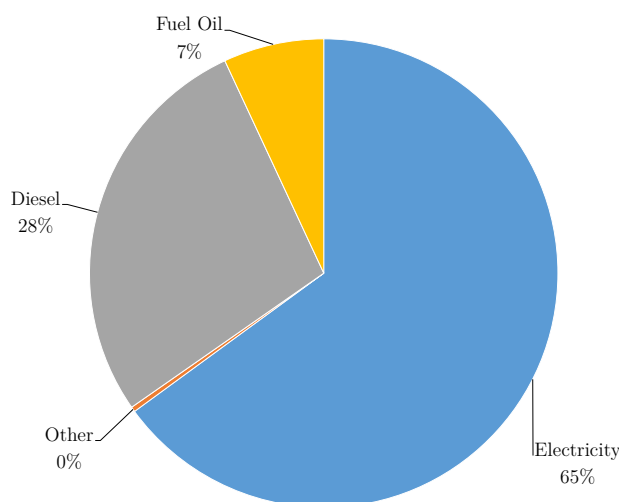


Figure 2.4: Zambian industry's total final energy demand in 2010

At company level, energy consumption trends are not different: electricity and diesel are still the main energy carriers. Below are figures that show the final energy consumption for Konkola Copper Mines Plc (KCM), the second largest mining company in Zambia, in 2012.<sup>16</sup> Figure 2.5 shows the breakdown of total energy consumption while Figure 2.6 shows a breakdown of consumption of electricity by Process Vs Support and Motor Vs

<sup>14</sup>See section 3.2.3 for a review of energy demand in the copper industry.

<sup>15</sup>See Table A.2 for the composition of electricity generation technology mix.

<sup>16</sup>KCM statistics were used because were available at a disaggregated level.

Support. Figures 2.5 and 2.6 below show that not only is electricity a major energy carrier but also that motors are the largest consumer of electricity.

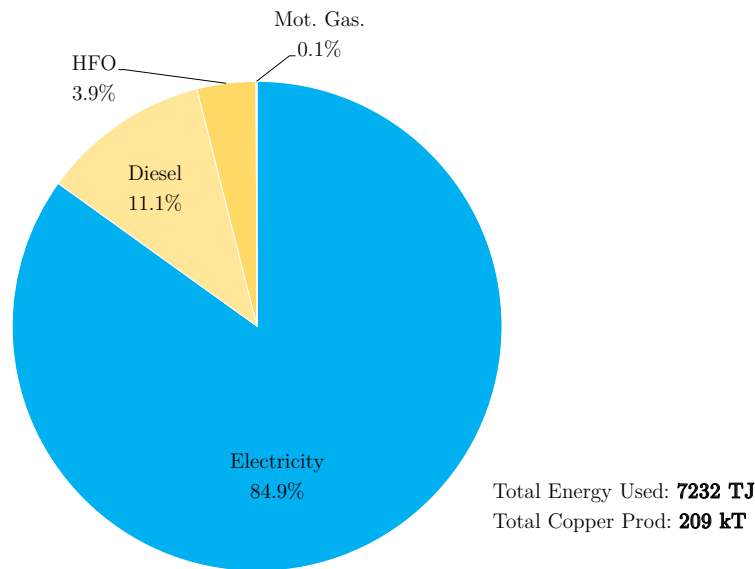


Figure 2.5: KCM total final energy demand in 2012

Further, it can be noticed that there is a significant difference in the share of electricity demand between industry level (Figure 2.4) and KCM (Figure 2.5). This difference is largely because KCM is predominately an underground mine while a considerable share of mines in Zambia are open pits (accounting for 59.8% of copper production): underground mines consume more electricity and less of diesel compared to open pit mining operations. Thus, being able to capture these characteristics in any analysis is essential (as was done in the mining model developed in Chapter 6).

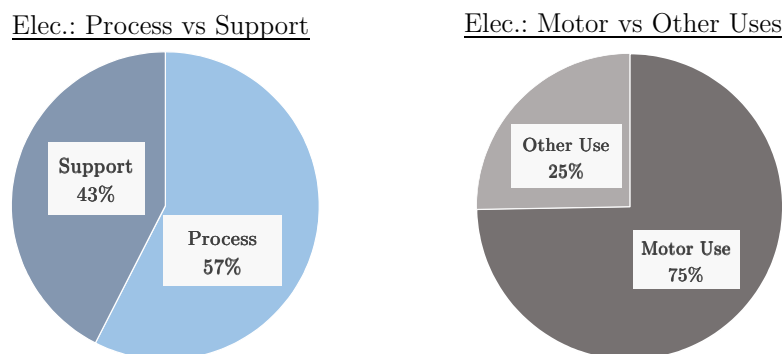


Figure 2.6: KCM's final electricity use in 2012

Electricity demand for KCM is further broken down into end-use ser-

vices as shown in Figure 2.7 below. This break down helps in attaching energy demand to specific energy drivers which is important when analysing the industry. For instance, milling process is influenced by [ore grade](#) while process heating is not.

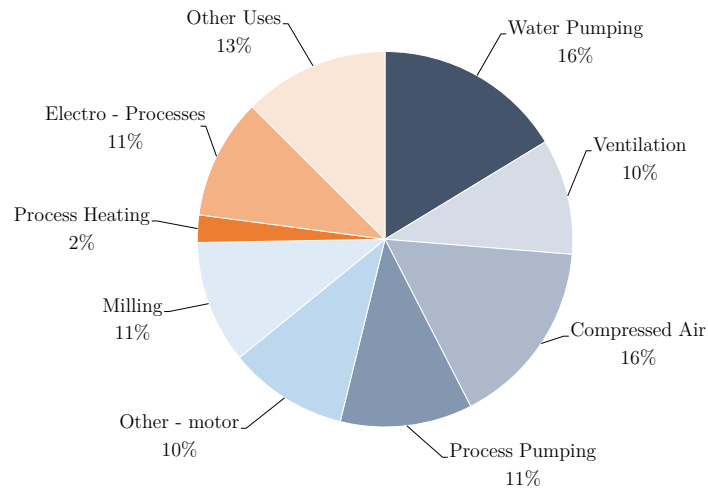


Figure 2.7: KCM's electricity demand at end-use level in 2012

## 2.3 Chapter summary

This brief chapter introduced some technical terminologies and concepts of the copper industry. It also presented the global production and consumption patterns. Finally, it presented the mineral resource base and final energy consumption of Zambia's copper industry (critical for the development of the mining model in Chapter 6), and also gave details of end-use energy consumption in Zambia's largest integrated mining firm ([KCM](#)). Overall, this chapter laid the technical context of the research.



# Chapter 3

## Literature review: Review of energy and mining models

This chapter is divided into four sections. The first section describes modelling frameworks used when studying energy and mining systems, the strengths and weakness of these frameworks, and the limitations and uncertainty of using models. The second section reviews and discusses literature on energy modelling (demand and supply) in developing countries, with a focus on sub-Saharan energy systems. It discusses how future energy demand has been modelled (a key driver of energy price) and also how the industrial [energy efficiency gap](#) and uptake of efficient technologies have been characterised. In the third section, a review of copper mining studies is done. This section focuses on studies that look at aspects that influence capital investment decision behaviour in mining firms. The fourth section looks at how the energy (the second section) and mining (the third section) systems are linked and impact each other. Finally, a chapter summary is given.

### 3.1 What is a model?

Models are stylised representations of real-world phenomena ([Godfrey-Smith, 2006](#); [Weisberg, 2007](#)). This representation, among others, can take a form of graphs, computer programs and mathematical equations. Models help in studying system interactions and behaviours in a relatively risk free and inexpensive environment. By analysing the model outcomes, we can get a deeper understanding of how real-world phenomena work and therefore enable us to design a policy environment that could lead to a desired system outcome.<sup>1</sup> Such an outcome could be increase in an organisation's productivity or increase in the adoption of energy efficient technologies. In other words, models are key decision aid tools.

On the whole, a model has three parts ([Weisberg, 2007](#)): assignment, scope and fidelity criteria. The assignment part focuses on the aspects of the real-world phenomena that need to be studied while the scope looks at the components of that system that needs to be included to effectively study the assignment. Finally, the fidelity criteria look at the capability of the model in representing the real phenomena that need to be studied. These fidelity criteria focus on the structure of the model that replicates the structure of the real system and also on how the behaviour (outputs) of the model compare to those of the system being studied.

[Li \(2013; pg. 39-40\)](#) summarises the series of steps that are taken in building a model and how to get useful insights from it:

- Choosing a model
- Finding a way of implementing that model
- Studying the output of the resulting model
- Using this entire process to make inferences
- Trying to justify those inferences

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<sup>1</sup>See [Wang et al. \(2017\)](#) for how a model was used to provide a better understanding of future socio-economic dynamics and [Koppelaar et al. \(2016\)](#) for how a model can aid policy and decision making.



### 3.1.1 Modelling paradigms

There are two energy main modelling paradigms: top-down and bottom-up. The top-down approach “breaks down a system to gain insight into its compositional sub-systems, while a bottom-up approach puts together elements of a system to give rise to grander systems, thus making the original systems sub-systems of the emergent system.” (Kesicki, 2012; pg. 73). An example of a top-down approach is a CGE model (computable general equilibrium), which focuses on the aggregate behaviour of a system (such as an economic system) due to change in policy direction or other external factors that would be acting on that system. This approach relies heavily on the historical trends and assumes that key underlying relationships of the model remain constant. On the other hand, energy system models are a typical example of a bottom-up modelling approach.

The bottom-up approach is built on an engineering thinking. It enables detailed modelling of components of a system. Thus, it is generally a suitable approach when the purpose of the model is to study the impacts that each component (disaggregated) has on a system. For instance, when modelling industrial energy use, a bottom-up approach is more appropriate because of its ability to capture many energy-related aspects of the system in disaggregated form (Bhattacharyya and Timilsina, 2010; Fleiter et al., 2011). This approach, for instance, makes it possible to analyse how investing in energy efficient technology would impact the total energy demand of the industry.

The use of either of these approaches (top-down or bottom-up) is determined by the modelling goal and scope (Fleiter et al., 2011). However, because this research hopes to understand how different aspects (components) of the model impact investment behaviour of a mining firm, a bottom-up approach is used.

### 3.1.2 Bottom-up model frameworks

Bottom-up models can be categorised into three groups; namely, accounting, optimisation and simulation models (Fleiter et al., 2011; Giatrakos et al., 2009). Accounting models are characterised by less dynamism and exogenous definition of variables. The model outcome is heavily influenced by the input assumptions and data. Thus, it is difficult to explicitly model firm's investment behaviour. However, because they are simple and transplant, these models are powerful tools for analysing energy demand. An example of an accounting modelling framework is LEAP<sup>2</sup>. Wang et al. (2007) use LEAP to assess the options for emissions abatement in China's steel industry.

Optimisation models are prescriptive models. The modeller defines relationship between variables and boundaries from which a solution can be picked, the model finds the optimal solution. These models are driven by an objective function, which would be made up of different variables such as costs and emission limits. This framework assumes that the decision maker has perfect foresight and knowledge. Thus, it implies that the decision maker can systematically plan their investment stock profile and also avoid technology lock-in. This weakness (assumption of perfect foresight and knowledge) notwithstanding, optimisation models are useful in estimating the efforts that would be required to achieve a desired goal based on what is currently known to the decision maker (and also based on what the decision maker thinks the future will be like). An example of an optimisation model is a MARKET ALlocation (MARKAL) framework. Gielen and Taylor (2007) analysed the role that different technologies could play improving energy efficiency and reducing  $CO_2$  emissions in the industrial sector using a MARKAL framework.

Simulation models are varied and follow different modelling philosophies (Fleiter et al., 2011). These models are used as descriptive tools. They help in understanding how a system would behave under different environments. These models help the decision maker (or modeller) to get a deeper under-

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<sup>2</sup>Long-Range Energy Alternative Planning System.

standing of how the system would behave under different scenarios such as varying policy instruments or relationship between two variables in a system. Put in another way, these models are used to answer ‘what if’ type of questions. This model has three main aspects: the representation of the problem being studied, the relationships and feedbacks between variables, and the decision rules. A combination of these three aspects makes the framework complex, abstract and sometimes less transparent (Giatrakos et al., 2009).

Two examples of simulation models are Nail (1992) and Worrell and Price (2001). Nail (1992) is a System Dynamics model<sup>3</sup> that studied the dynamics of energy supply and demand (of oil, gas, electricity and coal) in the USA economy. On the other hand, the NEMS (national energy modelling system) model (Worrell and Price, 2001) takes a form of an accounting model except with detailed modelling of technology stock and explicitly modelled technology adoption and firm behaviour. This model was used to study energy efficiency improvements in the USA’s industrial sector.

### 3.1.3 Uncertainty and risks in models

Regardless of the modelling paradigm, type of model or care taken to build models, uncertainty still remains. Uncertainty reflects the inability to estimate the exact value of a variable (Ross, 2004) or comprehensively capture a relationship. There are broadly two sources of uncertainty in models: parametric and structural (Kesicki, 2012; Usher, 2016). Methods used to analyse the impact of uncertainty are briefly discussed in sub-section 3.1.4 below. Apart from uncertainty, systems (being modelled) could also experience shocks. Shocks such as extreme prices, that would lead to unexpected model behaviour.

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<sup>3</sup>See section 4.3 for a discussion of System Dynamics model.

### **Parametric uncertainty**

Parametric uncertainty focuses on uncertainty that is introduced in a model due to the way input values are defined or calibrated. Apart from inputs into the model, this type of uncertainty also includes missing data, absence of information and errors in the available data. An example of such uncertainty is the estimation of [energy intensity](#) in an energy model.

### **Structural uncertainty**

This type of uncertainty focuses on the structural description of the model. Definition of system boundary, mathematical formulation and process flows fall under this type of uncertainty.

System boundary describes how parts of the model interact with each other and also whether these parts are modelled as exogenous or endogenous factors. An example of system boundary definition problem is how the reduction of renewable technologies investment capital cost is modelled. In most models, this is modelled as an exogenous factor yet the reduction of investment cost is a function of installed capacity, this (installation) is usually determined endogenously.

Mathematical model formulations are dependent on historical data and information, which only captures some variables.<sup>4</sup> Another source of uncertainty is the mental model description of a process flow. An example of this are models that assume that all the coal consumed in the industrial sector is for energy purposes, when some of the coal is used as a reducing agent (as a chemical in some industrial processes).

While some of the (parametric and structural) uncertainty can be minimised, simple representation is at the core of modelling philosophy. Therefore, it is more important that the modeller is aware of these uncertainty than to actually eliminate them. By being aware, the modeller can take them into account when interpreting the model results.

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<sup>4</sup>These formulae and relationships may change due to social, economic, political and technical reasons.

## System risks

System risks are shocks that can be experienced in a model. Shocks such as a spike in the crude oil or copper price. These could lead to other impacts depending on how model relationships are captured. For instance, the copper price is modelled as an exogenous factor using a mean reverting model<sup>5</sup>, this means that the price can suddenly increase or be depressed consistently at a level that has never been observed before. This could trigger uncharacteristic model behaviour (something possible but that has not yet been observed in the industry).

### 3.1.4 Sensitivity analysis

Whereas the aim of uncertainty analysis is to quantify the extent of uncertainty in an input variable through statistical analyses and other methods, sensitivity analysis focuses on determining the impact that the input variables have on model outputs (Usher, 2016). For instance, the standard deviation of a specified input variable can be 0.2 (uncertainty analysis) but that variable may have zero (0) influence on the model output (sensitivity analysis). Thus, by using sensitivity analysis techniques, the modeller can take mitigating actions to improve the quality of the model and its output (Ford and Flynn, 2005; Ford, 1999; Taylor et al., 2010).

Two approaches are used in parametric sensitivity analyses: local and global approaches. The local approach (the *one-at-a-time* (OAT) method) considers the impact of one variable at a time, before moving to the next. This method assumes that there are negligible interactions between model inputs. The method, nonetheless, is useful when the modeller wants to have an idea of the impact that each variable has on the model output. Also, because it is simple and transparent, most modellers will be able to at least interpret the results more accurately. However, the method can be inefficient when there are many model input variables that have to be analysed.

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<sup>5</sup>See section 3.3.5 for a discussion of models that are used for modelling commodity prices.

The second method, global approach, gives a better and more robust measure of influence that a variable has on the model output. This approach explores a range of possible input values and also consider all variables simultaneously. This approach thus accounts for possible interaction impacts that input variables would have on each other. In addition, because model sensitivity output files can be significantly huge, further statistical analyses of the results need to be done ([R Core Team \(2017\)](#) was used to further analyse the data for this research). For instance, for SD model sensitivity outputs, a statistical method called screening is usually used to analysis these outputs. [Chapter 6 section 6.4](#) gives a detailed description of this method (screening method).

Analysing structural uncertainty is challenging, partly because model contexts are variant. For instance, in the copper industry, it makes logical sense to model copper price as an exogenous factor when analysing a price taker industry but the price has to be modelled endogenously when analysing a price setter industry. Thus, an effective way to reduce structural uncertainty is for the modeller to have sufficient knowledge (through journal articles or industry reports) of the system being analysed. Alternatively, a modeller can set up different model structures and then analyse the model output, as was done by [Auping \(2011\)](#).

## 3.2 Studies on energy use and modelling

This section looks at common uncertainty in energy models, gives a review of how energy systems are modelled (in developing countries), how energy efficiency opportunities are evaluated and then proposes an approach for modelling energy efficiency decision making in the industrial sector. It also identifies knowledge gaps that exist in industrial energy efficiency studies.

In 2007, global total final energy consumption was 349 EJ; with the industrial sector consuming 28% ([IEA, 2015](#)). Energy demand in the industrial sector is projected to increase by at least 50% by 2050 compared to 2006 consumption ([Saygin et al., 2011](#)). Given that most sub-sectors

in the industrial sector are energy intensive and large contributors to  $CO_2$  emissions, efforts around the world have focused on how energy consumption can be reduced in the sector without impacting its production output. This reduction (energy consumption) is seen as a way of mitigating the impacts of energy use on global climate and local environment.

Further mining and non-ferrous metals sub-sectors are some of the major energy consumers in the sector (Gielen and Taylor, 2007); under which the copper industry falls. Apart from being an energy intensive industry and emitter of  $CO_2$ , the copper industry is a significant emitter of  $SO_2$  gas (Alvarado et al., 1999).

### 3.2.1 Uncertainty in the energy model

Energy models, particularly those focused on developing countries, suffer from energy intensity error (parametric uncertainty) and conceptualisation error (structural uncertainty) (Bhattacharyya and Timilsina, 2010; Pandey, 2002). Parametric uncertainty is largely due to lack or limited energy statistics in developing countries (Bhattacharyya and Timilsina, 2009).

The second and perhaps more problematic is the conceptualisation error. Most models tend to model developing countries' systems using frameworks of developed countries. They usually emphasise the impact of income and overlook the critical role that governments (in developing countries) play in the energy sector. An example of such a study is Zeyringer et al. (2015).<sup>6</sup> Pandey (2002) and Bhattacharyya and Timilsina (2010) proposes ways of modelling developing countries that could help reduce conceptualisation errors.

### 3.2.2 Industrial energy use and modelling

Globally, the industrial sector is the largest consumer of both primary and final energy. In 2013, this sector consumed 113 EJ of energy (IEA, 2015), an increase of 17 EJ between 2007 and 2013. Because of this continued upward

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<sup>6</sup>Details on the challenges of modelling energy systems in developing country contexts are discussed later in section 3.2.5 below

trend, there have been many studies (Fleiter et al., 2012; Giacone and Mancò, 2012; Gielen and Taylor, 2007; Phylipsen et al., 2002; Saidur et al., 2009; Saygin et al., 2011) that have focused on how energy consumption in the sector can be reduced.

Gielen and Taylor (2007) looked at the energy and  $CO_2$  emission reduction potentials that exist in the global industrial sector. The ETP MARKAL model<sup>7</sup> used in this study, explicitly considered different technologies, their technology learning and other related costs. A least cost framework was used to estimate the existing potentials in the industry. This study assumed that the decision makers were rational and had perfect foresight. The study found that not only will energy consumption increase, but also the sector's  $CO_2$  emissions. They recommended that in order to realise the reduction potentials in the industry, it would be essential to combine different regulatory and support measures, such as energy efficiency regulations.

The role that energy efficiency can play in reducing both energy consumption and  $CO_2$  emissions is studied in Saygin et al. (2011). The study divided the industrial sector into two: industrialised countries and developing countries sectors. The study found that while industrial energy demand in industrialised countries has remained fairly flat, energy demand in developing countries has been growing at an annual rate of 3.2% since 1971.<sup>8</sup> Further, when the current energy consumption is compared to the global best practice, it was found that about a third of the total final consumption can be saved in the industry, mostly (about 70% of the savings) from developing countries' industrial sector. This notwithstanding, they found that the estimations of energy saving potentials were highly uncertain because of limited data availability from developing countries.

The role that policy and regulation play in promoting energy efficiency in the industrial sector is studied in Tanaka (2011). The study focuses

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<sup>7</sup>International Energy Agency (IEA)'s Energy Technology Perspectives (ETP) MARKAL model.

<sup>8</sup>This increase could be in part because of increasing local demand in those group of countries and also because some rich countries have exported manufacturing of energy intensive goods and products to these countries.



on policies that have been implemented in [IEA](#) countries, Brazil, China, India, Mexico, Russia and South Africa. The study found that industrial energy use was influenced by many factors, among them, technologies used, processes involved, energy prices, operating environments, organisation's priorities and organisation's decision making paradigm. It was found that most energy efficiency improvements could only be achieved through technical actions. The paper focused three categories of policies that could be used to incentivise technical improvements within an organisation. These were prescriptive, economic and supportive policies.

Prescriptive policies focus on regulations and agreement that industries are subjected to in their operating environment. These policies generally take a form of equipment or plant efficiency regulation. Economic policies focus on market instruments that can be used to modify the energy use behaviour in organisations. An example of such policies are taxes and loan support schemes. The last category (supportive policies) looks at mechanisms that could be put in place to help organisations identify their energy saving opportunities, build capacity, get advisory services and similar support structures. The study argues that for any energy efficiency policy, a package of policies, to be effective, local context of an industry has to be considered. This is because of the variant barriers of energy efficiency that exist. [Worrell et al. \(2004\)](#) give summary of policies (see [Table 3.1](#) below) that can be implemented in order achieve the efficiency targets in the industrial sector.

Table 3.1: Portfolio of energy policy instruments (Worrell et al., 2004)

Instrument type	Policy impacts and program effects		
	Availability of energy efficient technologies	Incentives for decision making	Increased capability of companies
Regulation standards	Controls the set of technology choices	Induces high costs for the use of outdated equipment	
Subsidies, direct public spending, R&D support	R&D support enhances technical progress and innovation	Investment grants increase the economic attractiveness of options	
Pricing	Indirect incentive for R&D	Affects price relations in favour of energy efficiency measures	Contributes to higher awareness
Emission trading	Indirect incentive for R&D	Creates a price and market for energy eff. or emission reduction	Contributes to higher awareness
Negotiated agreements		Can create an environment for	Increases energy awareness,

*Continued on next page*

Table 3.1: Portfolio of energy policy instruments *Continued*

Instrument type	Policy impacts and program effects		
	Availability of energy efficient technologies	Incentives for decision making	Increased capability of companies
Public voluntary programs	Stimulates R&D	energy efficiency and innovation	communication & dissemination
Management tools		Lowers (in long term) transaction costs for efficiency action	Provides information, know-how, and management support
Labelling		Better communication of cost parameters	Increases information. Higher market transparency.
Technology procurement	Stimulates R&D and innovation		Dissemination of information and know-how.

*Continued on next page*

Table 3.1: Portfolio of energy policy instruments *Continued*

	Policy impacts and program effects	
Instrument type	Availability of energy efficient technologies	Incentives for decision making
Best practice dissemination		Increased capability of companies
Education, qualification, training		Qualification and training. Increases awareness and information
Agency networks		Provision of information and know-how Networking of actors

Peck and Chipman (2007) discuss industrial energy efficiency, the reasons there has been a strong drive for uptake of efficiency measures and the different policies that have been adopted to promote uptake of energy efficient measures. They argue that because the industrial sector is energy-intensive, many organisations have been forced to consider energy efficiency options to reduce their costs. They implicitly argue that energy cost is a significant component of production cost in the sector and as such any increase in the energy price impacts on the profitability of the sector. In addition, apart from the impact that energy efficiency would have on the sector's profitability, they argue that "in many developing countries energy efficiency is also a way to alleviate the investment costs for expanding energy supply infrastructure in the face of tight fiscal constraints." (Peck and Chipman, 2007; pg. 334) The latter argument is particularly valuable to Zambia.

A methodological framework that could be used to measure plant specific energy efficiency potential is described in Giacone and Mancò (2012). The paper argues that without taking into consideration the specifics of a plant being analysed, it would be difficult to measure, monitor and achieve the desired energy efficiency goal.

Fleiter et al. (2012) use a bottom-up technology-rich model to assess the energy efficiency opportunities that still exist in German's pulp and paper industry. The paper observes like many other studies (Rohdin et al., 2007; Saidur et al., 2009; Sola et al., 2011; Trianni and Cagno, 2012; Trianni et al., 2013) that implementation of energy efficiency measures has been low. They attribute this low implementation to lack of appropriate policies to overcome investment barriers. The study, however, is focused on the economics of the technologies being analysed. They assume that if a technology's economics makes economic sense, then that technology should be invested into, all things being equal. This is a similar rationale used in many other energy efficiency studies (Akbaba, 1999; de Almeida et al., 2003; Saidur et al., 2009; Thirugnanasambandam et al., 2011).

Saidur et al. (2009) focus on identifying equipment that are major con-

sumers of electricity in the Malaysian industry. The study found that electric motor, pump and compressor systems are the largest consumers. They argue that even though energy saving potentials exist, lack of government regulation and enforcement has led to low implementation. Similarly, [Akbaba \(1999\)](#) found that electric motors consume about 75% of the total electric energy in Bahrain. The paper focuses on the impact that replacing standard electric motors with energy-efficient motors would have on the total energy demand. As above, the rationale of the analysis was technology economics. [de Almeida et al. \(2003\)](#) look at electricity used by motors in European Union's industrial and services sectors, while [Thirugnanasambandam et al. \(2011\)](#) look at potential savings from electric motors in Indian's cement industry.

Technology-rich bottom-up method is the dominant approach used in quantifying the energy saving potential in the industrial sector. This approach takes one of the following forms: optimisation models ([Gielen and Taylor, 2007](#)), accounting models ([Fleiter et al., 2012](#); [Giacone and Mancò, 2012](#)), benchmarking ([Phylipsen et al., 2002](#); [Saygin et al., 2011](#)) or simple NPV and related methods ([Akbaba, 1999](#); [de Almeida et al., 2003](#); [Saidur et al., 2009](#); [Thirugnanasambandam et al., 2011](#)). These approaches are useful but not sufficient when analysing energy use and possible technology diffusion options, as decision makers also consider the economic value of each of their other investments.

### **3.2.3 Energy demand in the copper industry**

Energy use in the copper industry can be accounted for by using final production output ([Saygin et al., 2011](#)) or using equipment and process level approach ([Giacone and Mancò, 2012](#); [Norgate and Haque, 2010](#); [Norgate and Jahanshahi, 2010](#)). The main difference between the two approaches is that the latter approach is able to capture specific drivers of energy consumption such as mining methods used, type of ore processed and the impact that [ore grade](#) has on energy consumption. At process level (disaggregated level), it is possible to include all the required energy services of

a process.

The energy end-use services within the copper industry are numerous; among others, process heating, steam generation, lighting, conveyance, HVAC, water pumping, ore hauling, mobility and milling purposes. These services are met by mainly five energy carriers: coal, natural gas, heavy fuel oil, diesel and electricity. Coal, natural gas and heavy fuel oil are usually used for process heating and steam generation, while diesel is mainly used in open pits for ore hauling. Electricity has versatile uses, from hauling of ore to electrolytic processes. Of these energy carriers, the most energy saving potentials can be realised in the electricity system; both by replacing inefficient equipment and changing people's attitude towards electricity usage (UNIDO, 2012).

Production process stages in the copper industry can be divided into three parts: mining and mineral processing, smelting and refining components. The energy use in each of the stages can then be split into process and support related energy demand. Further, energy demand for electricity can also be split into electric motor and non-electric motor demand, as was done in Figure 2.6 above. The distinction between motor and non-motor energy demand is important because electric motor system is the largest consumer of electricity and also because most energy saving potentials can be realised from the electric motor system (Akbaba, 1999; de Almeida et al., 2003; Saidur et al., 2009; Thirugnanasambandam et al., 2011; UNIDO, 2012).

Industrial electric motor system includes pumps, fans, compressed air, conveyors, crushers, grinders and mixers (Sola and Mota, 2012). The prime mover in the system is the electric motor; making electric motors the most important electric load point (de Almeida et al., 2003). Electricity reduction in the motor system can be achieved by implementing several mechanisms such as replacing inefficient motors, adjusting motor loads, installing variable speed drive, correct motor sizing, power optimizing devices, maintenance management, information and education and capacitor banks (Bortoni, 2009; Sola and Mota, 2012). Of these mechanisms, re-

placement of inefficient technologies with efficient motors and installation of variable speed drive (VSD) would lead to significant reduction in energy demand (de Almeida et al., 2003; UNIDO, 2012).

The theoretical minimum energy intensity for primary copper production (for sulphide ore) is between 1.4 to 2.2 GJ per tonne of metal. However, the actual specific energy consumption (SEC) for ore from open pit mine at an ore grade of 1.32% is between 25 - 30 GJ per tonne of metal (Alvarado et al., 2002; 1999; Norgate and Jahanshahi, 2010). The actual SEC is largely influenced by the type of mining method, grade of ore and type of ore being processed (oxide or sulphide ore). For instance, the energy requirements for processing oxide and sulphide ores (ore grade of 0.5% from an open pit mine) is 30 and 65 GJ per tonne of metal respectively (Marsden, 2008).

The difference in energy requirements between Alvarado et al. (2002; 1999), and Marsden (2008) can largely be explained using Equation 3.1 (Gupta, 2003) below, type of ore being processed and energy efficiency of the processing system. From the equation, it can be seen that as ore grade reduces (relative to the reference ore grade ( $OG_r$ )) the quotient increases ( $\frac{OG_r - TG}{OG - TG}$ ), this has a multiplier effect on the total energy demand (for a particular energy service demand). This relationship (from Equation 3.1) is however only valid for the mining and mineral processing stage. Energy demand for smelting and refining stages are not affected by ore grade, thus only production output (blister or cathode) is important (keeping all other variables constant) at these two stages.

$$E_a = E_r \times \frac{(OG_r - TG)}{(OG - TG)} \quad (3.1)$$

where,

$E_a$  is the actual final energy demand,

$E_r$  is the reference energy demand (this relates to the ore grade at which the reference energy demand was calculated),

$OG_r$  is the reference ore grade at which  $E_r$  was calculated,

$OG$  is the ore grade, and



*TG* is the tailings grade.

### 3.2.4 Energy efficiency investments

Despite the existence of energy saving opportunities in the industrial sector, energy efficiency investments have been low. This low investment has been attributed to barriers (Fleiter et al., 2011; Sarkar and Singh, 2010; Sola et al., 2011; Weber, 1997). Barriers can be defined as all factors that hinder the implementation of energy efficient measures or adoption of energy efficient technologies. Empirical studies (Rohdin et al., 2007; Schleich, 2009; Trianni and Cagno, 2012) have shown the existence of these barriers in organisations. For instance, Rohdin et al. (2007) investigated the barriers and drivers of energy efficiency and the significance of each barrier and driver in the Swedish foundries. An econometric study on German's commercial and services sector (Schleich, 2009), considers the impact that these barriers have on heterogeneous organisations. The study found that although the barriers were significant at aggregate level, the significance of different barriers varied across sub-sectors. This study showed that different sectors require sector-specific (and organisation-specific) interventions in overcoming the barriers.

Weber (1997) categorises these barriers into four categories: institutional, organisational, behavioural and market. While Fleiter et al. (2011; pg. 3102) further classify the barriers into six groups namely; “imperfect information, hidden costs, risk and uncertainty, split incentives, access to capital and bounded rationality”. Table 3.2 below shows what constituents each of the barriers as classified by Fleiter et al.

Table 3.2: Classification of energy efficiency barriers

Barrier	Barrier component
Imperfect information	Lack of knowledge about the availability of an energy-efficient measure or technology.
	Lack of knowledge of the transaction costs that could be incurred.
	Lack of knowledge on the energy saving potential and actual energy consumption by a specific equipment.
Hidden costs	The unknown costs that could be incurred by an organisational which implements EE measures.
Risk and uncertainty	Uncertainty about future energy prices.
	Uncertainty about future energy policies.
	Uncertainty about technology development.
	Risk of production interruptions and impacts on product quality.
	Irreversibility of investments.
Split incentives	Heterogeneity of processes and organisations.
	Different incentive between the equipment producer and the equipment user.
	Lack of transparency and information about the actual efficiency of energy consuming equipment.
Access to capital	Lack of external investment capital funding.
	Competing choices on which projects should be prioritised within the organisation.
Bounded rationality	Decision-makers do not have perfect knowledge.

The benefits and barriers notwithstanding, [Jaffe and Stavins \(1994\)](#) and [Patterson \(1996\)](#) argue that the estimation of the available saving potentials are subjective. Different decision makers will have varying estimations of what they consider as potential depending on the indicator they use to assess the saving potential (the difference between the current energy use status and the optimal energy use status).

[Patterson \(1996\)](#) introduces four main indicators used to measure energy efficiency: thermodynamic, physical-thermodynamic, economic-thermodynamic, and economic. He also looks at the challenges that come with usage of any of these indicators and the steps that must be followed to overcome these pit-falls. Patterson further argues that developing a proper systems boundary is critical in quantifying the realistic amount of energy that can be saved by implementing a particular EE measure.

[Jaffe and Stavins \(1994\)](#) discuss the concept of energy gap. This concept looks at the differences that exist between the actual energy being used and what the optimal energy use should be. They argue that the magnitude of the gap is influenced greatly by the view an analyst or a decision maker take, which would either be: the economists' economic potential; the technologists' economic potential; hypothetical potential; the narrow social optimum; or the true social optimum. Similar to the selection of which EE indicator one uses, the energy-gap view that one takes would result in different estimations. In addition, as opposed to focusing on the barriers ([Weber, 1997](#)), [Jaffe and Stavins](#) argue that a holistic approach is what would be required to achieve optimal levels of energy use.

However, both [Jaffe and Stavins \(1994\)](#) and [Patterson \(1996\)](#), also like other studies presented in sub-section 3.2.2 above, implicitly argue that if the saving potentials can be properly estimated and that they make an economic sense then energy efficient technology investments should be made. This argument assumes that energy cost is a significant cost component and also that the decision maker's perspective of industry (organisation) related energy efficiency investments are mainly driven by the energy system.

This view, I argue, is narrow, because it overlooks the impacts that other costs such as labour cost or profitability would have on decision making. As [Haglund \(2010\)](#) observed that with mining organisations focusing on cost minimisation, it is important that energy costs savings opportunities are put in context of other costs saving opportunities available to the organisation. Most organisations make capital investment decisions relative to other factors (not just energy) and policies. Therefore, previous

studies have lacked a comprehensive view of the system and only focused on the energy system (shown in Figure 3.1 in the green boundary).

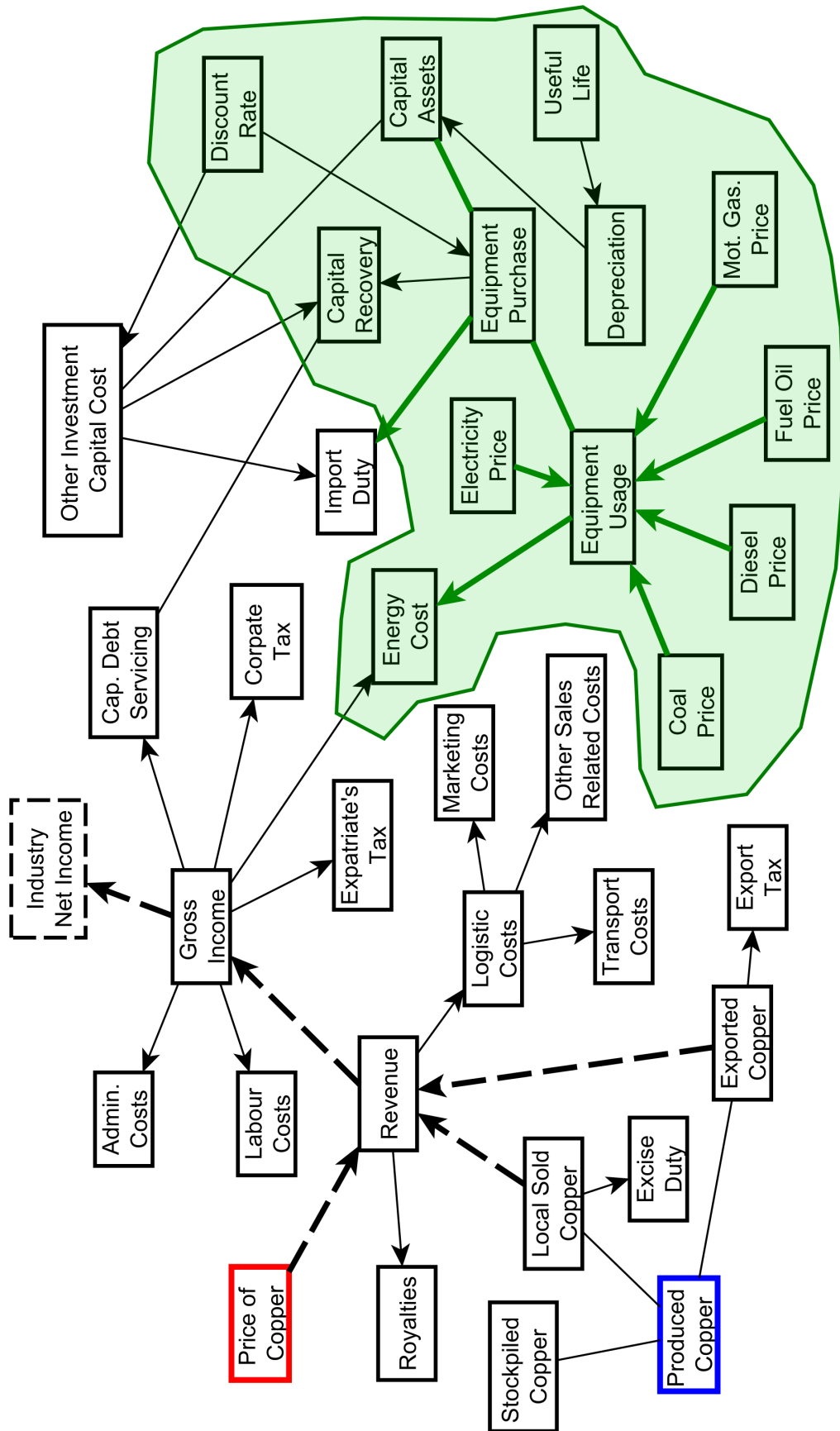


Figure 3.1: Copper industry financial model framework

For instance, to investigate how adoption of efficient technologies could be enhanced, past studies (Fleiter et al., 2011; Worrell et al., 2004) have used a high discount or hurdle rate. In this case, a high discount rate or hurdle rate just helps the decision maker to know if a particular option is viable or not. It does not, however, establish the state of that option relative to other options available to the decision maker. Thus, this thesis captures energy efficiency options<sup>9</sup> in the context of other key decision making drivers such as labour cost and commodity prices, as shown in Figure 3.1.

### 3.2.5 Energy systems in developing countries

Having discussed literature surrounding energy use and modelling in the industrial sector, this section discusses past studies on energy use and modelling in a developing country context. Particular attention is given to the residential sector (other sectors are transport, services industrial and others). The attention on residential sector is mainly because of the challenges of access to [clean energy](#) that the sector faces, it is the largest energy consumer in most sub-Saharan countries (due to usage of primary biofuels) and finally because many sub-Saharan governments have ambitious plans for this sector that would have significantly impact the development of the energy system.

Figure 3.2 below shows the total final energy consumption in Africa between 1971 and 2013 (IEA, 2015). The residential sector is by far the largest consumer of final energy in Africa, followed by the transport and industrial sectors respectively. Almost all the energy consumed in the transport sector is a product of crude oil (98%) while the industrial sector energy profile is a mix of coal, natural gas, biofuels, electricity and oil products.

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<sup>9</sup>See section 7.2.4 for an analysis that energy efficiency investments have on total copper production and firms' profits.

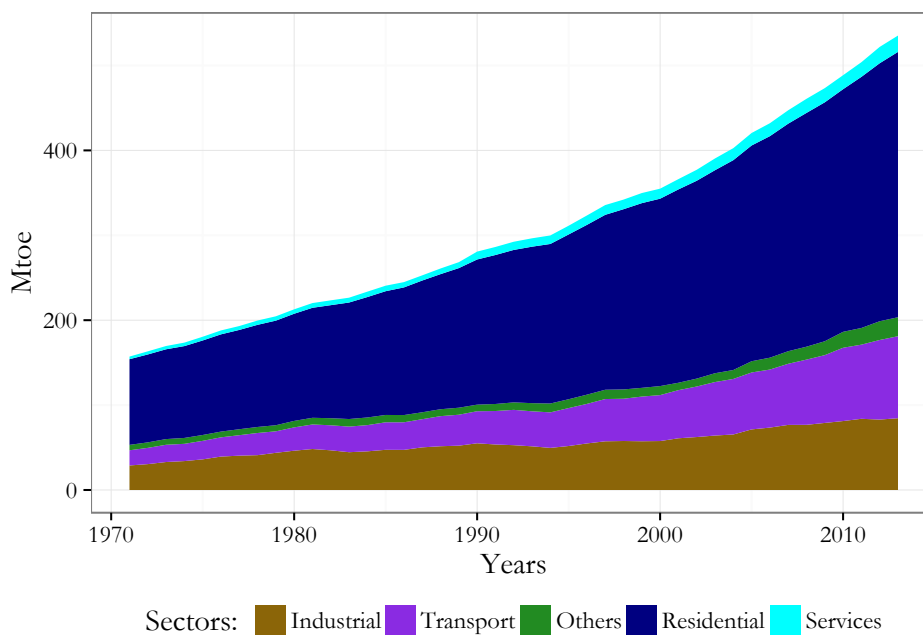


Figure 3.2: Energy consumptions in Africa by sectors

Different models, both top-down and bottom-up, have been developed to address some energy policy and planning challenges that developing countries face. However, as Pandey (2002) and Bhattacharyya and Timilsina (2010) observed the effectiveness of these models is limited because most of them do not capture specific features that are relevant to developing countries. Further, as opposed to Urban et al. (2007), which focused on the limitations of a modelling platform, one of the main challenges that models have is the conceptualisation of the problems or challenges being modelled. Even though model platforms like LEAP can adequately capture features relevant to developing countries, modellers who develop these models tend to build models in a way that developed countries problems could be modelled, when modelling the problems of developing countries. They, for instance, give income driven electrification more emphasis over government policy driven electrification (aided by energy subsidies).

Various literature (Bhattacharyya and Timilsina, 2010; Jebaraj and Iniyar, 2006; Suganthi and Samuel, 2012; Urban et al., 2007) reviews different energy demand and supply models that are used in planning energy infrastructure development and their suitability for modelling energy sys-

tems in developing countries. Most of the modelling gaps are in the demand models: methodological conceptual gaps. To be specific, how specific features for developing countries are captured. [Bhattacharyya and Timilsina \(2010\)](#) discusses the three demand modelling approaches: simple technique, econometric technique (top-down) and end-use technique (bottom-up).

The simple technique method uses indicators such as growth rate, elasticities and rate of change in [energy intensity](#) to forecast energy demand. This method mostly used as an ad-hoc approach in cases such as where the modeller does not have data or a solid rationale to base the projections on. This method is quite common in industry (not common in academic literature though). The econometric technique focuses on the aggregate level of energy demand and links the energy demand to economic theory. It assumes that changes in energy demand are correlated to changes in the economy. An example of such an approach is [Zeyringer et al. \(2015\)](#). The end-use technique builds energy demand from a micro-level of energy services to a macro-level of total energy demand. This technique is able to capture different energy services and their drivers. This technique is more suitable because it adequately captures features that are important in developing countries energy systems ([Bhattacharyya and Timilsina, 2010](#)). An example of an end-use model is [Daioglou et al. \(2012\)](#), a model built to analyse how a climate policy can be used to reduce emissions from the residential sector. They concluded that end-use models (bottom-up models) are more suitable for capturing features that are important for developing countries. However, in practice, these methods or techniques are not used in isolation but are sometimes combined.

Features that are peculiar to developing countries, include but not limited to, reliance on traditional energy, the existence of large informal sectors, electrification, urban-rural divide, prevalence of inequity and poverty, structural changes of the economy, energy transition behaviour from traditional to modern fuels, inefficient energy supply systems, existence of social and economic barriers to capital flow and slow technology diffusion ([Bhattacharyya and Timilsina, 2010](#); [Pandey, 2002](#); [Urban et al., 2007](#)).



For instance in 2013, according to [IEA \(2015\)](#) primary biofuels (traditional fuels) accounted for more than 50% of the total final energy consumption in Africa's energy system. But most models do not explicitly capture the key drivers of how energy consumption patterns change from traditional fuels to commercial fuels (electricity and gas).

Of these features listed above, studies that addressed electrification, urban-rural split, fuel switching and energy transition behaviour from traditional to commercial fuels are reviewed. This is because they are directly linked to energy use in the residential sector, which is one of the two main themes of this research (the other is decision making in the industrial sector, which also takes into account the change in energy use in the residential sector). Electricity and gas ([clean energy](#) fuels) account for less than 10% of the total final energy consumed in the residential sector. It is, therefore, important to study how increased access to [clean energy](#) can be achieved, understand how fuel transition happens in this sector and how this would impact the whole energy system.

Studies that focus on access to [clean energy](#) (in the residential sector that is) have dominated energy research in sub-Saharan Africa. This is because only 31% of the population has access to electricity, with 45% and 82% of the urban and rural population not having access to electricity respectively in 2011. Further, more than 80% of this population use traditional fuels and coal for their cooking and heating service ([OECD/IEA, 2010](#); [Zeyringer et al., 2015](#)).

[Zeyringer et al. \(2015\)](#) analyses cost effective options for meeting electricity demand in Kenya. The study has both energy demand and supply models. The demand model uses an econometric technique (an exponential regression model) to estimate electricity demand. Household characteristics such as income, household size, education level and age of the head of the household and urban-rural split were used as drivers of energy demand. On the supply, the analysis focused on the economics of grid extension and off-grid stand alone options (such as solar PV). The off-grid option was found to be more cost effective way of supplying electricity to rural house-

holds. [Komatsu et al. \(2011\)](#) examines the key determinants that would help predict if a household in rural Bangladesh would purchase a stand alone solar PV system or not. This study also uses an econometric model. [Javadi et al. \(2013\)](#) looked at the role of global policy in increasing electrification in rural areas. [Barnes and Floor \(1996\)](#) looks at how electrification and access to [clean energy](#) can be done in a sustainable way.

While these ([Javadi et al., 2013](#); [Komatsu et al., 2011](#); [Zeyringer et al., 2015](#)) and similar studies explore and contribute to how the energy access challenge can be solved, they fall short because they either take a narrow view of what electrification is or fail to distinguish the type of energy services that demand energy. For instance, in [Komatsu et al. \(2011\)](#) and [Javadi et al. \(2013\)](#) electrification was loosely defined to mean lighting. Therefore, a solution that met lighting service was presented as a solution for electrification or access to [clean energy](#). This narrow definition of access to electricity overlooks the big challenge of energy access: cooking and heating service. Cooking and heating service account for the largest share of a household's total final energy demand ([Daiglou et al., 2012](#)). Further, whereas lighting is optional, cooking and heating service is a primary demand.

The econometric methods, such as [Zeyringer et al. \(2015\)](#), aggregate household energy demand. It is then assumed that electricity supplied from a solar PV system can be used for cooking or heating the same way it can be used for lighting. However, this is not the case, because the solar PV system cannot support heavy loads such as cooking and heating (in the current form of stand alone solar PV technology). In addition, this method assumes that increase in electricity and other commercial fuels demand (non traditional fuels) is only driven by household dynamics such as increase in income and not, for example, by government policy.

Therefore, for governments that are seeking for solutions that do not only increase access to electric lighting but also that address other pressing issues such as reduction in deforestation (through changes in cooking and heating fuels), these studies would be of limited use. In addition, apart

from the need to reduce deforestation by increasing access to [clean energy](#), access to [clean energy](#) is central to addressing global challenges such as poverty, inequality, health and education, and it also comes with different health implications ([Cabraal et al., 2005](#); [Daioglou et al., 2012](#); [OECD/IEA, 2010](#)).

These limitations of econometric methods can be addressed by using an alternative method: end-use method. This is what [Daioglou et al. \(2012\)](#) did when analysing how climate policy can be used to reduce emissions from the residential sector. Individual drivers and services for energy demand in residential sector were explicitly modelled. This enables a detailed analysis that changing types of energy fuels of an energy service would have on the whole system. In this way, access to clean energy can be more appropriately analysed by using drivers such as income or government policy.

In order to understand how a household transitions from one fuel type to another, different theories that have been proposed ([Barnes and Floor, 1996](#)). At the core of these theories is the energy ladder concept. [Masera et al. \(2000\)](#) review the concept of energy ladder. The energy ladder concept studies the transitions that households go through when switching fuels. The underlying assumption of this concept is that a household decision maker has access to an array of energy supply (energy fuels) from which to choose. The concept hypothesises that as households' income increase, household abandon traditional fuels (such as primary biomass and coal) and adopt cleaner energy fuels (electricity and gas).

[Barnes and Floor \(1996\)](#) gives general trends of how household use energy relative to their levels of income. This paper uses the energy ladder to explain the linear transition from an inferior fuel to a superior fuel. This was the approach that [Masera et al. \(2000\)](#) used when studying the energy use transition in rural Mexico. The study, however, found that energy transition does not follow a linear path as defined in the classic energy ladder concept but that households use multiple fuel energy strategies (a mix of traditional and clean energy fuels) that are influenced, by among other factors, income and cultural preferences. [Hosier and Dowd \(1987\)](#) studied

the dynamics of energy use in households of varying incomes. The research applied energy ladder concept, using a multinomial logit formulation, when studying fuel transition in rural Zimbabwe. The paper focuses on how decision making changes among rural households as biomass fuels (traditional fuels) become scarce and as household income varies. The paper found that although increase in income is critical for households to transition, governments need to have policies that encourage such transitions.

These studies (focusing on fuel transition using energy ladder), however, assume that all the fuels under consideration are at the disposal of the household decision maker. They do not consider situations where traditional fuels are the only alternatives available to the decision maker. Thus, in order for energy transition to happen, a new energy system has to be created.

This research, therefore, studies the impact that increasing access to [clean energy](#) (either by government policy or household income) would have on the development of the energy system. This is important because: 1. many African countries have developmental targets of increasing access to [clean energy](#), 2. energy systems in Africa are experiencing supply challenges so even if household income increase, there would be limited fuel switching, 3. increasing energy access would mean increase in energy prices which would impact the growth of economic sectors, particularly the industrial sector.

The first aim links the impact that access to [clean energy](#) would have on deforestation, the second focuses on the understanding how much capital investment could be required to develop the energy system. The third aim links the impact that increasing access to [clean energy](#) would have on the industrial sector, through energy price. In later sections, these three aspects are analysed and discussed in the light of this thesis.

The details of both the energy demand and supply models are described in Chapter 5. The supply model captures the current state of the energy system, which includes the available energy resources and technical characteristics of the current and future supply technology stock. The model

solution is based on a cost minimisation objective function. Figure 3.3 below shows a reference energy system (RES) of how demand is linked to supply (This is the RES diagram on which the supply model in this thesis was based).

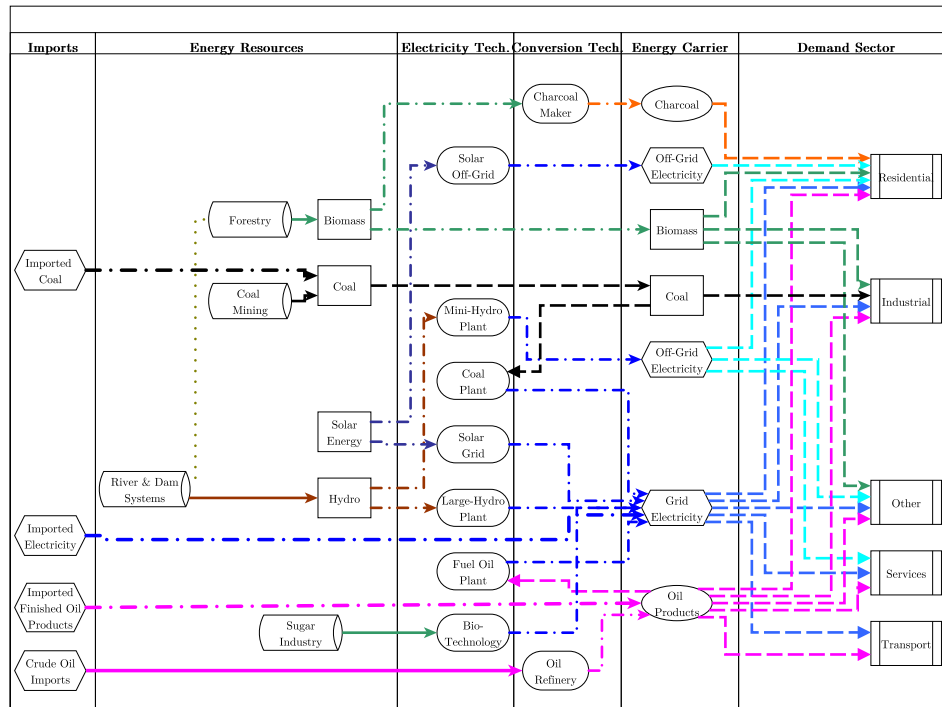


Figure 3.3: Reference Energy System for Zambia's energy model

### 3.3 Studies on copper industry

Studies on the copper industry can be divided into four groups (Aguirregabiria and Luengo, 2015). The first group looks at the impacts that price and uncertainty have on the firm's investment behaviour (see Dimitrakopoulos and Sabour, 2007; Moyen and Slade, 1996; Slade, 2001). The second group focuses on the impact that production output has on industry's dynamic efficiency (see Gaudet, 2007; Young, 1992). The third group of literature looks at the impact that taxation and environmental policies have on production and decision making in the industry (see Foley and Clark, 1982; Slade, 1984; Tole and Koop, 2013). The final group studies competition and strategic interactions in the industry (see Agostini, 2006). This study focuses on the first group of literature as it sought to explore

the investment behaviour of a mining firm. The impact of taxation (mineral royalty taxation to be specific) on industrial profitability will also be discussed and analysed in later chapters (Chapters 6 and 7).

Industry investment behaviour can be modelled and studied using top-down or bottom-up models and analysed using either an optimisation or simulation framework (Aguirregabiria and Luengo, 2015; Montaldo, 1977; Sverdrup et al., 2014). To comprehensively explore the behaviour, the model should capture both the physical (material) and financial components of the industry.

The physical component (material module) consists of mining and mineral processing, smelting and refining. It focuses on the material production process particularly on variables such as the quantity of ore resources available, type of ore resources, ore grade, methods of mining and capacity of mining equipment (Mudd et al., 2013; Norgate and Jahanshahi, 2010; Northey et al., 2014). The financial component (module) focuses on the investments and profitability of the production capacity and operations (Auger and Ignacio Guzmán, 2010; Boulamanti and Moya, 2016). In order to have a better understanding of factors that influence investment behaviour, these modules have to be analysed together (Aguirregabiria and Luengo, 2015; Montaldo, 1977; Sverdrup et al., 2014).

### 3.3.1 Uncertainty in the copper industry

The value of all mining projects is evaluated based on the characteristics of their mineral resources<sup>10</sup> and the commodity price. It is this valuation that drives investment decisions such as the mining method to use and the size of production capacity to invest in. These investments are huge upfront capital costs yet their economic operational viability are subject to uncertainty. The value of these resources is significantly influenced by economic (such as commodity prices) and physical (such as quantity of ore resources and ore grade) uncertainty (Savolainen, 2016; William et al., 2012). Mayer and

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<sup>10</sup>Characteristics of the mineral resource (ore reserve in particular) directly influences the unit production cost.

Kazakidis (2007) identify sources of uncertainty (predominately parametric uncertainty) in mining projects; shown in Table 3.3 below is a summary of these sources. Whereas physical uncertainty of a project can be reduced by acquiring more information, Ross (2004) observes that reducing economic uncertainty (such as copper price) is challenging because this uncertainty varies in unpredictable manner, influenced by events (of a particular period) that cannot be known in advance.

Table 3.3: Sources of uncertainty in mining projects

Endogenous (internal)	Exogenous (external)
<ul style="list-style-type: none"> <li>• Ore grade distribution</li> <li>• Ore reserve quantity</li> <li>• Infrastructure</li> <li>• Equipment</li> <li>• Recovery method</li> <li>• Management/operating team</li> <li>• Labour force</li> <li>• Ground condition</li> <li>• Societal issues</li> <li>• Environmental issues</li> </ul>	<ul style="list-style-type: none"> <li>• Market prices</li> <li>• Government policies</li> <li>• Country risks</li> <li>• Industrial relations</li> <li>• Legislation and regulation</li> <li>• Societal issues</li> <li>• Environmental issues</li> </ul>

### **Economic uncertainty**

For a copper mining project, economic uncertainty includes, but is not limited to, copper price, raw material input prices (such as energy price and chemical costs), taxation, industrial relations and government policies. This category of uncertainty is the most important driver for decision making in the metal mining industry (Savolainen, 2016; William et al., 2012). This research focuses on the impact that copper price, input prices and taxation have on a firm's profitability.

Uncertainty impacts the firm's profitability in two ways: operational profitability and recovery of capital investment. Operational profitability affects the firm's performance in the short-term. However, uncertainty can also lead to long-term losses should the firm fail to realise the expected revenue for its capital investment project. This long-term loss can be due to a sudden collapse of the commodity markets as was observed between the early 1970s and 2000s (for the copper markets). To minimise the risks of long-term loss, it is common practice for firms to use an average commodity price of three (3) to five (5) years when evaluating a capital project (DiNuzzo et al., 2005; Hearne et al., 2006; Lambert and Stone, 2008; Peters et al., 2013). This is approximately the half life of copper price oscillation<sup>11</sup>.

### **Physical uncertainty**

Physical uncertainty includes [ore grade](#), quantity of ore resources, equipment and ground condition to mention but a few. However, the main physical uncertainty in a mining project is [ore grade](#) and quantity of ore resources (Dimitrakopoulos et al., 2002). This could not only lead to over designing of a mine (which in turn leads to under utilisation of the capacity) but it also impacts the unit production cost and the expected net present value of a project (Dimitrakopoulos and Sabour, 2007). This uncertainty can be reduced by investing more in information acquisition processes such as exploration (Botín et al., 2012; Ross, 2004).

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<sup>11</sup>See section 3.3.5 for a description of copper price modelling.



### 3.3.2 Material production modelling

The production process of primary copper can be divided into three stages: mining and mineral processing, smelting and refining (see [Davenport et al. \(2002\)](#) for a thorough description of the copper production processes). The mining and mineral processing stage focuses on how copper ore is extracted from the ground using open pit or underground methods and processed to produce concentrates (under pyro-metallurgy route) or leach solution (under hydro-metallurgy route). This mineral processing is usually done within the perimeters of the mining operations as it would not make economic sense to transport the ore to another facility for processing, considering that only about 0.5-3% of the material that would be transported has economic value.

If the ore being processed follows the pyro-metallurgy route, then the next stage of processing is smelting. At this stage, copper concentrates (20%-50% copper content) is transformed into blister copper (99.5% copper content). The final stage is electro-refining in the pyro-metallurgy route, this produces copper cathode (99.9% copper content). The smelting and electro-refining processes can be done at a facility away from the mining site or even at a facility owned by another mining firm. If the process takes the hydro-metallurgy route, the next stage from mining and mineral processing is solvent extraction-electro-winning (SX-EW). The end product of SX-EW stage is copper cathode at 99.9% copper content. Further, because of the configuration of the SX-EW process, this stage is done near to the mining site in order to avoid transport and other logistical costs. This, therefore, implies that a company that uses hydro-metallurgy to produce copper will have their capital investment locked in a particular country of operation as opposed to a firm which uses a pyro-metallurgy route. This is an added risk dimension for a firm using hydro-metallurgy. [Figure 3.4](#) below shows the main energy inputs in the production process flow.

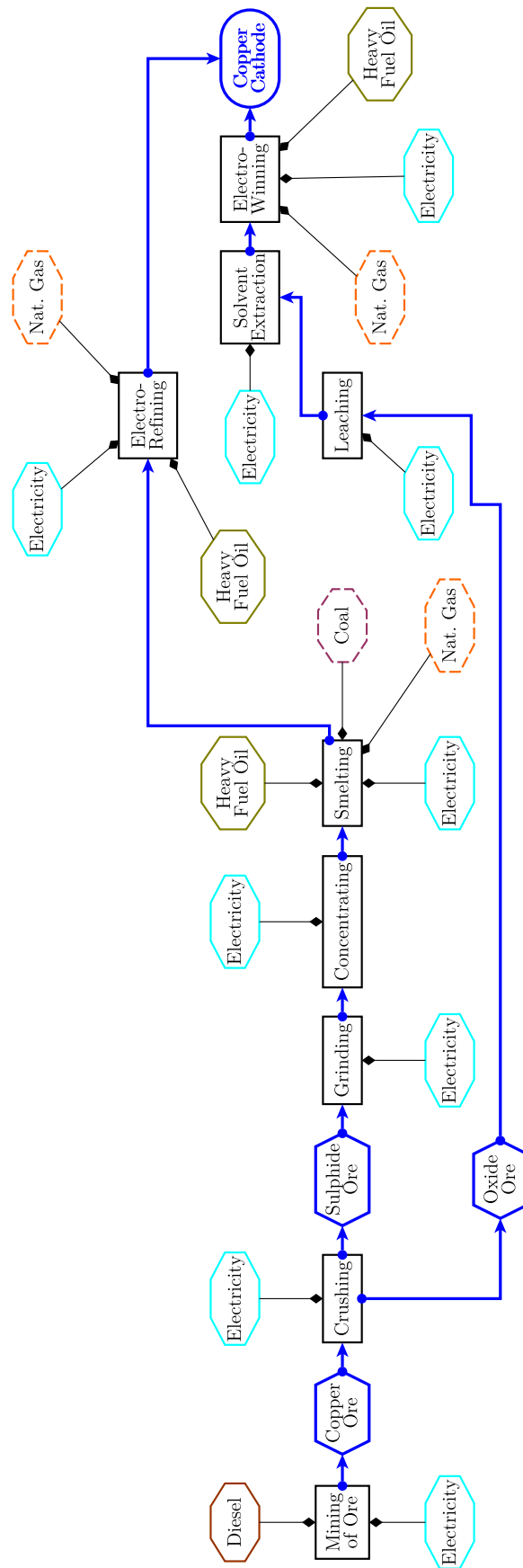


Figure 3.4: A generic process flow in primary copper production and energy inputs

Total copper production (global) has increased from 10, 000 tonnes in 1750 to 20 million tonnes in 2011<sup>12</sup>. There have also been changes in the industry's key production players, from China (70%) and Europe (30%) in 1750 to Chile (32%), China (7.8%), Peru (7.6%) and USA (7%) in 2011 (Cochilco, 2012; Radetzki, 2009). Apart from changes of key industry players, other changes have been in mining methods (mass open-pit production was introduced in 1905), processing of sulphide ore (flotation process was introduced in 1911) and processing of leachable ore (largely oxide ore, was introduced in 1968). Changes in mining methods and the introduction of flotation process made it economically possible to mine and process low grade sulphide ore. Further, despite the decreasing ore grades, these two changes (open-pit and flotation process methods) led to a 20% decline in costs between 1918 and 1923 (Aguirregabiria and Luengo, 2015). The introduction of leaching process (a primary process for oxide ore) lowered the investment capital cost, shortened the project lead time and provided an environmentally friendly method of processing copper. It also made it possible to set-up small scale processing operations (Radetzki, 2009).

Copper output from the leaching process (SX-EW) has continued to rise (accounting for 18.4% of global output in 2011 from 14% in 1997), this is partly because of the lower investment capital cost (less than two-thirds of the traditional pyro-metallurgy process). The process, however, is operational cost intensive and it also relies on acid from the pyro-metallurgy process (Davenport et al., 2002; Rothschild, 2008), particularly for land-locked copper producing countries. Figure 3.5 below shows the shares of pyro-metallurgy and hydro-metallurgy processes.

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<sup>12</sup>See Tables 2.2 and B.1 in Chapter 2 and Appendix B for production and consumption statistics respectively.

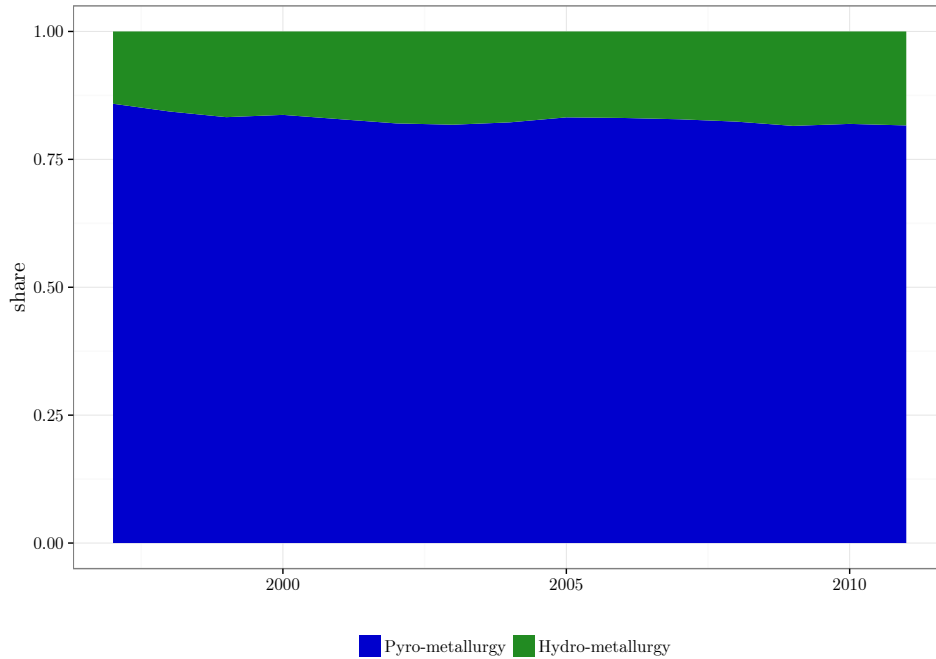


Figure 3.5: Copper production process shares (Cochilco, 2012)

### 3.3.3 Production costs modelling

Despite advances in the copper production processes, Cochilco (2012) observes that the global average unit production cost (in 2010 US\$ terms) has increased from \$2, 660 per tonne (in 1997) to \$3, 370 per tonne (in 2011)<sup>13</sup>. This increase has been attributed to changes in mining firms' behaviour during the copper price boom between 2004 and 2011, increase in input commodity prices and continuous reduction in ore grade (ME#2, 2014<sup>14</sup>; Aguirregabiria and Luengo (2015)). As ME#2 (2014) urged when the copper price drastically increased, mining firms (in Zambia) were incentivised to produce copper from ore that was previously uneconomical. This, in turn, raised their unit production cost, however, they still made a profit from such a behaviour because their average cost was still lower than the average price. This was also observed by Krautkraemer (1988; 1989) and Farrow and Krautkraemer (1989), who noted that mining firms change their behaviour during price boom. The firms tend to produce copper from

<sup>13</sup>See Figure 3.6 for the regional unit production costs.

<sup>14</sup>This was part of the information that was collected during my fieldwork. See Appendix D section D.3 for the description of respondents.

low [ore grade](#) when the copper price is high.

Two other plausible explanations are the inaccurate statistics used to calculate these costs<sup>15</sup> and the tendency of some mining companies of not reporting the value of by-products credits that they get, say, from acid, cobalt or gold. This behaviour (of not reporting by-products credits) has been observed in Zambia (see [Vedanta \(2015\)](#), no revenue from cobalt is reported despite the mine having an operational cobalt plant). To elaborate on the first plausible reason, in 2010, despite Africa having higher [ore grade](#) (of 1.34%) than Chile (of 0.54%),<sup>16</sup> Africa's unit production cost was 50% more than Chile's cost ([Cochilco, 2012](#); [Mudd et al., 2013](#)). Three counter-arguments as to why this would be true could be presented, namely that Africa's industry is:

1. significantly underground relative to the Chilean industry,
2. not as mechanised as the Chilean industry, and
3. highly taxed and pay higher interest rates compared to the Chilean industry.

The first argument focuses on the assumption that because underground mine requires high capital investment costs than open pit, then copper from those mines will be more expensive to produce. The second argument assumes that because labour cost accounts for the largest share<sup>17</sup>, then a more mechanised mine will always produce cheaper copper. This argument, however, does not take into account the trade-off between labour cost and additional capital and operation costs that comes with mechanising a mine. The final argument assumes that mining companies in Africa pay higher taxes and financing costs than their counterparts in the Chilean industry. These arguments notwithstanding, [ore grade](#) has the largest impact on the production cost, so on face value, they (arguments) do not make a strong case. Thus, without any analysis showing the relative importance of mining

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<sup>15</sup>Cochilco relied on statistics (for non-Chilean statistics that is) from Brook Hunt and Associates, a commercial company.

<sup>16</sup>See Table 3 in [Mudd et al. \(2013\)](#) for a summary of copper resource data.

<sup>17</sup>See section [E.3](#) in Appendix [E](#) for the cost structure of [KCM](#).

method, mechanisation and taxation and interest rate on production cost, one should question these arguments.

The key production cost components are labour, cost of capital, repair and maintenance, energy, inventory, consumables and other on-site costs (Boulamanti and Moya, 2016; Rothschild, 2008). Aguirregabiria and Luenigo (2015; pg. 15-16) summaries the three categories of unit production costs as follows, “costs are mainly classified in [sic] cash costs, operating costs and total costs. Cash costs (C1) represent all costs incurred at mine level, from mining through to recoverable copper delivered to market, less net by-product credits. Operating costs (C2) are the sum of cash costs (C1) and depreciation and amortization. Finally, total costs (C3) are operating costs (C2) plus corporate overheads, royalties, other indirect expenses and financial interest.” Figure 3.6 below shows the total unit cost (C3) as compiled by Cochilco (2012).

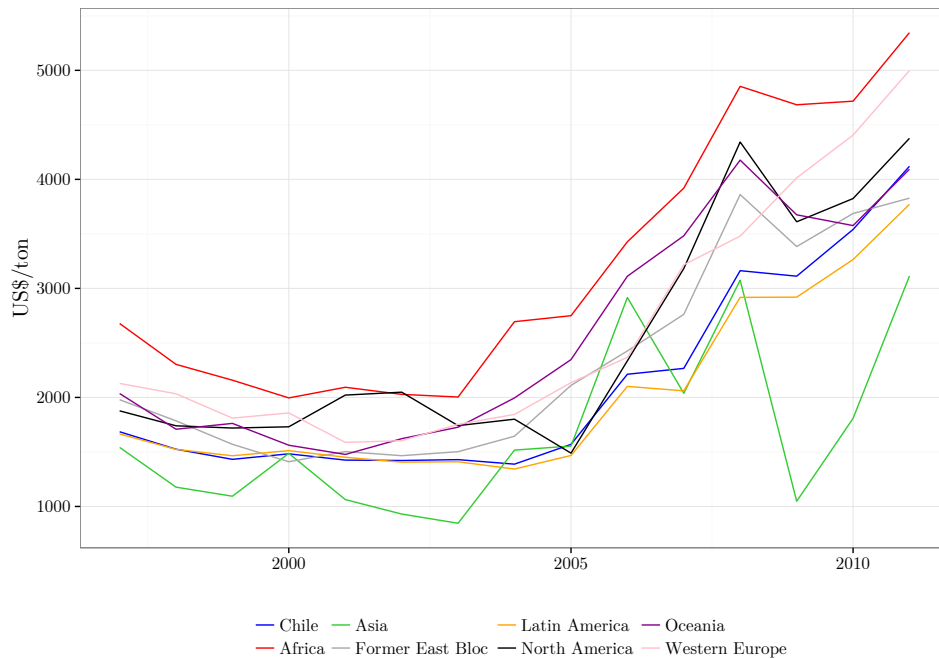


Figure 3.6: Unit production cost by region

### 3.3.4 Valuation of copper reserves

All mining investment decisions are based on the estimated (or perceived) value of the mineral resources of a mine at particular time period (Savolainen, 2016). Valuation is a process used to estimate the mineral value of a mine. There are three main valuation approaches: income, cost and market (CIMVAL, 2003). Income approach focuses on the anticipated benefits from a mine, this is largely driven by the commodity price. Methods such as discounted cash flow (DCF), Monte-Carlo analysis and option pricing are used in this valuation process. The cost approach looks at how the mine's aggregated costs compare with the price a buyer is willing to pay. This approach includes methods such as appraised value and multiple exploration expenditure. Finally, the market approach considers how a mine (asset) compares with a similar mine that was transacted in open market. Methods under this approach include comparable transactions and market capitalisation. The appropriateness of each approach depends on the type of mineral property (mine) being valued. Table 3.4 below gives a general guideline of when an approach is appropriate to use (CIMVAL, 2003).

Table 3.4: Valuation approaches for different types of mineral properties

Valuation Approach	Exploration	Mineral resources	Development	Production
Income	No	In some cases	Yes	Yes
Cost	Yes	Yes	Yes	Yes
Market	Yes	In some cases	No	No

As William et al. (2012) notes, after the mine's physical characterisation has been completed (post exploration), the single dominant factor in the valuation of a mine is the price of the commodity (in this case, copper price). This is because the physical uncertainty (see sub-section 3.3.1 above) are relatively within the control of a mining firm, while the firm has little if any, influence on the commodity price (more so for a price taker industry). Further, the income approach, particularly the DCF

method, dominates valuation of mining projects (Bartrop and White, 1995; Bhappu and Guzman, 1995; CIMVAL, 2003). The popularly notwithstanding, DCF method tends to underestimate the mine value (Dimitrakopoulos and Sabour, 2007; Moyen and Slade, 1996), however, its ease of use and robustness are its strength (Phelan, 1997).

### 3.3.5 Copper price modelling

One of the main limitations of the DCF method is its reliance on a constant future commodity price, overlooking the observed price fluctuations. However, modelling of commodity prices is challenging, because of the uncertainty in the behaviour of markets. Dixit and Pindyck (1994) proposes two stochastic models for modelling commodity or asset prices: Geometric Brownian Motions (GBM) and Mean-Reverting Process (MRP).

The GBM model (Equation 3.3) is used to model commodities or assets that are non-stationary such as gold price, stock prices and interest rates. However, for commodities such as base metals (copper, aluminium etc) an MRP model is used (Equation 3.4). This is because in the long-run their prices tend to move towards the marginal production cost (Dimitrakopoulos and Sabour, 2007; Dixit and Pindyck, 1994; Suarez and Fernandez, 2009). The model equations are described below:

Let  $S$  be

$$S = \ln(P) \tag{3.2}$$

with  $P$  being the commodity price (in US\$ per unit).

Then GBM model will be described as

$$dS = \alpha S dt + \sigma S dz \tag{3.3}$$

where  $\alpha$  is the expected trend (drift parameter),  $\sigma$  is the standard deviation (variance parameter),  $dt$  is the time interval and  $dz$  is the standard Weiner process.



While MRP model will be described as

$$dS = \mu(\bar{S} - S)dt + \sigma dz \quad (3.4)$$

where,  $\mu$  is the speed of reversion and  $\bar{S}$  is the long-run marginal cost of production of the commodity.

Given that  $S$  is the uncertain variable and following Equation 3.4, it follows that when  $\bar{S} < S$  then  $dS$  will more likely to be negative, to push the price down in the following time interval; and the converse is true (when  $\bar{S} > S$ ).

The speed of reversion,  $\mu$ , is the time it takes for the price shock dissipate ( $\bar{S} - S$ ), this is closely related to the half life of the shock. Half life,  $H$ , is defined as

$$H = \frac{\ln(2)}{\mu} \quad (3.5)$$

Further, the expected future price,  $\mathbf{E}[S_t]$ , and the price variance,  $\mathbf{V}[S_t - \bar{S}]$ , of a commodity (that follows an MRP model) at any given time,  $t$  are defined below in Equations 3.6 and 3.7 respectively

$$\mathbf{E}[S_t] = \bar{S} + (S_0 - \bar{S})e^{-\mu t} \quad (3.6)$$

$$\mathbf{V}[S_t - \bar{S}] = \frac{\sigma^2}{2\mu} (1 - e^{-2\mu t}) \quad (3.7)$$

where,

$\bar{S}$  is the long-run marginal cost of production of the commodity,

$S_0$  is the initial commodity price at time  $t_0$ ,

$S_t$  is the commodity price at time  $t$ ,

$\mu$  is the speed of reversion, and

$\sigma$  is the standard deviation.

In order to estimate the model, the Equation 3.4 can be expressed as an  $AR(1)$  model<sup>18</sup> as was done by Dixit and Pindyck (1994) and Suarez

<sup>18</sup>Auto-regressive model of order 1.

and Fernandez (2009). This implies that Equation 3.4 is transformed from a continuous time process to discrete time process. The resulting equation is described below

$$S_t - S_{t-1} = \bar{S} (1 - e^{-\mu}) + (e^{-\mu} - 1) S_{t-1} + \epsilon_t \quad (3.8)$$

with  $\epsilon_t$  (the error) following a normal distribution with a standard deviation of  $\sigma_\epsilon$ .

$$\sigma_\epsilon = \frac{\sigma^2}{2\mu} (1 - e^{-2\mu}) \quad (3.9)$$

If  $a = \bar{S} (1 - e^{-\mu})$  and  $b = (e^{-\mu} - 1)$ , it follows that

$$\bar{S} = \frac{-a}{b} \quad (3.10)$$

$$\mu = -\ln(1 + b) \quad (3.11)$$

$$\sigma = \sigma_\epsilon \sqrt{\frac{\ln(1 + b)}{(1 + b)^2 - 1}} \quad (3.12)$$

Having estimated the MRP model<sup>19</sup>, the half life of the shock can be calculated. This half life is important for estimating the long-run price,  $\hat{S}$ , on which an investment decision is based. It has been observed that decision makers base their capital investment decisions on an average historical price (DiNuzzo et al., 2005; Hearne et al., 2006; Lambert and Stone, 2008; Peters et al., 2013) covering a time interval similar to the half life. Further, because of the nature of the commodity price behaviour, the range of time series data used in estimating the model will significantly impact how the projected price will look (Sick and Cassano, 2012). The model is sensitive to both  $\mu$  and  $\sigma$ . Model estimation results are given in section E.4 of Appendix E.

<sup>19</sup>See Table E.4 of Appendix E for estimates.

### 3.3.6 Feedback relationships within a firm

The link between the physical (material) and financial components (modules), which are discussed on page 84 above, is what determines the investment behaviour of the mining firms (Aguirregabiria and Luengo, 2015; Montaldo, 1977; Sverdrup et al., 2014). This linkage can be captured by using four main feedback loops<sup>20</sup>, which would also have a time delay in them. These are the production-ore grade loop, ore grade-production cost loop, profitability-investment loop and investment-production loop.

- The production-ore grade loop: considers how production of copper leads to reduction in the ore grade.
- The ore grade-production cost loop: focuses on how reducing ore grade impacts production cost.
- The profitability-investment loop: looks at how reduction in profitability (as a result of increasing production cost and fluctuating copper prices) impact capital investment behaviour of a mining firm.
- The investment-production loop: focuses on how investments (in production capacity and other strategic stock) impacts production.

Apart from these four main loops, there is a minor loop, energy efficiency-production cost loop, that looks at how investment in energy efficient technologies could help reduce energy cost (which is a component of production cost). This loop captures the general arguments (Jaffe and Stavins, 1994; Patterson, 1996; Peck and Chipman, 2007; Sola et al., 2011) of how energy efficiency would help reduce production cost (assuming that the energy cost is a major contributor)<sup>21</sup>. Apart from these feedback loops within a firm, there is also another exogenous feedback loop between the mining and energy systems: the production-energy price-production cost loop. This loop is described in the section below.

<sup>20</sup>See section 4.3 for a discussion on loops in models.

<sup>21</sup>See section 7.2.4 for an analysis of the impact of energy efficiency investments.

### 3.4 Linkage of energy and mining systems

Having discussed past studies in the energy and mining sectors, the key energy demand drivers and the main aspects that influence decision making in the mining sector, this section describes how the models representing the energy and mining sectors are linked in this study (Chapters 5 and 6 gives a full description of the Zambian energy and mining models respectively).

There are two important aspects that this link captures: the impact of copper production on national energy demand and the impact of other sectors on national energy demand. The impact of copper production on energy demand focuses on how mining activities would impact on the energy price. And how the energy price would, in turn, impact the copper production cost, via the production-energy price-production cost loop. All things held constant, it follows that increase in energy demand from the mining sector leads to more investments in the energy infrastructure which leads to increase in the energy price (and vice-versa is true).

Apart from the increase in energy price as a result of increase in mining energy demand, the price is also influenced by the developments in other sectors such as increased electrification in the residential sector and the growth of the agricultural sector. Therefore, the increase in energy price due to growth in other sectors would still impact the copper production cost. This linkage is important because there is uncertainty of how the energy demand (particularly electricity demand) would evolve<sup>22</sup>.

Therefore, the energy price is driven by two components, demand from the mining industry and from other sectors. Figure 3.7 below shows the interaction between the models (energy and mining). The mining model requires energy in order to produce copper and the energy model meets this demand at a cost (the energy price).

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<sup>22</sup>See section 7.1.1 of Chapter 7 for projected energy demands.

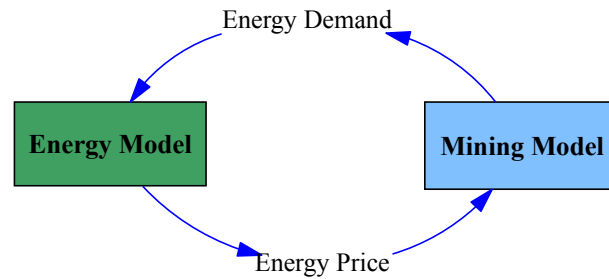


Figure 3.7: The linkage between energy and mining systems

## 3.5 Chapter summary

This chapter described and discussed how energy systems (particularly energy demand) have been modelled in the past and identified the weakness and gaps in the way energy systems were modelled in these past studies. It then proposed a more robust way of modelling energy demand (as energy demand influences the technologies that are developed and the energy price). The chapter also discussed the approaches used to define the existing [energy efficiency gap](#) (which influences an organisation's decision making relative to energy efficient technologies). It was found that the past studies took a narrow view of how energy efficiency related decision making is done in organisations, by focusing on the energy system without considering other cost saving opportunities that are available to an organisation. These studies also assumed that energy cost greatly influenced the organisation's total production cost. The next chapter (Chapter 4) discusses, in detail, how capital investment decisions are made in organisations.

Production processes, their accompanying energy carriers and key uncertainties in the copper industry were discussed. The chapter looked at factors that influence industry's profitability, which is key in decision making. Copper price was identified as the most uncertain variable in the investment decision making process in the industry, as it is not under the control of the firm nor that of the host government. The chapter then concludes by explaining the importance of considering the feedback loop (see section 4.3 for a discussion on feedback loops) within the mining system

and also of linking the energy and mining systems when studying capital investment decision making behaviour in the mining industry. This is because both feedbacks within and outside the mining system could potentially influence how energy is used in the industry, the copper production levels and the total production cost of the industry.

# Chapter 4

## Literature review: Investment decision making

This chapter has two main goals: to discuss how investment decisions are made in organisations (in sections [4.1](#) and [4.2](#)) and also to discuss and describe the main models used to study decision making in organisations. This is important because investment decision making is affected by a variety of factors. Thus, by understanding how organisations make investment decisions, different policies and measures that can enhance strategic investments could be analysed.

The chapter begins by discussing decision making theories and processes in organisations. It defines what investment decisions are and the processes that organisations follow when making such decisions. The next section then discusses different paradigms used in studying decision making. The appropriateness and limitations of these paradigms are also discussed. Then sections [4.3](#) and [4.4](#) discuss and describe the approach and scope that was considered in this research. Overall, this chapter lays the foundation on which the mining model (in Chapter [6](#)) is developed.

## 4.1 Investment decision making in firms

The primary motivation for organisations to invest is to create value (Cor-tazar and Casassus, 1998). These investment decisions are influenced by many factors, among them but not limited to these; compliance to the local regulations, replacement of obsolete equipment, desire to increase production capacity of the organisation, enhancement of company image and enhancement of company's competitive edge. An investment, from an economic perspective, would be defined as "the act of incurring an immediate cost in the expectation of future rewards" (Dixit and Pindyck, 1994; pg. 3). A decision can also be defined as a commitment of resources to achieve the desired result (Mintzberg et al., 1976). Thus, an investment decision can be defined as an act committing organisational resources with the hope of having better returns.

Generally, investment decisions have three broad characteristics: irreversibility, uncertainty and timing. Firstly, investments require an upfront cost, this cost can be either partially or completely irreversible. A partial irreversibility is a situation where the decision maker can recover part of the upfront cost should they decide to halt the investment project development. In a situation where the decision maker cannot recover any of the upfront cost, such an investment is referred to as a completely irreversible. An investment decision can be reversed or abandoned because the decision maker realises that the investment will not deliver the expected results, this could be because of changes in market drivers on which the decision was based. Secondly, due to limited knowledge and information about future events, such as commodity prices or regulatory controls, there is uncertainty over the outcome of any investment. The ability of a decision maker to put off making a decision as more information about an investment option is collected is the third characteristics of the investment decision (Dixit and Pindyck, 1994). The interaction of these three characteristics is what makes decision making a complex process.

Further, investment decisions can be divided into two: strategic and non-strategic. Strategic investment decisions are those investments that



require organisations to commit significant resources to achieving a desired outcome, and are usually made by top management. These types of decisions contribute to the creation, maintenance and development of an organisation's long term performance and sustainable competitive advantage (Butler et al., 1991; Cooremans, 2012; Mintzberg et al., 1976). On the other hand, non-strategic investment decisions do not significantly impact organisation's resources pool, and could be made at lower levels of company management. This research and chapter focus on strategic investment decisions.

Empirical research in decision making can be broadly classified into three categories: research done by cognitive psychologists; social psychologists; and management theorists and political scientists (Mintzberg et al., 1976). Cognitive research focuses on how individuals make decisions by exposing them to different situations through the usage of games. This research (cognitive research) has found that when decision makers are faced with complex and unusual decisions, they seek for ways to break down the decision situation into smaller and simplified chunks. By solving these smaller and simplified chunks, a decision maker can then come up with a final decision. This final decision is usually a sub-optimal decision. Social psychologists' research, on the other hand, focuses on group decision making by studying group dynamics and interactions among participants in controlled environments such as laboratories. The last category of decision making research focuses on processes involved in making decisions at organisational level.

#### 4.1.1 Strategic decision making process

“Strategic investment decision making involves the process of identifying, evaluating, and selecting among projects that are likely to have a big impact on a company's competitive advantage” (Adler, 2000; pg. 15). Mintzberg et al. (1976) studied 25 strategic decisions by collecting empirical evidence in organisations of a span of five years. In all the 25 processes studied, they found that the decision situations were characterised by novelty, complex-

ity, and open-endedness; and organisations generally had limited information of the problem at hand. Of the processes studied, there was a wide variation in the length of time it took to get to the final decision, ranging from less than one year to above four years.

Decision making process is made up of three parts: stimuli, solution, and process (Mintzberg et al., 1976). The stimuli component focuses on understanding what triggers the decision situation; these could be things such as perceived opportunity or crisis moments like losing market share. On the continuum scale of stimuli, opportunity moments see organisations take a proactive step to initiate the idea of seeking to improve or grow the organisation while on the other extreme of crisis moment, organisations are more reactive. The decision on how the organisation responds to the stimuli is found in the solution component. Solutions would be already made, newly created or modified. The process component studies the steps taken to move from stimuli to a solution.

In 1910, a framework of decision making was proposed by John Dewey. This framework consisted of five phases: “(1) suggestion, wherein the mind leaps to a possible solution; (2) intellectualization [sic] of the felt difficulty into a problem or question; (3) development of hypotheses; (4) reasoning or mental elaboration of these; and (5) testing of the hypotheses.” (Mintzberg et al., 1976; pg. 251-252) Based on this framework, other variations of this framework have been developed to study decision making. Mintzberg et al. (1976) use a three-phase framework and defines them as identification, development, and selection. In the identification phase, organisations, decision makers to be precise, identify the real stimuli (from the ‘noise’) of the situation, determine cause-effect relationships that the stimuli could affect and look for appropriate possible activities that could be taken to address the stimuli. The development phase is characterised by activities, techniques and processes that will be used to arrive at a solution or solutions. Under this phase, the organisations, search for information that would lead to finding desired solutions and also seeks to find better ways of how these solutions can be modified to fit into the organisation’s operations. The

final phase, selection, is where the organisation makes the final decision on which solution it will adopt and commits its resources in implementing the solution. However, even though these phases seem to be sequential, many studies have found that decision making process is iterative (Butler et al., 1991; Cauwenbergh et al., 1996; Mintzberg et al., 1976).

There are three modes of choice selection that could be used by a decision maker: judgement, bargaining and analytic modes. The judgement mode relies heavily on the decision maker's experiences. This also requires the decision maker to consider aspects of decision options that cannot be quantified (Butler et al., 1991). The judgement mode has also been found to be the fastest method of decision making (Mintzberg et al., 1976). When decisions are contentious and involve many other stakeholders, the bargaining mode is adopted and used. The final decision is generally a compromise of interests among involved stakeholders. The most reported selection mode in literature is the analytic mode. This mode emphasises on the quantitative aspects of the solution alternatives that can be evaluated, and assumes that the alternative that has the maximum utility is the best and should be chosen. However, the actual selection mode in organisations is usually a combined of all the three modes.

In their study, Butler et al. (1991) studied how complexity and politics can influence strategic decision making processes. The decision process was conceived to involve two fundamental problems: technical and political. The technical problem looks at which decision would be the best from the given alternatives and available information, while the political problem looks at how conflicting targets and interests within the organisation can be resolved.

The technical model employs various forms of techniques to solve the problem, such as optimisation techniques, pay-back period, net present value (NPV) and return on investment (RoI) calculations. This model assumes that decision makers are rational and will choose the best solution all the time in order to achieve the organisation's goal. However, research (Alkaraan and Northcott, 2006; Butler et al., 1991; Cauwenbergh et al.,

1996) has suggested that this is not the case. This was also the finding of my fieldwork (see Appendix D section D.4). The political model considers decision makers as individuals who come together to realise the organisational goals but they also have personal goals, which may be in conflict with organisational goals. When personal goal and politics take centre stage of the decision process, the final decisions can have negative implications for the organisation. These two problems (technical and political) make decision making process complex.

Technical or political models notwithstanding, organisations have general procedural guidelines on investments. These guidelines outline how resources of an organisation should be committed for all investment decisions (Alkaraan and Northcott, 2007; Butler et al., 1991). The guidelines also provide decision makers with indicators of what they should and should not consider when making investment decisions, these decision guidelines are essential for the organisation's growth and survival. Further, these management control systems also provide both pre-decision and post-decision guidelines. Among other benefits, the former, helps the organisation to: 1. avoid implementation of unplanned investments; and 2. reduce the risks of personal liability when making organisational decisions, as most strategic investments involve enormous financial commitments, which are risky and uncertain. While the latter helps the organisation to monitor and evaluate the effectiveness of the past decisions taken. This also helps organisations to learn from its past decisions.

#### **4.1.2 Identification of strategic issues**

Recognition of stimuli that would lead to a strategic decision is not easy, as decision makers are constantly faced with many different organisational issues (both strategic and non-strategic) that require their attention (Cohen et al., 1972; Dutton et al., 1989). Thus, organisations have mechanisms that help their decision makers to be able to easily separate strategic issues from non-strategic issues. A strategic issue could be defined as “events, developments or trends that are perceived by decision-makers as having

the potential to affect their organization's [sic] performance." (Dutton et al., 1989; pg. 380)

There are three groups of literature that discuss the aspects that decision makers use to define strategic issues; these are environmental scanning, issues management, and issue formulation and diagnosis (Dutton et al., 1989). Environment scanning literature focuses on how decision makers use their external environment to identify issues. This is done by monitoring the trends that are emerging from the environment. Issues management literature is concerned with how organisations, top management in particular, respond to social issues and corporate responsibilities rather than the identification and evaluation. The final group of literature is issue formulation and diagnosis, it focuses on early stage of decision making where stimuli are identified and evaluated.

Four dimensions are used to define strategic issues. The first is the analytic dimension, which focuses on specifics of the issues, such as visibility, complexity and potential impact of an issue. The second is the content dimension, which pertains to the nature of the issue such as type (economic, social, political or technical) and geographical boundaries. Action dimension is the third class, it looks at the effort and action that is required to handle the issue, such as controllability and feasibility. The fourth and final dimension is the source of an issue. This dimension looks at who initiates the issue and how influential this initiator is. This class has a strong connotation of how organisation politics play a major role in strategic decision making (Dutton et al., 1989).

### 4.1.3 Decision effectiveness

Having looked at decision making processes in the preceding sub-sections, this sub-section focuses on how decision processes influence decision effectiveness. Decision effectiveness can be loosely defined as the extent to which the process achieves the outcome as intended by the decision maker at the time the decision was made. This relationship, between process and outcome, has been studied by Dean and Sharfman (1996). The re-

lationship rests on two assumptions: (1) that different processes lead to different choices and (2) that different choices lead to different outcomes. Furthermore, for a relationship to exist, both assumptions have to be true.

In addition to the arguments presented by [Dutton et al. \(1989\)](#) and [Eisenhardt and Zbaracki \(1992\)](#), that bounded rationality (see section 4.2 for further description) and organisation politics are best suited to model strategic decision making processes, [Dean and Sharfman \(1996\)](#) suggests that it is also essential for decision effectiveness to be studied within defined constraints. In this regard, [Dean and Sharfman \(1996; pg. 373\)](#) suggests that for decision processes to result into effective decisions, process have to be “(1) oriented toward achieving appropriate organizational goals, (2) based on accurate information linking various alternatives to these goals, and (3) based on an appreciation and understanding of environmental constraints.”

To ensure that the process is oriented towards organisational goal, it is important that a deliberate process of collecting information and analysing the collected information (which are part of the organisation’s guideline) is followed. Thus, if such a deliberate process is followed, this process can be considered rational within constraints – as not all available information is collected nor analysed. Collection of information and analysing it will: firstly, create a clearer picture that links proposed solution options to their outcome. This will give a decision maker an opportunity to clearly see the relationship between a possible alternative solution and its outcome. Secondly, this will help decision makers to identify trends that are emerging from the environment in which the organisation operates. Finally, this will reduce personal influences (the political model) in coming up with the final decision. As there will be a clearer picture of what each solution option holds, and also the decision makers will be more aware of the environment in which their organisation is operating and also easily recognise emerging trends. Further, in dynamic environments, the more an organisation collects information about its environment and carries out analyses, the more it is likely to perform better ([Dean and Sharfman, 1996](#)).

Nevertheless, even when chosen options are in line with organisational goals, this does not automatically translate into desired decision outcomes. There are other factors that can affect decisions' effectiveness such as, among others, the financial position of the organisation, growth prospects, competitors' decisions, political environment of the country in which the organisation is operating and quality of implementation.

## 4.2 Choice paradigms

Decision making theory at organisational level is dominated by three choice paradigms: rationality and bounded rationality; politics and power; and garbage can ([Eisenhardt and Zbaracki, 1992](#)). Under the rationality and bounded rationality paradigm, the rational model assumes that the decision maker has a set of known decision objectives when they get into a decision situation. The decision maker then collects the right information to aid the decision situation and analysis for all possible alternatives, then chooses the optimal option. The alternative model to the rational model is bounded rationality. The bounded rational model argues that decision makers have limited cognitive capacity, are pressed for time and that their decisions are influenced by experience ([Todd and Gigerenzer, 2000](#)). Further, this model contends that decision goals are not always known at the start of the process and keep changing over the decision process. Rather than seeing the rationality and bounded rationality paradigms to mean that the decision makers are either rational or bounded rational, all decision makers exhibit both trends. They are rational in other aspects while being bounded rational in others. See sub-section [4.2.2](#) for a detailed discussion.

Politics and power paradigm has its roots in political science. This paradigm assumes that even though organisations can have clear organisational goals, the decision makers (in organisations) have different goals; as a result of functional, hierarchical and personal factors, personal goals that could potentially be in conflict with organisational goals. Further, this paradigm argues that although decision makers can be individually

rational, a collection of them may not lead to rational decisions because they could have competing preferences. Therefore, because of competing preferences among decision makers, final decisions can be thought to follow the choices of the most powerful person in the organisation (Dutton et al., 1989; Eisenhardt and Zbaracki, 1992).

The final paradigm is the garbage can. This paradigm was first described by Cohen et al. (1972) who studied decision processes with a view that various kinds of problems (stimuli for decisions) and solutions come to a decision maker at the same time but in an ill-defined and ever changing way. When compared to the first two paradigms, the garbage can focuses on the role of chances in decision making process. It contends that final decisions are not a product of deliberate analysis or political power, but a matter of random outcome of events (Eisenhardt and Zbaracki, 1992). However, empirical studies of decision making found that “strategic decision making is best described as a combination of boundedly rational and political insights.” (Eisenhardt and Zbaracki, 1992; pg. 31) Thus, garbage can paradigm is found to be of less relevance in describing how actual strategic decisions are made; because it is not robust as the other two paradigms.

Covin et al. (2001) studied how the environment and organisation structure impacts the relationship between choice paradigm and firm performance. Depending on the choice paradigm, organisation’s decisions can be analysed for different insights. For instance, if the organisation’s decision making paradigm is predominantly ‘political and power’, then understanding the individual decision making style of the most powerful person would give more insights on how that organisation makes decisions. This research focuses on understanding how various input costs, taxation policy and copper price impacts on the organisation’s profitability, a key component in investment decision making. Thus, the rationality and bounded rationality paradigm is the main focus.



### 4.2.1 Decision environment

There are two categories of environments in which organisations operate: stable and uncertain environments. In stable environments, organisation's future is fairly predictable as opposed to uncertain environments such as the mining industry where key decision drivers like commodity price change constantly. Because of this, organisations that operate in uncertain environments make decisions based on limited and ever changing information. Thus, their decision rules are usually simplified, more "like rules of thumb than on extensive analysis of all available data" (Artinger et al., 2014; pg. 3). However, these organisations have concrete operational procedures (decision guidelines) and also fairly rigid organisation structures.

Literature (Dutton et al., 1989; Eisenhardt and Zbaracki, 1992; Fredrickson and Mitchell, 1984) that studies decision making under uncertainty in organisations suggests that decision makers rely considerably on rational procedures (such as decision guidelines). It also found that some aspects of decision making rely on decision maker's experience (judgement and intuition). It is, therefore, essential to understand how the two aspects of decision making interact and how they can be effectively modelled.

### 4.2.2 Rationality and bounded rationality

Research focusing on how individuals and organisations make decisions is well documented in literature (Alkaraan and Northcott, 2007; Cooremans, 2012; Covin et al., 2001; de Groot et al., 2001; Decanio and Watkins, 1998; Dutton et al., 1989; Eisenhardt and Zbaracki, 1992; Fredrickson and Mitchell, 1984; Wilson and Dowlatabadi, 2007). Most of this literature focuses on the rational model of decision making. As mentioned earlier, this model assumes that the decision makers know exactly what they want to achieve and are certain (or have known margins of error) about the all possible decision outcomes and their effects. It further assumes that the decision maker makes the best decision out of a given decision situation, within specified constraints; such as alternatives from which a decision

maker chooses.

A conceptual rational model has three parts (Simon, 1955): a set of alternatives to choose from (represented by vector  $[A]$ ), a function (such as  $F([A])$ ) that links alternatives to their pay-offs and pay-off's probability distribution, and the function that determines the model's preference ordering (such as  $a_1 = F(A_1)$  is preferred to  $a_3 = F(A_3)$ ). An example of a rational model (a linear optimisation model) is described below (Bisschop, 2008):

$$\text{Minimise: } \sum_{j \in J} c_j x_j \quad (4.1)$$

$$\text{Subject to: } \begin{aligned} \sum_{j \in J} (a_{ij} x_j) &\geq b_i & \forall i \in I \\ x_{j \geq 0} & & \forall j \in J \end{aligned} \quad (4.2)$$

where,

$c_j$  is the cost coefficient of variable  $j$ ,

$a_{ij}$  is the constraint coefficient  $i$  relative to variable  $j$ , and

$b_i$  is referred to as a requirement.

Note: To maximise the objective function (Equation 4.1), simply multiply it by '-1'.

Despite the strengths of rational model, it has been observed that decision makers do not make decisions using this model because, among other reasons, decision makers do not have the cognitive ability to process all the available information and pick the best option among possible alternatives. It is further argued that decision makers do not always have the information that is required when making decisions (Mintzberg et al., 1976; Todd and Gigerenzer, 2000). These and similar criticisms have persuaded researchers to find alternative models for decision making at both individual and organisational levels, studies such as Simon (1955), Kahneman and Tversky (1979), Byron (1998), Levy and Wiener (2013) and Carpinelli and Russo (2014) capture aspects of the alternative model. The alternative model is the bounded rational model. This model takes into account the

behavioural aspects of decision making.

Whereas a rational model could have infinite choice alternatives, a bounded rational model always has finite alternatives. This is a critical characteristic of the model because it simplifies the decision process, making it similar to how decision situations are like in organisations. This implies that instead of a decision maker seeking a solution from a range of possible alternative, a decision option is always picked from known and available alternatives. To illustrate this using an analogy of The Secretary's Problem ([Bearden et al., 2005](#); [Ferguson, 1989](#); [Freeman, 1983](#)). A rational model would be described as The Secretary's Problem in a dynamic environment with a known probability distribution while a bounded rational model would be a Problem with a known desired applicant threshold.

Thus, to get a bounded rational model, three key modifications have to be made to the rational model ([Simon, 1955](#)): simplification of a pay-off function, simplified information searching rule and partial ordering of pay-offs.

Simplification of a pay-off function narrows down choice alternatives to two or three values. A two-value functions could be interpreted as a satisfactory or unsatisfactory function, whereas a three-value function could be a win, draw or lose function. The point at which each value is picked (from the simplified pay-off functions) is defined by thresholds. This simplified function implies is that the decision maker is satisfied by any alternative that is equal to or better than the set threshold. Further, the magnitude by which the alternative exceeds a set threshold is irrelevant.

Simplified information searching rule focuses on only a section of information that is critical for making decisions. This rule takes into consideration that decision makers have limited time that they can dedicate to each decision process. This rule is in line with what researchers ([Kerstholt, 1994](#); [Payne et al., 1988](#)) found, that decision makers only focus on specific information indicators in their decision making.

The third modification is to their pay-off rule. This focuses on how a decision maker gets to a decision point (choosing between alternatives).

A summary of these modifications is given below ([Artinger et al., 2014](#); [Byron, 1998](#); [Simon, 1955](#)):

1. Set the target thresholds or criteria for each decision category.
2. Search for information that can be used to assess whether an alternative satisfies the target thresholds or criteria.
3. Pick any alternative that satisfies all target thresholds or criteria.

[Todd and Gigerenzer \(2000\)](#) studied the concept of how decision makers make decisions within the bounded rationality model. They focused on how decision makers make decisions under time pressure, limited information and cognitive capacity. They introduce a concept of heuristics; heuristics are strategies used to solve problems that cannot be easily solved by logic and probability theory ([Artinger et al., 2014](#)). Heuristics help reduce the requirement of cognitive demands of the decision makers; because heuristics simplify how a decision maker decides. This is done by, among others, any of the following heuristics; satisficing, recognition, elimination and availability. Under satisficing heuristics, the decision maker sets a threshold of what a good enough decision would be. Recognition heuristics is when the decision maker bases a decision on what he/she had previously chosen. When the decision maker, however, chooses to eliminate some alternative simply because they have a low score, for example, such a heuristic is called elimination heuristics. The final heuristic is called availability heuristic. This is when a decision maker makes a choice based the alternative that is readily available to them ([Wilson and Dowlatabadi, 2007](#)). For a comprehensive description of various types of heuristics, kindly see [Payne et al. \(1988\)](#) and [Todd and Gigerenzer \(2000\)](#).

[Byron \(1998\)](#) study looks how decision makers pick their preferred alternative in a decision situation where there are multiple decision thresholds or criteria. The paper presents global and local goals concept. A global goal describes the general direction that a decision maker would want to go while a local goal focuses on the specifics of what the decision maker would have to do to achieve the overall goals. For instance, a decision maker could

want to have a healthy cash-flow, as a global goal, and cutting down on energy bills by investing in energy efficient technologies and retaining the best employees would be defined as local goals. In this case, a global goal could indicate the relative importance of each of the local goal to achieving its desired cash-flow.

This concept of global and local goals is critical when analysing decision making in organisations because organisations have many different and unrelated options to achieving their desired goal. For instance, many studies (Fleiter et al., 2011; Sarkar and Singh, 2010; Sola et al., 2011; Weber, 1997) found that even though the benefits of energy efficiency measures are obvious, barriers hinder their implementation. However, another plausible argument, which I presented in section 3.2.4, would be that energy efficiency studies have a narrow perspective of how organisations make decisions (they mostly focus on an organisation's energy system, as shown in Figure 3.1 in Chapter 3). If these energy efficiency opportunities are analysed in the context of a global goal, one could find that they do not offer the best return.

Simon and Newell (1958) discuss two categories of decision problems that decision makers face: well-structured and ill-structured problems. They argue that rational models are suited to handle well-structured problem while ill-structured problems are better studied using bounded rational models. A well-structured problem is a problem that can be formulated explicitly and quantitatively (Simon and Newell, 1958). An ill-structured problem, therefore, is any problem that is not a well-structured problem. Its objective is vague and usually not easy to quantify. All well-structured problems satisfy these criteria (Simon and Newell, 1958):

1. It can be described in terms of numerical variables, scalar and vector quantities.
2. The goals to be attained can be specified in terms of a well-defined objective function, such as profit maximisation.
3. There exist computational routines (method) that permit the solution

to be found and stated in actual numerical terms, such as linear programming algorithms.

[Simon and Newell \(1958\)](#) further argue that organisation's top management decision environments are made up of ill-structured problems. They observe that decisions in these environments are almost always made based on judgement and intuition. These judgement and intuition decisions are rational choices ([Byron, 1998](#)). For instance, if a decision maker is faced with two decision alternatives (one that satisfies the target threshold and the other that does not), the decision maker will always pick an alternative that satisfies the target threshold. As choosing the one which does not, would make them irrational. This was what [Butler et al. \(1991\)](#) and [Alkaraan and Northcott \(2007\)](#) also found, that organisations have guidelines that decision makers follow when making decisions. As part of the decision process, analytic techniques are used to evaluate all the decision alternatives ([Alkaraan and Northcott, 2006](#); [Cauwenbergh et al., 1996](#)).

### **4.2.3 Analytic techniques and their criticism**

Strategic investments present a dual problem to an organisation, on one hand, if an organisation gets the decision right that organisation will reap enormous dividends from that decision. On the contrary, the opposite is also true. Thus, organisations approach these decision situations with great caution. In order to reduce uncertainty in decision making, many organisations employ usage of analytic techniques to evaluate decision options, techniques such as discounted cash flow (DCF), internal rate of return (IRR) and pay back period ([Ashford; et al., 1988](#); [Cauwenbergh et al., 1996](#)).

For instance, between 1992 and 1994, a study that looked at how formal (analytic) analysis plays in strategic decision making processes was done in 50 organisations in Belgium ([Cauwenbergh et al., 1996](#)). The organisations that were interviewed during the research indicated that use of formal analysis varies. Some organisations use it as an aid to decision making while others use it as a communication tool, and of course a mix of these within

organisations. They also found that even though formal analysis was common, the results from these analyses were not the sole factor in decision making. However, perhaps one of the most important findings from this study was that all the final decisions considered the analytic evaluation of the decision options (alternatives).

### Pay back period

Pay back period of an investment is the length of time it takes for an organisation to recover its capital investment cost of a project. It is defined as the total capital cost of a project divided by the total savings realised from the project per year. This is a simple technique as it ignores to measure the profitability of the project, by only focusing on the time it takes to recover the money. Despite its limitations, pay back method is widely used in organisations ([Alkaraan and Northcott, 2006](#); [Sola et al., 2011](#)). Some of the strengths of pay back period technique are its simplicity of use and easiness to quantify business risks that could otherwise be difficult to quantify.

### Discounted cash-flow

Discounted cash flow (DCF) uses the concept of time value of money, by considering the in and out flows of cash from the organisation as a result of a particular investment (being analysed). Central to DCF, is the net present value (NPV) concept. The NPV measures the expected financial return on an investment throughout its entire life. The simple NPV rule is that if the expected value is greater than zero, then the project should go ahead otherwise, it should be shelved. This technique is popular in analysing investments in copper industry ([Auger and Ignacio Guzmán, 2010](#)). The definition of NPV is shown in the equation below:

$$NPV = A \times \frac{(1+r)^n - 1}{r \times (1+r)^n} - I \quad (4.3)$$

where,

$A$  is savings (or avoided costs) as a result of the investment,

$r$  is the discount rate ( $r > 0$ ),

$n$  is the life span of the investment, and

$I$  is the total capital investment cost of the project.

Like many other techniques, the output of this technique (NPV), is susceptible to input assumptions and discount rate. High discount rates tend not to incentivise long term investments that are profitable, but incentivise short term investments that could be less strategic (Moyen and Slade, 1996) but whose benefits can be easily quantified. On the other hand, this technique is theoretical rigorous and can treat risk and uncertainty more explicitly than other traditional techniques (Phelan, 1997).

### **Internal Rate of Return**

Internal rate of return (IRR) can be defined as the discount rate ( $r$ ) of an investment at which the NPV becomes zero ( $NPV = 0$ ). This technique is used to test if an investment will ever break even, and if there is a break-even point, when would it be.

Apart from the evaluation of whether an investment option can be viable, these tools are also used to compare the profitability of investment options against each other. However, even though these tools and techniques have stood a test of time and have played a critical role in strategic decision making, they have been heavily criticised for their limitations. Overall, the major weaknesses are their inability to capture qualitative and non-financial aspects of an investment and results output as hugely influenced by the input assumptions such as discount rate. The weaknesses notwithstanding, these techniques are essential to appraising of investment options. Therefore, to get the most out of them, these techniques should not be used as sole informants to decision processes (Adler, 2000; Alkaraan and Northcott, 2006; Ashford; et al., 1988; Phelan, 1997).

There have been calls for improvement of these techniques and for development of completely new techniques for analysing investment options in organisations. Among the techniques proposed are strategic cost manage-



ment (SCM), multi-criteria decision making (MCDM), value chain analysis and real options analysis (Adler, 2000; Alkaraan and Northcott, 2006; Phe-lan, 1997). All these proposals nonetheless, assume that decision makers are rational and will choose the options that have the maximum benefit. However, empirical studies of decision making in organisations have shown that decision makers also use experience when making decisions.

### 4.3 Modelling decision making process

In Chapter 3, different modelling approaches and frameworks used to model energy, organisation and other general systems are discussed. Under the simulation framework, one of the methods is System Dynamics (SD): a method used to study the dynamic behaviour of systems. SD modelling approach provides a good platform for modelling decision making in an organisation because heuristics decision rules can be adequately captured. Moreover, because of the myopic and sequential nature of decision making in organisations (mining firms in particular), this approach provides a framework in which effects of decision feedbacks can be represented.

Furthermore, the use of an SD model enables easy capture of operational behaviours that have been observed in the mining sector. After a capital investment decision has been made, the way the capital stock is used (i.e. operational behaviour) varies from one time step to the other (Cortazar and Casassus, 1998; Sabour, 2001). This is because, among other factors, the commodity prices may decline to unfavourable levels such that the mining firm has to decide whether to reduce production, suspend operations (temporal closure) or completely abandon the project. The three behaviours<sup>1</sup> are:

- Loss tolerance: This focuses on the length of time that a mine operator can continue producing despite being in a loss position. Mining operations do not stop production at the first sight of operational losses.

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<sup>1</sup>See Chapter 6 section 6.3.3 for the description of the governing decision rules.

- Closure or suspension of operations: This is the operational state that an operator uses to minimise the losses the operation would incur due to the reduction in commodity price or profits.
- Re-opening of the mine: The behaviour describes the price conditions under which an operator would re-open the mine after suspending operations. This explains why mine operations do not re-start at first sight of higher commodity price than their unit production cost.

### 4.3.1 Characteristics of a system dynamics model

A system dynamics model is characterised by three types of variables: stocks (levels), flows (rates) and auxiliaries. A stock describes the state of the system such as accumulation of profits or losses, the derivative of the stock is called flow which is also called system policy. Any other variable intermediate to stocks and flows is called an auxiliary. An SD model can be thought of as a set of differential equations, where the state of the system ( $\dot{x}$ ) at time  $t$  is dependent on the history of the system ( $x$ ), the system flows ( $p$ ) and the exogenous factors ( $\varepsilon$ ) that might be acting on the system. Below is an equation that gives a general description of the system:

$$\dot{x} = F(x, p, \varepsilon) \tag{4.4}$$

where,

$\dot{x}$  is the current position or state of the system,

$x$  is the history of the state of the system,

$p$  are the policies of the system,

$\varepsilon$  are the exogenous factors acting on the system, and

$F$  is a function defining the relationship between variables of the system.

An SD model is a series of nested equations (as described in the equation 4.4 above), with an established relationship between them. Change in a sub-system  $a$  ( $\dot{x}_a$ ) impacts how another dependent sub-system  $n$  ( $\dot{x}_n$ )

changes. These impacts (feedbacks, which are endogenous) can be immediate or delayed. This characteristic is essential when studying change in an organisation, change that is driven by different decisions that are made within an organisation. For instance, a decision made in time-step  $t_1$  will have an impact on the decision environment ( $x(t_n)$ ) of time-step  $t_n$ .

Figure 4.1 below shows a generic structure of an SD model. The figure shows the seven basic elements of the model: source, inflow, outflow, stock, sink, variable and feedback loop. Using the terminology of types of variables defined above, “inflow” and “outflow” fit in the classification of flows; the “stock” element fit in the classification of stock type while the auxiliary type contains the “variable1” and “variable2” elements. Source and sink show the beginning and an end of a flow respectively. The “feedback loop” is a link between the state of the stock and the flow. This loop carries information or instructions of how the rates (inflows or outflows) of the system should respond based on the state of the system (stock). It is in this link where conditions that influence and affect decisions are contained (Forrester, 1991).

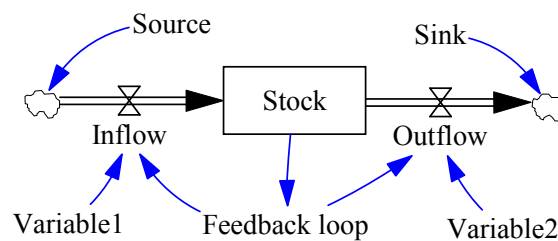


Figure 4.1: A generic system dynamic model

### 4.3.2 Decision making in SD models

Decision making in SD models (just like in actual organisations) take a form of heuristics. Decision rules are based on thresholds, following the logic of satisficing heuristics (see sub-section 4.2.2 above). These thresholds are determined by the decision makers (Sterman, 2000). Thresholds are simple decision rules that determine the behaviour of a decision maker. An example of a set of satisficing decision rules in an SD model is, if the RoI (return on investment) of an investment is above 50%, invest in new

capacity of that technology, if it is below 50% but above 15%, only replace the capacity that is being retired otherwise do not invest in any capacity.

For decision rules to be useful, they have to at least mimic the behaviour of real decision makers. These rules have to be realistic and also robust enough for different decision point scenarios. Decisions are a product of decision rules. [Sterman \(2000; pg. 514\)](#) defines decision rules as “the policies and protocols specifying how the decision maker processes available information.” These decision rules assume a degree of rationality both of the decision maker and decision process.

There are five basic principles that every modeller has to follow in order to effectively model decision making in SD models. Below is a list of these principles as described by [Sterman \(2000; pg. 517\)](#).

1. The inputs to all decision rules in models must be restricted to information actually available to the real decision makers.
  - The future is not known to anyone. All expectations and beliefs about the future are based on historical information. Expectations and beliefs may, therefore, be incorrect.
  - Actual conditions and perceived conditions differ due to measurement and reporting delays, and beliefs are not updated immediately on receipt of new information. Perceptions often differ from the actual situation.
  - The outcomes of untried contingencies are not known. Expectations about “what if” situations that have never been experienced are based on situations that are known and may be wrong.
2. The decision rules of a model should conform to managerial practice.
  - All variables and relationships should have real world counterparts and meaning.
  - The units of measure in all equations must balance without the use of arbitrary scaling factors.

- Decision making should not be assumed to conform to any prior theory but should be investigated first-hand.
3. Desired and actual conditions should be distinguished. Physical constraints to the realization [sic] of desired outcomes must be represented.
    - Desired and actual states should be distinguished.
    - Desired and actual rates of change should be distinguished.
  4. Decision rules should be robust under extreme conditions.
  5. Equilibrium should not be assumed. Equilibrium and stability may (or may not) emerge from the interaction of the elements of the system.

The interactions between the stock (State of the System) and flows (Inflow and Outflow) are controlled by the decision rules that are contained in the Input and Output functions, as can be seen in Figure 4.2 below. The decision maker has an idea of the current state of the system (based on the Cues) and what the stock (State of the System) should be, then makes decisions that take the “State of the System” closer to the desired stock (Desired State of the System). Suppose that the stock (State of the System) at  $t_0$  is 10 units, but the desired stock (Desired State of the System) is 12 units. In the next time-step  $t_1$ , the decision maker decides on how many units to invest in based on the Input function and also how many units to retire based on the Output function. These functions are governed by the decision rules of the system.

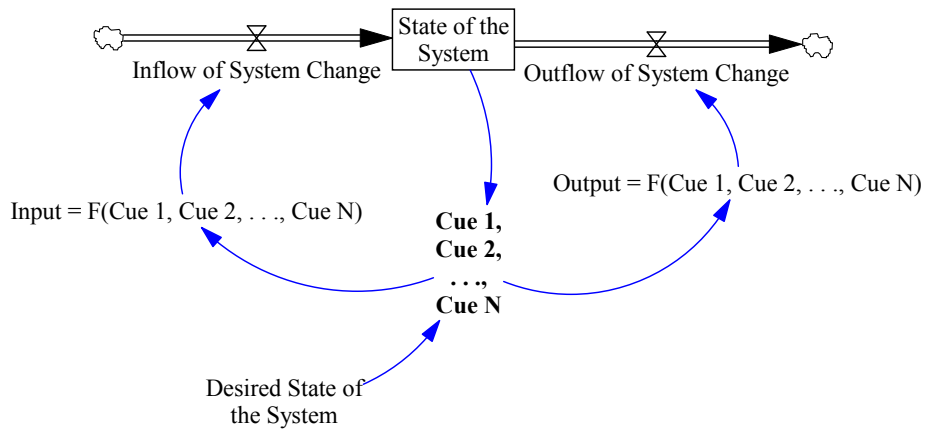


Figure 4.2: Decision rules govern the rates of flow in systems

### 4.3.3 Model validation process

As discussed above, the mining decision model (described in Chapter 6) is developed using system dynamics (SD) modelling framework. This is because SD framework is suitable for analysing how a decision made in one time step affects those that are made in subsequent time steps (Forrester, 1991; Wolstenholme, 1982). This characteristic (feedback loop effect) is important to capture because it has been observed that mining firms' operational behaviour vary between time steps (Cortazar and Casassus, 1998; Sabour, 2001).

An example of a feedback loop effect is shown in Figure 4.3 below. The diagram shows the impact that copper price has on demand and also on supply. A high price stimulates investment in copper production (supply technologies) but at the same time leads to reduction in demand. Depending on the length of the cycles, copper supply and demand can potentially be mismatched. This implies that at every time step, conditions driving decision making could be different and would, therefore, require different actions to be undertaken.

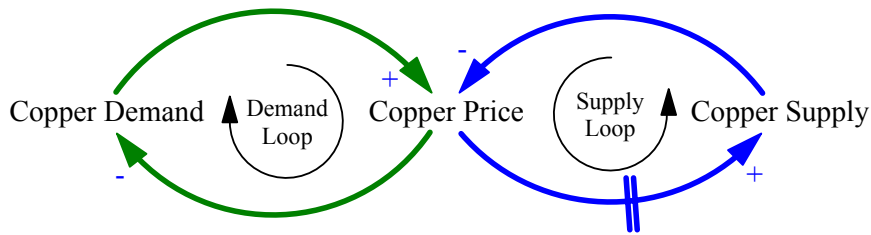


Figure 4.3: A stylised causal loop diagram

Thus, to ensure that the model behaves consistently and gives reasonable results relative to the real system being analysed, a series of validation tests are applied to the model<sup>2</sup>. This validation process is important in building confidence that the model is fit for purpose. SD validation process has, however, been criticised for not employing formal, objective and quantitative procedures, which are regarded as fundamental to any scientific enquiry (Barlas and Carpenter, 1990). Forrester and Senge (1980), Barlas and Carpenter (1990) and Sterman (2000) however disagree with this approach of defining what a scientific enquiry is and also on the possibility of a model being validated. They argue that all models are wrong, making it impossible to validate. They further argue that instead of taking a “true or false” paradigm, model validation process should focus on the usefulness of the model rather than on the validity.

Model validation process in SD is iterative. The focus of the process is on the suitability of the model to aid decision making and how internally consistent the model is. The model validation procedures can be broadly divided into three categories: verification of model structure; validation of model behaviour; and consistency with systems rules (Coyle, 1983; Forrester and Senge, 1980).

Verification of model structure considers, among others, the consistency of individual relationships and flows in the model relative to what is known about a real system. It focuses on ensuring that the parametric values and units used in the model are correct. This process includes testing for boundary definition, ensuring that all important variables are captured in the model. This verification can be done by checking with actual organi-

<sup>2</sup>See Appendix D section D.6 for a list of tests that could be applied to a model in order to improve it.

sations or by using literature.

Under this category, tests for extreme conditions are also done.<sup>3</sup> An example of an extreme condition is when the energy consumption is zero, system production is zero. Extreme condition tests are important because they help discover model structure flaws and they also test the robustness of the model for conditions that have not yet happened but could happen in future.

The second category, model behaviour, looks at how the model responds to different endogenous stimuli relative to the established real system's behaviour. Behaviours such as, 'does the model invest in capital equipment of 20 years life span when only one year worth of resource value is available?' or 'does the energy consumption increase as the copper ore grade reduce?' Depending on how the model behaves, inconsistencies in the model can be identified and rectified. And finally, system rules focus on how a model responds to different system rules or policies relative to corresponding reality. An example of such a system policy is how the model responds to influence of commodity price. Say if price is a key driving factor, variance in price would be expected to produce variance in the model response.

## 4.4 Decision making research context

This section focuses on describing the decision situation (environment) that will be considered in this research. The study covers copper production from mining stage through to refining stage (from cradle to gate). It considers the cost of production and the energy types consumed by different ore types, as shown in Figure 2.1 of Chapter 2 above. The research looks at Zambia's copper industry, a price taker. As a price taker (the industry's production patterns does not significantly influence the price of copper on the global market), Zambia's industry is exposed to have greater uncertainty when compared to Chile's industry (the leading producer of copper) for example. Apart from the uncertainty of price, the uncertainty for other

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<sup>3</sup>See section D.6.1 for five extreme tests that were applied to the mining model developed in Chapter 6.



commodity prices such as energy prices, raw material prices and labour costs are considered.

Capital investment and operational decisions are analysed, with capital decisions being long-term while operational decisions are short-term. Capital investment decisions are divided into two categories: production capacity and electric motor capacity investments. Production capacity investments are driven by the price of copper, available copper resources and an organisation's profitability while investments of electric motor stock are driven by electricity price, production capacity, the organisation's profitability and [energy efficiency gap](#). As for operational decisions, they are driven by the organisation's profitability. Decision rules and functions that govern each of these decisions are described and defined in Chapter 6 below.

These three decisions can be thought of as being made by three different actors, whose aims are also different – with all the decisions driven by both exogenous and endogenous factors. The actor (say actor 1) who makes decisions of production capacity is driven by the desire to increase or maintain production of copper (related to organisation's market share). By investing in efficient electric motors, the actor (actor 2) hopes to increase the organisation's productivity for every tonne of copper produced in the long-term. Finally, the actor (actor 3) who makes operational decisions focuses on minimising operational losses which would result from fluctuations in commodity prices or reduction in [ore grade](#) quality. A combination of these three decisions could further help in understanding how the organisation's energy efficiency would change over time, the energy efficiency indicator used here is the average efficiency of the electric motor system.

Figure 4.4 below shows an interaction of these three decisions (outputs).

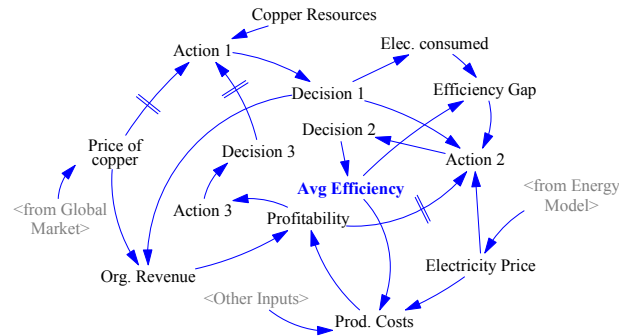


Figure 4.4: Interactions of decision outcomes

## 4.5 Chapter summary

This chapter described the processes that organisations go through when making capital investment decisions. The main models (rational and bounded rational models) used in studying investment decision making in organisations were discussed. Based on the literature reviewed, it was found that bounded rational models capture the decision process better than the rational model. Firstly, because decision makers have limited knowledge, time and resources to optimise their decisions. Secondly, because the copper industry (the focus of this study) operates in an uncertain environment. In order to better represent and capture the dynamics and feedback mechanisms of the industry, an SD modelling approach (one of the models under the bounded rational paradigm) was picked. The chapter then concluded by establishing the research scope that is considered.

# Chapter 5

## Modelling of Zambia's energy system

This chapter addresses the first theme of this research, which focused on the development of Zambia's energy system model (described in sub-section [1.1.1](#)). This model was used to study how the energy system would evolve under a range of demand scenarios. It also looked at the technology stock and how much capital investment cost that would be required in each of these demand scenarios. The model helped to answer four sub-questions:

- How would residential energy demand change?
- Which supply-side technologies would be required to meet Zambia's energy demand?
- How much capital investment would be required to develop Zambia's energy system?
- How would the average generation cost change over time?

Two energy models were developed for this study: demand and supply models. The demand model was developed using a [LEAP](#) platform (see [Heaps, 2016](#)) and [OSeMOSYS](#) platform (see [Howells, 2009](#); [Howells et al., 2011](#); [Osemosys, 2013](#); [Welsch et al., 2012](#)) was used to build the supply

model. All the data used in the development of these models can be found in Appendix C.

The chapter is organised as follows: Section 5.1 identifies and describes the key drivers of energy demand and how future demand was modelled. The second section (section 5.2), describes the resources available in and around Zambia to meet this energy demand. An optimisation model was developed that linked energy resources to demand. Finally, section 5.3 describes the scenarios that were used in this study. These scenarios were particularly useful when studying the impact of increasing access to [clean energy](#) on the mining industry. The chapter then concludes with a chapter summary (section 5.4).

## 5.1 Demand model

Energy demand arises from satisfying an energy service through usage of an appliance or technology. Total energy demand is, therefore, dependant on the [energy intensity](#) of a service, the choice of a technology and its (technology) efficiency ([Bhattacharyya and Timilsina, 2009](#)). An example of energy service is a cooking or lighting activity. The choice of technology to use in order to satisfy an energy service depends on, among others, the availability of the technology, affordability (i.e. investment cost) of the technology, the cost of using that technology and preference of the technology user. Technology efficiency is an embedded characteristic of a technology.

The transition from one technology use to another (observed using changes in fuel energy shares and intensities) has exhibited inertia. Apart from the common reason of affordability (for example in the case of residential sector), two main aspects are usually overlooked. These are technology lock-in and unavailability of preferred energy carriers. The first aspect looks at the cost of disposing off a technology stock that still has operational life and investing in a new technology that uses a preferred energy carrier (if available). It argues that sometimes, it is cost effective to con-

tinue using a technology which is inefficient than to invest in an efficient technology. The second aspect focuses on the choice options available to the user. It argues that no matter how desirable an energy carrier could be, if it is not available then it will not be used. This study using these three aspects (affordability, technology lock-in and availability) to show how energy demand would evolve.

Drivers of energy use and energy transition in different sectors have been generally understood (Barnes and Floor, 1996; Bhattacharyya and Timilsina, 2009). However, the major challenge has been how we think about energy demand going forward. This is because the future is full of uncertainty, due to the complex interactions between many different drivers (Ruijven et al., 2010).

Furthermore, when studying a developing country's energy system, unavailability of data and statistics make projecting energy demand challenging (Ruijven et al., 2008). However, projection of demand would even be more challenging in some countries with *suppressed energy demand*. As Bhattacharyya and Timilsina (2009) observe, availability of statistics in itself does not imply that all possible demand has been captured because there would be considerable unmet demand due to the supply shortages that those countries are experiencing. This, therefore, means that the estimated *energy intensity* (from such statistics) would have significant errors (parametric uncertainty). Despite these limitations and uncertainty, models (in developing or developed countries) are important tools for aiding decision making and they also help in assessing what would happen if no action is taken to change the way energy is used.

Two main methodologies are used to model demand: econometric and end-use approaches. As discussed in sub-section 3.2.5 of Chapter 3, end-use approach is used in this research because of its ability to adequately capture features that are important in developing countries' energy systems (Bhattacharyya and Timilsina, 2010) and also because energy services and their associated energy carriers can be explicitly represented (Craig et al., 2002). Further, as Bhattacharyya and Timilsina (2009) observes, the econometric

approach tends to ignore the non-priced transactions of traditional fuels; the most significant energy carrier in Zambia's energy sector. Moreover, for priced transactions but in regulated energy markets (like Zambia), the relationship between energy price and demand may not be meaningful. This challenge (energy price and demand relationship which is central to the econometric approach) would be worsened when one factors in the supply shortages that are experienced in many developing countries.

On the contrary, the end-use approach accounts for energy from end-use service level; end-use services such as cooking, heating, motive power, cooling, hauling, conveyance and lighting. The approach accounts for where energy is used and also which type of energy carriers are used. Further, depending on the sector or industry being modelled, energy demand could be modelled as driven by income, climate, population, floor space, physical output, value added or GDP; activities that lead to energy demand.

In this research, this approach was, however, only used to model energy demand in residential and mining sectors. For two reasons, these sectors (the largest end-use sectors) are the focus of the research and secondly because of availability of better statistics and data for these sectors. In addition, because of limited statistics and data, simple technique (discussed in sub-section 3.2.5) was used to model agricultural, services, transport and other industries sectors. The simplicity and usefulness of the simple technique notwithstanding, this method (technique) lacks theoretical foundation and hence relies heavily on the judgement of the modeller (Bhattacharyya and Timilsina, 2009).

Examples of end-use and simple technique models are given below in Equations 5.1 and 5.2 respectively.

$$E_a = A \times \frac{U}{\eta} \quad (5.1)$$

where,

$E_a$  is the total final energy demand of activity  $A$ ,

$A$  is the activity that demands energy, such as lighting or industrial output,

$U$  is the useful [energy intensity](#) of the activity, and  
 $\eta$  is a set containing technologies, their accompanying energy carriers (fuels) and efficiencies that could be used to satisfy energy demand.

$$E_a(t) = E_a(t_0) \times (1 + gr)^{dt} \quad (5.2)$$

where,

$E_a(t)$  is the total final energy demand of an activity or sector at time  $t$ ,

$E_a(t_0)$  is the actual energy demand at time  $t_0$ ,

$gr$  is the growth rate of the demand, and

$dt$  is the time interval for the projection.

[Bhattacharyya and Timilsina \(2009\)](#) summaries the general steps involved in the end-use approach:

- Disaggregation of total energy demand into relevant homogeneous end-use categories or modules
- A systematic analysis of social, economic and technological determinants
- Organisation of determinants into a hierarchical structure
- Formalisation of the structure in mathematical relationships
- Snap-shot view of Reference year
- Scenario design for the future
- Quantitative forecasting using mathematical relations and scenarios

### 5.1.1 Energy consumption in Zambia

Final energy demand in Zambia is dominated by the residential and mining sectors. Energy carriers currently used in Zambia's energy system are wood, charcoal, electricity, coal, diesel, motor gasoline, fuel oil and other petroleum products. Traditional fuels (wood and charcoal) are the most

consumed energy carriers, accounting for approximately 71% of the total final energy in 2010. The total final energy consumed in 2010 was 230 PJ, of which 76% and 12% was consumed by the residential and mining sectors respectively (IEA, 2012) as shown in Figure 5.1 below.

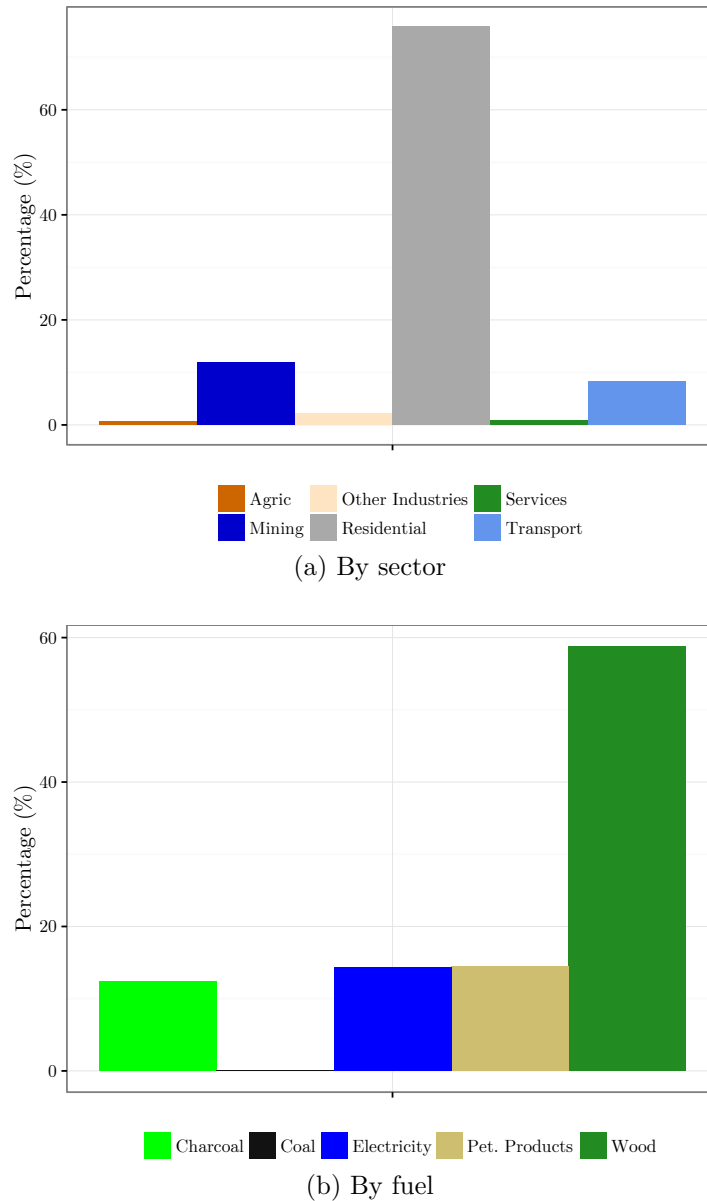


Figure 5.1: Zambia's total final energy consumption in 2010

Figure 5.2 below shows the consumption of electricity, which is dominated by the mining sector (more than 50% of total final electricity). This suggests that developments in the mining sector (such as increasing production capacity, reduction in [ore grade](#) or adoption of efficient technologies) would have significant impact on the outlook of the electricity supply sys-



tem. Further, it also means that as other sectors' demand increase without corresponding investments in the energy supply infrastructure, growth of the mining sector will be constrained.

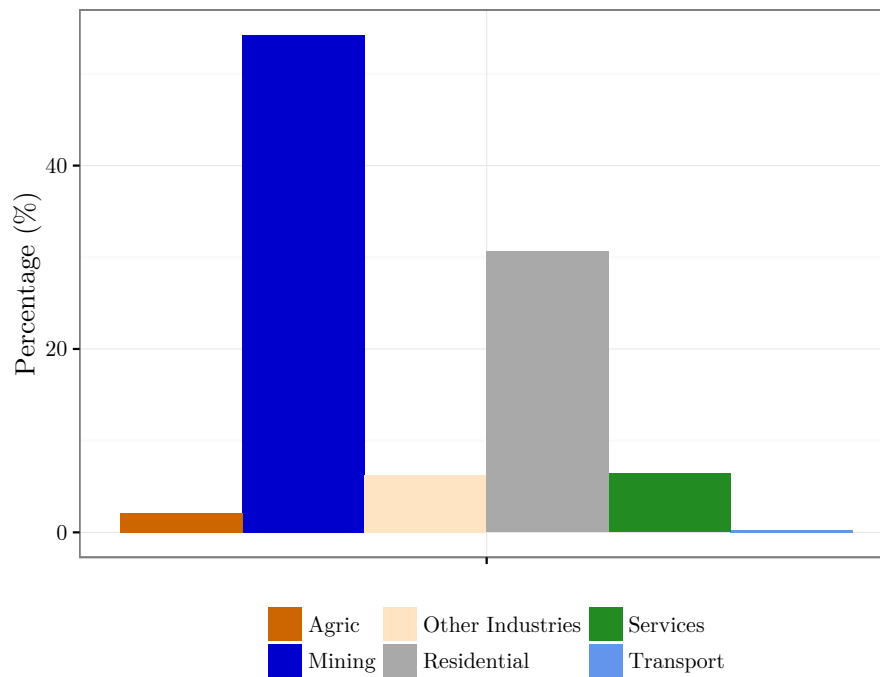


Figure 5.2: Zambia's total final electricity consumption in 2010

Description of the demand sectors (residential, other industries, agriculture, services and transport)<sup>1</sup> is given below.

### Residential sector

Energy consumption in the residential sector (like in all other sectors) comes at a cost: either private or social cost (Bhattacharyya, 2006). Private cost could be in form of money spent or the time it takes to collect the energy carrier (such as wood from the forests). Social costs arise from externalities, such as health problems, as result of using energy.

When studying energy use and transition, it is essential to understand why households use the fuels they use. This is important because, at household level, energy use choices are determined by complex decision making processes (Daioglou et al., 2012; Ruijven et al., 2008). For instance, for a household to switch from fuel A to fuel B, it has to take into account

<sup>1</sup>Description of the mining demand is given in Chapter 6.

the cost of using fuel B relative to A and also whether the technology is available.

Therefore, in order to capture the details of how energy consumption would change in Zambia's residential sector, three key aspects of energy use were captured: specific end-use functions and their drivers, ranking preference of energy fuels (using the energy ladder concept) and distinction of household energy use in urban and rural areas. See section 3.2.5 above for a discussion on energy modelling in developing countries.

Specific end-use services were grouped into three: cooking and heating, lighting and other uses. The main energy service is cooking and heating, which accounts for more than 80% of final energy. The share of cooking and heating service is large because of the consumption of inefficient traditional fuels (woods and charcoal). Electricity is another fuel that is used for cooking and heating service (with gas being a possible future alternative for cooking and heating service). Lighting is mainly serviced by electricity, kerosene and candles in Zambia (candles are not included in the model). For other uses, only electricity is used (these uses include refrigeration and space cooling). At national level, Figure 5.3 shows the shares of end-use services (these shares are calibrated average of statistics (15-year series) based on Central Statistics Office (CSO) reports<sup>2</sup>).

Energy use patterns and appliance ownership in Zambia has been documented by CSO in their reports (CSO, 1994; 1996; 2003; 2005; 2012). In 2010, it was estimated that 77% and 66% of all households with access to electricity in urban and rural areas respectively used electricity for cooking. Similar patterns for appliance ownership (like refrigerators and televisions) were also observed (CSO, 2012). Further, electricity access and usage patterns seem to be influenced by location, both at urban-rural split and province levels. Provinces along the line of rail have higher rates of access than those away from the rail (CSO, 2005), this is an enduring development trend in Zambia. For instance, in 2004 period, 46% and 13% of urban and rural households respectively were classified as non-poor<sup>3</sup>, yet

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<sup>2</sup>Reports references are CSO (1994; 1996; 2003; 2005; 2012).

<sup>3</sup>Non-poor households were those with a monthly income of K600, 000 or more.

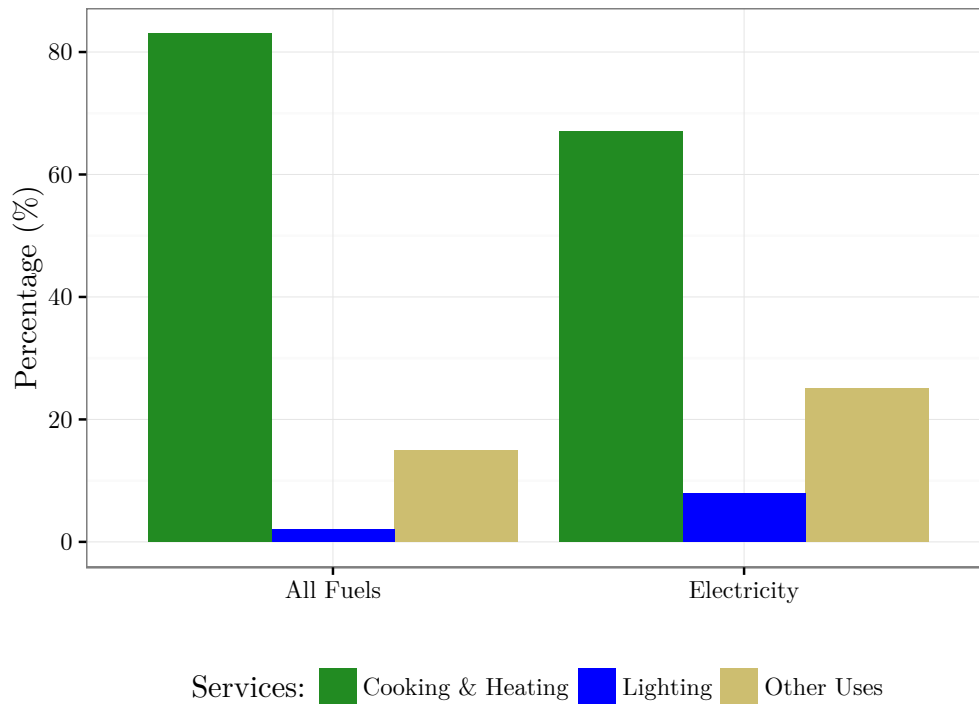


Figure 5.3: Residential sector's energy end-use services demand

47.6% of urban and only 3.1% of rural households had access to electricity for lighting<sup>4</sup>. This discrepancy between the level of household income and access to and usage of electricity among rural households was also observed in a CSO survey in 2015 (CSO, 2016). This confirms that income is not the sole and perhaps the most important determinant of access to electricity in Zambia. Figures 5.4 and 5.5 below show shares of fuel usage by end-use service for lighting and cooking respectively, in urban and rural areas in 2010.

<sup>4</sup>Tables C.1 and C.2 in Appendix C gives percentage classification by lighting and cooking fuels respectively (CSO, 2005).

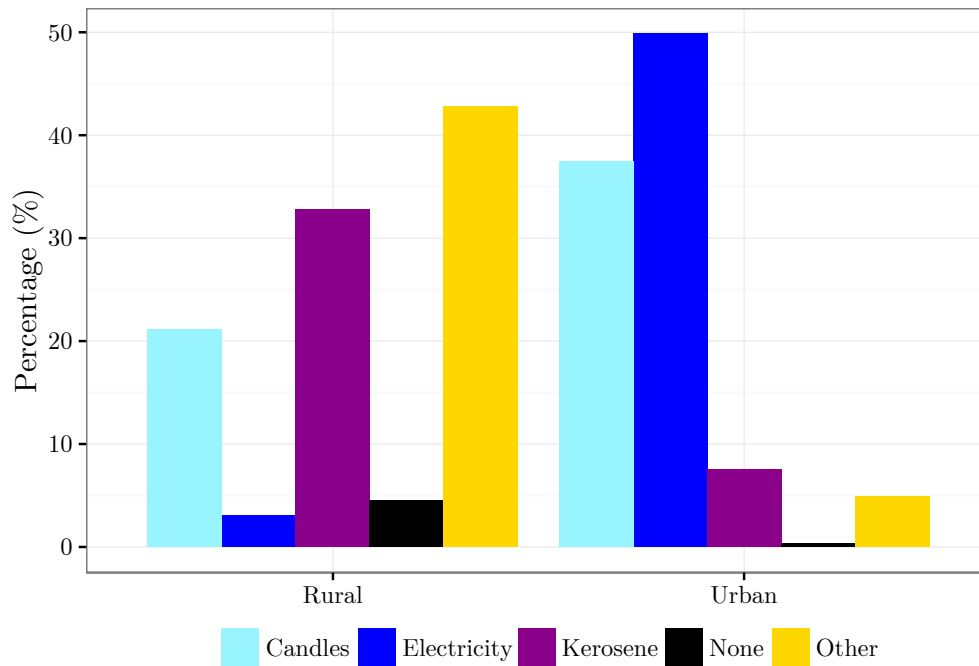


Figure 5.4: Lighting usage patterns

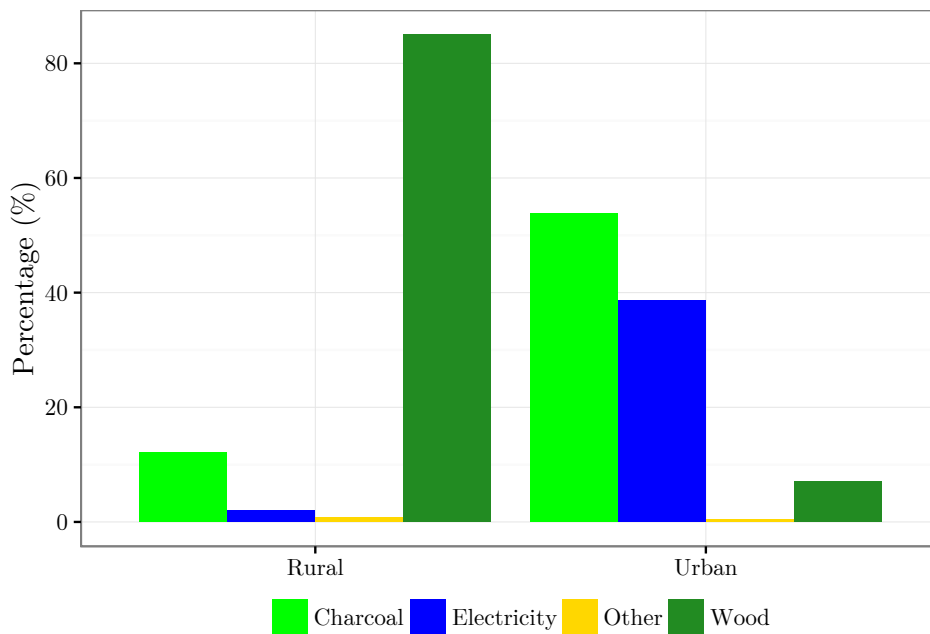


Figure 5.5: Cooking and heating usage patterns

Furthermore, it can be inferred from [CSO \(2005\)](#) that location is a stronger determinant than income of whether households in Zambia would have access to electricity or not. This is important because it implies that some households in Zambia do not use electricity because it is not available rather than that they cannot afford it. To put the argument of

affordability into context, in 2010, an average Zambian household consumed about 5, 000 kWh per year (415 kWh per month) of electricity, this would translate to approximately 7% of total household income of a rural non-poor household<sup>5</sup>, a share significantly lower than that of a poorer household in urban area which uses electricity for both lighting and cooking services. Therefore, if availability is the main challenge to access to clean energy for households in rural areas, it then implies that more investment in the [clean energy](#) supply infrastructure is required.

The other aspect which was considered in the demand model was the energy carrier preference ranking; it was assumed that after electricity, charcoal (which is almost always purchased ([CSO, 2005](#))) is thought to be a better and cleaner fuel than wood. However, energy use in rural areas is dominated by wood, partly because wood can be collected from the forests for free and also because there are more poor households in rural areas (who cannot afford to purchase charcoal).

Apart from availability (access to a particular fuel) and affordability (household income); household size, floor-space, climate and population growth are some of the key energy drivers in the residential sector ([Daiglou et al., 2012](#)). However, because of limitations of available data, the model developed for Zambia's residential sector only considered access to [clean energy](#) (electrification), household income, household size and population growth as key energy drivers. A schematic representation of the relationship between energy drivers (considered in the model) and energy end-use services is given in [Figure 5.6](#) below.

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<sup>5</sup>In 2004, electricity price was K90 per kWh with a fixed monthly charge of K5, 266 for residential customers ([ERB, 2013](#)).

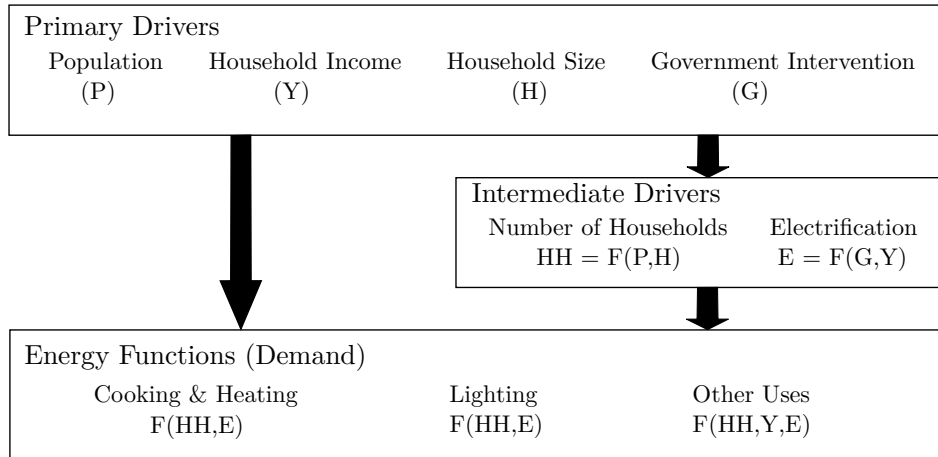


Figure 5.6: Relationship between energy drivers and end-use services

The demand model<sup>6</sup> was developed in a way that facilitates exploration, the generic model<sup>7</sup> is described below

$$E_a = F(A, U, \eta) \quad (5.3)$$

where,

$E_a$  is the total final energy demand,

$A$  is the activity (key energy drivers) that demands energy,

$U$  is the useful [energy intensity](#) of the activity, and

$\eta$  is a set containing technologies, their accompanying energy fuels and efficiency that is used to meet the energy demand.

In addition, it is assumed that a household uses only one energy carrier to satisfy an energy service (no use of multiple fuels to meet a single service demand within a household).<sup>8</sup> Total energy demand (at sector level) is broken down as shown below

<sup>6</sup>See section [C.4](#) for projections of energy demand drivers.

<sup>7</sup>All data estimates, assumptions and sources are given in Appendix [C](#) sections [C.2](#) and [C.3](#).

<sup>8</sup>This assumption was made for simplicity reasons. [Masera et al. \(2000\)](#) found that households in Mexico use multiple fuels to satisfy the same energy service need. This finding is also true from the author's lived experience in Zambia.

$$E_a = E_{ch} + E_{lig} + E_{oth} \quad (5.4)$$

where,

$E_a$  is the total final energy demand,

$E_{ch}$  is the total final demand for cooking and heating,

$E_{lig}$  is the total final demand for lighting, and

$E_{oth}$  is the total final demand for other uses.

Cooking and heating service demand is a primary demand (all households have cooking and heating activity (CSO, 2012)). This service is assumed to be driven by household size (and total households at sector level). The fuels used to meet this demand are electricity, charcoal, wood and gas (future fuel option). It is also assumed that identical households (same household size) in urban or rural area, use the same quantity of useful energy ( $U$ ) for their cooking and heating service. The final energy, however, could be different depending on the type of fuel and the efficiency of the technology that is used.

Further, it is assumed that increase in electrification ( $\varphi_{elec}$ ) leads to increase in the share of households using electricity for cooking and heating ( $\phi_{elec}$ ), all things held constant. The share of these fuels (electricity, charcoal, wood and gas) are modelled as exogenous factors, as described in the scenarios section (section 5.3) below. This is important because it enables flexibility to explore what would happen if certain set targets are achieved (such as increasing electrification). Total demand for cooking and heating service ( $E_{ch}$ ) is defined below

$$E_{ch} = HH \times U_{ch} \times \sum_{i=0}^t \sum_{j=1}^{j=4} \frac{[\phi_{ij}]}{[\eta_j]} \quad (5.5)$$

where,

$E_{ch}$  is the total final demand for cooking and heating,

$HH$  is the total number of households,

$U_{ch}$  is the useful energy for cooking and heating per household,

$[\phi_{ij}]$  is the share of an energy carrier (electricity, charcoal, wood and

gas) in a particular time period (where  $\sum \phi_i = 1$ ), and

$[\eta_j]$  is the efficiency of the technology that consumes an energy carrier used to satisfy the demand (where  $\eta_j \leq 1$ ). The efficiencies for electrical, charcoal and wood technologies as modelled are 65%, 24% and 14% respectively. These efficiencies are calculated based on the calibration of energy use from 1993 to 2010 as recorded by [CSO](#) and [IEA](#) statistics.

Lighting service is considered as secondary energy service (the level of lighting service penetration is currently less than 100%). It can be seen in [Figure 5.4](#) that some households go without lighting service. The total lighting demand ( $E_{lig}$ ) is defined below

$$E_{lig} = HH \times (F_{elec} \times \varphi_{elec} + F_{kero} \times \varphi_{elec}) \quad (5.6)$$

$$\varphi_{elec} \geq \phi_{elec} \quad (5.7)$$

where,

$E_{lig}$  is the total final demand for lighting,

$HH$  is the total number of households,

$F_{elec}$  and  $F_{kero}$  are the final energy intensities for electricity and kerosene respectively,

$\varphi_{elec}$  and  $\varphi_{kero}$  are the shares of households that use electricity and kerosene for their lighting service respectively (where  $\varphi_{elec} + \varphi_{kero} \leq 1$ ),

$\phi_{elec}$  is the share of households using electricity for cooking and heating, and

Equation [5.7](#) implies that the number of households using electricity for lighting will always be greater than or equal to those using electricity for cooking and heating.

Other uses service demands (such as air-conditioning, dish washing and refrigeration) are satisfied only by electricity. These uses are driven by assets ownership and income of a household. Not only does increasing income enable households to acquire assets (technologies) that they use for



these uses, it also enables households to use more of those technologies. For instance, if two households own an air-conditioner, it is assumed that the richer household will use the air-conditioner more than the poorer household. Further, it is assumed that the richer household will have more of electrical appliances than the poorer household. This, therefore, increases the richer household's average [energy intensity](#) for other uses. Similar to cooking, the share of households with other uses demand ( $\psi$ ) is always less than or equal to those with access to electricity ( $\varphi_{elec}$ ). Total other uses demand ( $E_{oth}$ ) is defined below

$$E_{oth} = HH \times \psi \times X \quad (5.8)$$

$$X = \ln(I) \times 6.504 - 45.045 \quad (5.9)$$

where,

$E_{oth}$  is the total final demand for other uses,

$HH$  is the total number of households,

$\psi$  is the share of households with other uses demand (currently,  $\psi < 1$  for both urban (73%) and rural (70%) areas),

$I$  is the income (in US\$ per household in real terms), and

$X$  is a regression function used for estimating the [energy intensity](#) of Other Uses (GJ per HH) in the residential sector. This function was estimated using statistics from [CSO](#)<sup>9</sup>.

## Economic sectors

In economic sectors (services, agriculture, transport, other industries and mining), energy is used as an input to their production processes. Below is a brief description of what constituents each of these sectors and their key energy drivers (for mining sector see Chapter 6).

The services sector includes trade, hotel and restaurant, real estate and business services, financial institutions and insurance, community and

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<sup>9</sup>See Appendix C section C.3 for the regression details.

personal services, education and health, and public administration sub-sectors. Energy services required in this sector are heating, lighting, HVAC and other utilities (Haw, 2007). Demand is mainly influenced by floor space and occupancy of the building.

Agriculture sector comprises of agriculture and hunting, forestry, livestock and fishing sub-sectors. This sector is the largest employer in Zambia, employing about 63% of the total workforce in 2010 (CSO, 2012). Most of the economic activities are done at subsistence level, the largest economic activity in rural areas (by size of workforce population). Agriculture sector requires energy for irrigation, harvesting and packing, transportation, processing, thermal purposes, lighting and other energy uses. However, as noted above, much of the output in the sector is at subsistence level (which uses more animal-driven equipment than energy). Thus, energy services described here are mainly for commercial farmers.

Transport and communication sub-sectors make up the transport sector. Energy demand in the sector is driven by private, public and freight transportation. Income and location determine if a person will use private, public or non-energy based transportation. For instance, the transport system in rural and some urban areas is largely non-motorised based. Further, private car ownership at national level in 2010 stood at 4.9% (24% in urban and 1.25% in rural areas).

On the other hand, freight transportation is driven by goods produced by the agriculture, mining and other industries sectors. Thus, an increase in any one of the sectors leads to an increase in energy demand for freight transportation, all things held constant. The sector is dominated by road-based transportation; local aviation and railway modes are not well developed while the communication sub-sector is not energy intensive. Thus, petroleum products dominate the transport sector as energy carriers.

Food, beverage and cigarettes; textiles and leather; petroleum; chemicals; other manufacturing; electricity, water and gas; construction and civil work; and any other sub-sector not covered in sectors above are under other industries sector. This sector (other industries sector) offers, as noted in

GRZ (2006), the most industrialisation opportunities for Zambia. It is also identified as a sector with the largest economic growth potential in Vision 2030 (GRZ, 2006). The sector's energy demand services are for lighting, HVAC, process heating, conveyance and transportation. Energy demand is driven by physical production output, value addition and energy efficiency practices.

Nevertheless, because of the lack of data, these sectors' energy projections were modelled as driven by GDP growth of each sector.<sup>10</sup> GDP growth rates were exogenous factors described in the scenarios section (section 5.3 below). These projections used a simple technique model<sup>11,12</sup> defined below

$$E_a(t) = [F_i] \times [GDP_j(t)] \quad (5.10)$$

where,

$E_a(t)$  is the total final energy demand of a sector at time  $t$ ,

$[F_i]$  is a set containing final energy intensity (GJ per US\$ GDP) for a sector,

$i$  is the type of fuel (i.e. electricity, diesel, petrol etc), and

$[GDP_j(t)]$  is the GDP of a sector at time  $t$ .

## 5.2 Supply model

An energy supply model<sup>13</sup> was developed using OSeMOSYS (Howells, 2009; Howells et al., 2011; Osemosys, 2013; Welsch et al., 2012). OSeMOSYS (an open source platform) is a full-fledged systems optimisation model for long-term energy planning. This platform uses an optimisation framework, which is often used for energy system analysis (other similar tools to OSeMOSYS are MARKAL, TIMES, MESSAGE and TEMOA)<sup>14</sup>.

<sup>10</sup>This is a similar approach that was taken in Fais et al. (2016).

<sup>11</sup>All data estimates, assumptions and sources are given in Appendix C sections C.2 and C.3.

<sup>12</sup>Section C.4 gives the projections of GDP.

<sup>13</sup>The Reference Energy System (RES) diagram is given in Figure 3.3 above.

<sup>14</sup>Models built using this framework are also referred to as Energy System Optimisation Models (see Daly et al., 2015; DeCarolis et al., 2017; Strachan et al., 2016)

This model captured, in detail, the available energy resources and supply technologies but has stylised demand and transmission technologies. Exogenous variable costs were included in the model to represent the cost of operating the transmission network (for grid technologies only) while no operation or investment costs were considered for demand technologies. This is because energy demand was exogenously determined using a [LEAP](#) model described in section 5.1 above and the mining model described in Chapter 6 below.

The supply model was solved by minimising the discounted total energy system costs. The objective function (an expanded version of Equation 4.1) is defined below

$$\min \sum_{t=0}^T \left( I_{t,g} + OM_{t,g}^{fix} + OM_{t,g}^{var} + C_{t,g}^{fuel} + C_{t,g}^{carbon} \right) \quad (5.11)$$

where,

$t$  is a one-year time step from 2010 to 2050,

$g$  is a set of energy technologies,

$I_{t,g}$  is the capital inv. costs at time  $t$  for a particular technology in  $g$ ,

$OM_{t,g}^{fix}$  is the fixed ops and maintenance costs for a technology in  $g$ ,

$OM_{t,g}^{var}$  is the variable ops and maintenance costs for a technology in  $g$ ,

$C_{t,g}^{fuel}$  is the fuel cost for a technology in  $g$ , and

$C_{t,g}^{carbon}$  is the carbon tax for a technology in  $g$ .

Most of the techno-economic data for energy technologies used in the model are based on the [Southern Africa Power Pool \(SAPP\)](#) study ([Nexant, 2007](#))<sup>15</sup> while technology learning (for renewable technologies) assumptions are based on [RMI \(2015\)](#). The [SAPP](#) study was a regional study of Southern Africa power utilities, thus, the main source of the information was from the utilities themselves and Zambia's power utility ([ZESCO Limited \(ZESCO\)](#)) being one of them. However, in instances where the [SAPP](#) study information is dated, it was replaced by latest available information such as [ERB \(2008\)](#), [ZESCO \(2008; 2009\)](#), [JICA/MEWD \(2009\)](#) and [DHEC](#)

<sup>15</sup>Note that all costs were adjusted to 2010 US\$ price.

(2011). Information for other energy supply technologies<sup>16</sup> was based on published sources such as IPA (2007), CSO (2007) and ERC (2013)<sup>17</sup>.

It should be noted though that because costs of using traditional fuels and benefits of avoided health complications as a result of increased access to clean energy are difficult to quantify, they were not included in the model. However, a trade-off analysis that focused on increasing access to clean energy in order to avoid deforestation was done (using OSeMOSYS output but away from OSeMOSYS). The energy resources of the model were grouped into three sectors: forestry, electricity, and fossil fuels sectors.

The forestry sector is the main source of energy in Zambia, it is the source of traditional fuels (charcoal and wood). Traditional fuels are particularly important in rural areas and other urban areas with limited access to the national grid<sup>18</sup> since cooking and heating service (the largest end-use service in residential sector) is currently satisfied only by electricity and traditional fuels. Apart from it being a major energy supplier, the forestry sector is a critical link between the energy sector in general and bio-diversity and it is also a carbon sink. Therefore, increased consumption of traditional fuels in Zambia could lead to deforestation. This, in turn, would lead to extinction of certain plant and animal species and also reduce the ability of the forests to absorb  $CO_2$  emissions.

Thus, explicitly modelling this interaction between energy demand and available forestry energy resources is important in three main ways. Firstly, it enables analysis of the impacts that energy use would have on deforestation or how increasing access to clean energy would help reduce deforestation. As van Ruijven et al. (2012) observed there is little evidence in literature that show that increasing access to clean energy helps in reducing deforestation.

Secondly, a cost-benefit trade-off analysis between increasing access to clean energy and deforestation could be done. In this research, an analysis that compared the total system costs required to increase access to clean

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<sup>16</sup>See Appendix C for the list of other supply technologies.

<sup>17</sup>See Appendix C section C.5 for all the model assumptions.

<sup>18</sup>See sub-section 5.1.1.

energy and the funds that countries like Zambia receive through the [Reducing emissions from deforestation and degradation and enhancement of carbon stocks \(REDD+\)](#) initiative<sup>19</sup> to enhance forest management (for reducing deforestation) was done. From a cost perspective (externalities not included), I argue (see Chapter 7) that it is cheaper for countries reliant on traditional fuels to continue deforesting then afforesting than to avoid deforestation by increasing access clean energy (i.e. if the only purpose of increasing access is to reduce the rate of deforestation).

Finally, the available forestry resources could be included as one of the key constraints in the model. For instance, about 70, 000 hectares of forests<sup>20</sup> are cleared every year in order to provide an equivalent of 120 PJ (CSO, 2007). Energy demand currently accounts for 10% of forest cover losses with the remainder coming from the agriculture sector (through land use changes). However, as more households shift from wood (currently at 59%) to charcoal (currently at 12%) a better fuel<sup>21</sup>, the rate of deforestation would increase; due to the conversion efficiency of the charcoal making process.

The electricity sector is dominated by hydro technologies.<sup>22</sup> For instance, in 2010, the installed capacity of electricity was 1, 900 MW, of which hydro technologies accounted for 97% and 99% of total capacity and electricity generation respectively. Further, hydro and coal technologies dominate the planned (ZESCO plans that is) capacity expansion portfolio. However, Zambia has a range of other supply technologies such as solar and geothermal technologies, though no major comprehensive expansion plan has been developed for these technologies.<sup>23</sup>

The model assumes that all fossil fuels are imported. This is because Zambia does not have crude oil resources and also because the coal mining

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<sup>19</sup>Details for [REDD+](#) mechanism can be found in [Jindal et al. \(2008\)](#), [Parker et al. \(2009\)](#) and [Cacho et al. \(2014\)](#).

<sup>20</sup>Total forest cover in 2004 was about 440,000 sq. km (CSO, 2007).

<sup>21</sup>See [Hibajene and Kalumiana \(2003\)](#) for a discussion of why charcoal is a better fuel than wood.

<sup>22</sup>See section [A.1.2](#) of Appendix [A](#) for the list of electricity generation stock.

<sup>23</sup>See section [C.5](#) of Appendix [C](#) for the energy supply technologies information in Zambia.

activities are erratic. All crude oil is imported through [Tanzania Zambia Mafuta Pipeline Limited \(TAZAMA\)](#) pipeline to the refinery in Ndola. The refinery products are diesel, motor gasoline, fuel oil, [LPG](#), domestic kerosene, aviation kerosene, refinery gas and other products in minor quantities. Apart from petroleum products, Zambia also consumes coal. The country has considerable coal resources, however, the output of coal from the mines (under Maamba collieries) is erratic. Thus, it is assumed, in this model, that all the coal requirements are imported from Zimbabwe.

### 5.2.1 Average generation cost of electricity

In order to estimate the average electricity generation cost of the energy model<sup>24</sup> (electricity was the main fuel that was analysed as an option of increasing access to [clean energy](#)), the levelised cost approach was used ([IEA/NEA, 2010](#); [Ouedraogo et al., 2015](#); [Ramana and Kumar, 2009](#)). This approach assumes a constant discount rate ( $r$ )<sup>25</sup> and energy price throughout the economic life,  $n$  years, of a technology. Further, because Zambia's energy markets are largely monopolised and regulated, and market and technology risks exist, this method (LCoE) is appropriate for estimating the real cost of electricity generation investments ([IEA/NEA, 2010](#); [Tembo, 2012](#)).

The levelised cost of electricity (LCoE) for a generating technology during its operating life is defined below,

$$LCoE = \frac{\text{Operational life cycle cost}}{\text{Total electricity generation}} \quad (5.12)$$

$$\text{Operational life cycle cost} = \sum_{n=0}^n \frac{Costs_n}{(1+r)^n} \quad (5.13)$$

$$\text{Total electricity generation} = \sum_{n=0}^n \frac{Elec_n}{(1+r)^n} \quad (5.14)$$

<sup>24</sup>The estimation of costs is based on the least cost system that is developed above.

<sup>25</sup>“ . . . the discount rate used in LCOE calculations reflects the return on capital for an investor in the absence of specific market or technology risks.” ([IEA/NEA, 2010](#); pg. 33).

where,

$Costs_n$  is the total sum of investment capital, fixed, variable, fuel and carbon costs in a particular year,

$n$  is the operational life of a technology,

$r$  is the discount rate ( $r > 0$ ), and

$Elec_n$  is the annual generated electricity.

The average LCoE of the electricity generation system is defined as follows

$$LCoE_{system} = \sum(\xi_k \times LCoE_k) \quad (5.15)$$

$$\sum \xi = 1 \quad (5.16)$$

where,

$\xi_k$  is the share of a particular technology ( $k$ ) in the system, and

$LCoE_k$  is the generation cost of technology  $k$ .

### 5.3 Scenarios

Five scenarios<sup>26</sup> were developed to explore plausible energy demand futures for Zambia from 2010 (base year) to 2050 (end year), with a strong emphasis on the residential sector as it is the main consumer of final energy (see Figure 1.1 above). These scenarios are important because they contain exogenous factors that influence both the demand and supply sides. As Rosnes and Vennemo (2012) observed demand projections and supply side investment costs estimations are influenced by the approach and framework (bottom-up or top-down and optimisation or simulation), the data and exogenous variables such as technology capital cost, economic growth and rates of access to clean energy. The scenarios, therefore, focused on describing the exogenous variables used in this study. Apart from that,

<sup>26</sup>Put correctly, many scenarios were developed and explored but only five scenarios were reported.



these scenarios form a neat framework from which the impact of access to [clean energy](#) on mining production output is analysed.<sup>27</sup>

It is worth mentioning that carbon tax was not modelled in any of the scenarios because [Tembo \(2012\)](#) found that the tax did not change the capacity mix in Zambia's electricity system but just increased the cost of generating electricity. However, the impact of restricting (reducing) electricity generation from carbon emitting technologies on total system capital investment cost, deployment of renewable technologies and energy price was analysed. Further, [OAT](#)<sup>28</sup> sensitivity analyses<sup>29</sup> were done on the model by varying key inputs<sup>30</sup>. Key drivers of these scenarios were energy use in the residential sector and economic growth.<sup>31</sup> Two economic growth assumptions (base path at 4.5% and high path at 6% annual growth rates) considered are based on Zambia's Vision 2030 ([GRZ, 2006](#)).

Table 5.1 below gives the components of these economic assumptions. The two key assumptions of energy use in the residential sector are that access to [clean energy](#) is driven exogenously (that is through government policy) and that energy fuels preference ranking order is electricity, gas (when available), charcoal and wood. The first assumption (of energy use) enables analysis of what (in terms of capacity stock and investment costs) would be required of government in order to meet its development aspirations of access to [clean energy](#). The second assumption focuses on how households transition from one fuel to the next. For instance, even if wood could be freely collected from the forest (by the energy user), a user would rather use charcoal when it is available at their income level. Hence, as cleaner energy carriers become available (and/or with increasing income), residential users abandon traditional fuel (first wood then charcoal) for gas or electricity.

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<sup>27</sup>See sections 7.1.1 (on page 188) and 7.2.1 (on page 219) for how the energy and mining models were linked and synchronised.

<sup>28</sup>[OAT](#) is an acronym of one-at-a-time.

<sup>29</sup>See section 3.1.4 of Chapter 3 for a discussion on sensitivity analysis.

<sup>30</sup>See Appendix C section C.6 for the full list of variables on which [OAT](#) sensitivity analysis was applied.

<sup>31</sup>See section C.4 for projections of energy demand drivers such as number of households and GDP.

Table 5.1: Economic assumptions

	Base path	High path
Economic growth	4.5%	6%
Income (by 2030)	US\$950/capita	US\$1,600/capita
Income (by 2050)	US\$1,500/capita	US\$2,850/capita
Gas availability	No	Yes

Apart from the energy and economic assumptions, these five scenarios also contain assumptions for the mining model. Two mining assumptions are considered: the copper price and the maximum copper production growth rate. Being a critical driver of decision making<sup>32</sup>, the copper price was assumed to remain constant at US\$ 7, 000 per tonne in all the five scenarios. This assumption made it easier to compare production outputs across energy demand scenarios (as all of them were exposed to the same price). See section E.5 for the impact that copper price has on production at industry level.

The second assumption, production capacity growth rate, captures the general picture of what the maximum production output could be achieved if the investment environment enhances increased capacity investments, and also controls for unusual sudden increase in production output (if not controlled for) from one time step to another. Furthermore, the production capacity growth rate could be thought of as an exogenous factor that captures the human resource, policy, infrastructure and other economic limitations of industry growth. Considering this exogenous factor (besides the energy price) is important because much of the discourse in Zambia around the bottlenecks of copper industry's growth has focused on energy price, put more precisely, high energy price is presented as limiting factor to the growth of the industry by Zambia's mining firms (in their strategic engagements with government). Two production capacity growth rates are considered: 0.25% per month and 0.55% per month. The 0.25% per

<sup>32</sup>See sections 3.3 and 7.2.2 for key uncertainty and drivers in decision making process of the mining industry.

month rate captures a situation where the industry targets to maintain its production output at the current level while the 0.55% per month captures a situation where industry targets to double its production output by or before 2050. The 0.55% per month situation could be thought of as having fewer growth bottlenecks in the industry than the 0.25% per month (the 0.55% per month rate also captures the government's optimistic view of the industry).

Thus, by considering these assumptions together (the energy demand, economic and mining model assumptions) analyses of the impact of access to [clean energy](#) on mining production output could then be carried out. This was done and presented in section [7.2.3](#) below. Further, while production capacity growth rates for scenarios 2 to 5 (see the paragraph below) were the same, the energy prices were different. This is because of different energy demand and economic assumptions and final copper production output of each scenario. The five scenarios are described below:

**Scenario 1:** considers a slow economic and electrification growth, with a maximum copper production capacity growth rate of 0.25% per month (i.e. at best, maintaining production at 900 kton per year). The national average share of households (of those connected to electricity) using electricity for cooking and heating is 75%.

**Scenario 2:** considers slow economic and electrification growth, with a maximum copper production capacity growth rate of 0.55% per month (i.e. at best, increasing production to a maximum of 1, 900 kton per year). The national average share of households (of those connected to electricity) using electricity for cooking and heating is 75%.

**Scenario 3:** considers slow economic growth but with fast electrification growth and a maximum copper production capacity growth rate of 0.55% per month (i.e. at best, increasing production to a maximum of 1, 900 kton per year). The national average share of households (of those connected to electricity) using electricity for cooking and heating is 100%.

**Scenario 4:** considers fast economic and electrification growth and a maximum copper production capacity growth rate of 0.55% per month (i.e. at best, increasing production to a maximum of 1, 900 kton per year). The national average share of households (of those connected to electricity) using electricity for cooking and heating is 50% because of the introduction of gas as a cooking fuel. Gas displaced both electricity and traditional fuels.

**Scenario 5:** considers fast economic and electrification growth and a maximum copper production capacity growth rate of 0.55% per month (i.e. at best, increasing production to a maximum of 1, 900 kton per year). The national average share of households (of those connected to electricity) using electricity for cooking and heating is 100%.

The scenarios are summarised in Table 5.2 below<sup>33</sup>.

Table 5.2: Scenario description summary

	Economic path	Elec. access (in 2050)	Elec. Cooking (in 2050)	Cap. growth rate range (per month)
Scenario 1	Base	Urban - 86%	75%	0–0.25%
		Rural - 50%		
Scenario 2	Base	Urban - 86%	75%	0–0.55%
		Rural - 50%		
Scenario 3	Base	Urban - 86%	100%	0–0.55%
		Rural - 50%		
Scenario 4	High	Urban - 100%	50% (Gas)	0–0.55%
		Rural - 70%		
Scenario 5	High	Urban - 100%	100%	0–0.55%
		Rural - 70%		

<sup>33</sup>See Appendix C section C.4 for a detailed breakdown of residential energy use assumptions

## 5.4 Chapter summary

This chapter discussed the methods used and challenges of estimating future energy demand. It then described the steps that were taken to model Zambia's energy demand. The demand model (LEAP model) focused on the residential sector because the Zambian government has ambitious plans of increasing access to clean energy and also because energy consumption in this sector (use of traditional fuels) is directly linked to deforestation. Demand in the residential sector was captured at end-use service level, this enabled capture of different government policy targets (such as electrification). Other sectors (transport, services etc) were modelled in a stylised way because of limited data and statistics. The chapter also highlighted the role that availability of fuel plays in energy transition, as CSO reports showed that fuel transition was not only driven by affordability but also by location (availability). A description of how investment decisions of electricity generation technologies are made in the supply model was given. The supply model focused on the resources and technologies that were available to satisfy the demand and also on the costs that come with satisfying this demand. Finally, the main scenarios used in this research were described.



# Chapter 6

## Modelling of strategic investment decisions

### 6.1 Introduction

This chapter addresses the second theme of the research, which focused on understanding decision making in mining firms and also on the development of a mining model. The purpose of this model was to simulate different energy demand and copper production scenarios and analyse how the copper industry would evolve over time. The model captures decision rules and processes as described by the mining firms (see section 6.2) and supplemented by literature (see Chapter 4).

The chapter has three aims: Firstly, to describe and present the steps that were taken to identify the key decision variables and the decision processes that mining firms in Zambia take when making strategic investment decisions (section 6.2). Secondly, to define and describe the key interactions within the mining model and also identify exogenous interactions that influence decision making (section 6.3). Thirdly, to describe the method that is used to analyse the mining model, a system dynamics model (section 6.4). The chapter then concludes with a chapter summary (section 6.5).

These three aims helped to answer the sub-research questions<sup>1</sup> below:

- How do mining firms in Zambia make strategic investment decisions?
- What are the key decision variables in the mining sector in Zambia?
- What techniques are used by mining firms when evaluating strategic investment options?
- What is the outlook for Zambia's mining sector?

## 6.2 Identification of decision processes

This section describes the research design that was used to study decision making in Zambia's copper industry. As mentioned earlier (in Chapter 1), the research is divided into two themes: development of the energy system and decision making in the mining sector. The research design used to study the energy system is described in Chapter 5. The second theme, which is the focus of this Chapter, focuses on understanding how mining firms make decisions and simulate how these decisions would impact the firm's copper production. In order to capture the different aspects of this complex process (i.e. the decision making process), a mixed method approach was used.

This approach combines both qualitative and quantitative methods. The qualitative method (in form of semi-structured interviews) was used to capture the description of the decision processes in a mining firm, the techniques used to evaluate their investment options and what the decision makers thought the key variables were in their organisation's decision making process. This was necessary because what literature says and what happens on the ground could be variant. Secondly, it was important because decision making is context dependent and thus key decision variables vary from one context to another. The information collected using the semi-structured interviews<sup>2</sup> and industry's statistics<sup>3</sup> formed part of the

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<sup>1</sup>Chapter 4 gives a description of how organisations make strategic decisions.

<sup>2</sup>See section D.1 for the interview questions that were used.

<sup>3</sup>See section 6.3.1 for the statistics that were collected.



basis of relationship definitions in the mining model; are given in subsection 6.2.1. Interviews were conducted in September to October of 2013 and again in August to October of 2014. In-country mining firms' representatives<sup>4</sup>, aligned government departments and agencies, and Zambia's mining industry experts were interviewed.

Apart from getting the description of the decision processes, the interviews with mining firms focused on understanding how they perceive their energy use and production costs, the decision rules they use when evaluating investment options, what they thought were key threats and drivers to their operations, what they thought about government policies and regulations, how they thought their future costs structures would change and finally how they would respond to presented scenarios (three scenarios were presented to them)<sup>5</sup>. Interviews with representatives of government departments and agencies focused on understanding what the government thinks are key factors in mine operation's profitability and how government policies would help enable long-term planning and investment in the local industry<sup>6</sup>. Finally, local industry experts interviews covered the issues discussed with representatives of the mining firms and government. Knowing what the local experts think about the industry is important because they are critical players in policy development in the country.

A summary of key findings of these interviews is given below in subsection 6.2.1. These interviews helped to parameterise decision rules and also to capture key relationships and behaviours in the mining industry. These findings together with the statistics (see the immediate paragraph below) were then integrated into a system dynamics<sup>7</sup> model (i.e. the mining model)<sup>8</sup>. This model was used to analyse how decision rules could affect the industry's copper production and the profitability of the industry over

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<sup>4</sup>See section B.2 for the list of mining companies operating in Zambia.

<sup>5</sup>See Appendix D in section D.1.3 part 4 for the questions that were asked and section D.4.5 for the summarised responses to the questions.

<sup>6</sup>The government's view on energy use and efficiency in the mining sector was also discussed during the interviews.

<sup>7</sup>The system dynamics model was built using Vensim (Ventana, 2015).

<sup>8</sup>See section 4.3 of Chapter 4 for why an SD approach was used to study decision making.

time. Description of the SD model is given in section 6.3 below.

Further, during the course of the study, industry statistics (both local and international) had been collected from various sources: the mining companies, government departments and agencies, energy suppliers and different international organisations. A description of key statistics is presented in section 6.3.1 below. Details of all statistics used in this chapter are presented in Appendices B and D.

### 6.2.1 Key interview findings

This sub-section presents key findings of the interviews.<sup>9</sup> The interviews helped to frame how strategic investment decisions are made in the mining model. The key aspects were: decision making process, project evaluation, project financing and operational behaviour.

The decision making process informed the study on the motivation and procedures used when making strategic decisions. This aspect highlighted that while decision making process can be modelled in various ways (such as rational, bounded rational, politics and power, and garbage can choice paradigms), in the mining industry this process is a deliberate and directed process. Mining firms have concrete procedures and guidelines of how investment options should be evaluated and steps that should be followed when making strategic investments. Overall, *ore grade*, recoverable copper from the ore, copper price and local policy environment (such as stability of the policies and level of taxation) were identified as key factors (by the firms) that determine whether an investment would be made or not.

It was found that main method of evaluating strategic investment decisions was the Discounted Cash Flow (DCF) technique; while IRR and pay-back analysis are optional. The importance of the DCF technique is also confirmed in literature as an acceptable method of evaluating projects in the industry. It was also found that all projects that mining firms in Zambia invest in, have a return on investment (RoI) of at least 15%. However, not all investment options that meet this criterion are implemented

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<sup>9</sup>Summary findings of the interviews are given in section D.4 of Appendix D.

because the firm has to consider the country risks; such as political risks and consistency in fiscal policies. Furthermore, apart from the analytic techniques used to evaluate investment options, it was found that experience (judgement) of key decision makers play a critical role in the investment decision process. This, therefore, implies that final investment decisions in mining firms are not optimal.

While local policy environment could greatly impact the profitability of a project, it was found (from a financier's perspective) funding of projects is largely determined by the long term outlook of the industry, not short-term policy inconsistencies. Financiers also consider three other additional factors when approving funding and analysing risk of an investment opportunity in Zambia namely: 1. who their off-taker [the buyer of their produce] is; 2. the role that the Zambian asset plays in the group (in terms of value); and 3. the parent organisation of the firm. Thus, accessing finance for projects in Zambia's industry is more determined by global factors (basically the outlook of the copper price) and the organisation's structure than local policies because firm's market is outside the country.

The other key finding was on the operational behavioural of the mining firms. It was found that while the price of copper plays a key role in their production and decision making, change in copper price does not always lead to change in their production patterns. This is so because production level of a firm is determined using thresholds set by the firm itself and not relative to change in profitability. That is to say, even though profitability of an operation could reduce because of the reduction in copper price, this could not lead to change in production patterns because the price change would be with the firm's acceptable range. It was also found that firms have options of suspending their operations in order to reduce the losses as a result of lower copper price (relative to their unit cost of production). The rules that govern the decision to suspend or re-start their operations are determined by the firms themselves. For instance, firms do not suspend the operations at first sight of losses and similarly, they do not re-start their operations at first sight of high copper price (after suspending the

operations). These behaviours were captured in the mining model.

### 6.3 Mining model

This section describes and defines the formal relationships and the dynamics of the copper mining model. The model is used to study how investment decisions change over time as key decision drivers (such as [ore grade](#) and copper price) change.<sup>10</sup> To comprehensively capture the dynamics of the industry, the model has two modules: material and financial.

The material module focused on the material production process particularly on variables such as the quantity of ore resources available, type of ore resources, [ore grade](#), methods of mining and capacity of mining equipment ([Mudd et al., 2013](#); [Norgate and Jahanshahi, 2010](#); [Northey et al., 2014](#)). This module captured mining activities at ore production level ([Norgate and Haque, 2010](#); [Norgate and Jahanshahi, 2010](#)), instead of copper cathode production level as was done in other studies ([Saygin et al., 2011](#)). This is important because mining capacity investments are measured by the quantity of ore the production line can handle and not by the copper contained in the ore. In addition, by modelling at ore level, the impact of reducing [ore grade](#) can be properly analysed.

The financial module focused on the investments and profitability of the firm's production capacity and operations ([Auger and Ignacio Guzmán, 2010](#); [Boulamanti and Moya, 2016](#)). This module captured the production costs and the impact they have on the decision making process via decision rules. The production costs are categorised into two: operational costs and capital costs. The operational costs cover all direct costs of producing copper, these costs are short-term focused and include costs such as energy and labour costs. On the other hand, capital costs have a long-term focus and account for the costs that a mining firm incurs to keep producing copper over a period of time, costs such as capital investment cost of mining capacity.

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<sup>10</sup>See section [D.6.1](#) in Appendix [D](#) for five extreme tests that were used to test the behaviour of the mining model.

Figure 6.1 below shows the linkages between the material and financial modules and the key outputs of each module. The main outputs of the material module into the financial module are total energy consumed and copper produced while from the financial module, it is the profitability. Depending on the information (values) in the profitability feedback loop, the mining firm could vary its investment and operational behaviour (Montaldo, 1977).

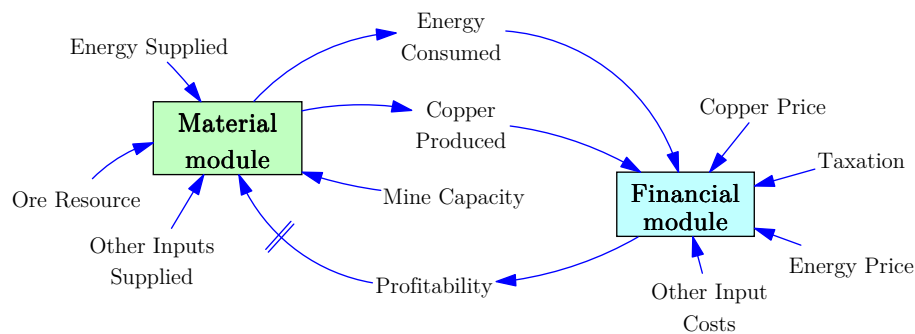


Figure 6.1: Linkage between the material and financial modules

### 6.3.1 Data

Below are the data sources used in developing the mining model (Details of the data is given in Appendix D):

- Interview data: This data was collected from mining firms, mining industry experts and governments departments and agencies. The data described the decision processes in mining firms, key decision variables and methods used in evaluating decision options. The collection process is described in section 6.2 above.
- Energy data: National energy statistics (for fuels and electricity) were collected from ZESCO, Copperbelt Energy Corporation Plc (CEC) and ERB; and in cases where the statistics were missing, IEA statistics were used. One mining firm released their company level energy statistics.<sup>11</sup> Further, statistics from ZESCO and CEC contained monthly electricity statistics for all the mining companies from 2002

<sup>11</sup>See section 2.2.1 above for a summary of energy consumption at firm level.

through to 2013. Statistics from [ERB](#) contain information on energy prices (for both fuels and electricity).

- Resource data: This contained statistics of how much copper cathodes were produced in a particular year (or quarter), the average [ore grade](#) and type of ore that was mined, the quantity and grade of ore resources. This data was collated from mining companies annual reports and [SNL Metals and Mining \(SNL\)](#) database.
- Technology cost data: Technology costs were obtained from technical reports of mining projects evaluations (from [SNL](#) database). These technical reports covered different projects in Zambia and also other countries such as DR Congo and Chile. These reports also give an indication of the RoI or IRR that is considered acceptable for project development. Where specific data was not available in these reports, journal articles data was used.
- Commodity price data: Commodity price data were collected from [The World Bank Group \(World Bank\)](#) and [SNL](#) database.
- Copper production costs data: Companies annual reports were the main sources of production costs statistics. However, because all of these statistics (production costs from annual reports) were aggregated, a [KCM](#) Valuation report ([Rothschild, 2008](#)) was used to calibrate the costs of each process stage and end-use service. Journal articles were also used in calibrating the cost of production at mining grouping and industry levels.

### 6.3.2 General Assumptions

Being a stylised representation of a real system<sup>12</sup>, assumptions were made in developing the mining model. These assumptions focused on aspects of the mining model that directly impact the firm's profitability (i.e. the focus

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<sup>12</sup>See section [3.1](#) for a discussion of what models are and why they are used

of the model being decision making). Below are the main assumptions of the model:

- **Time:** The model is a dynamic model, meaning decision environment of time  $t_1$  would be different from that of time  $t_2$ . An aggregate time step of one month<sup>13</sup> was used and with a time horizon up to 2050. The model base year is 2010. This base year was used because of the availability of reliable data.
- **Model aggregation:** The mining firms are aggregated into three, using mining method: Copperbelt Underground, Copperbelt Open-pit and North-Western Open-pit.<sup>14</sup> This is because all mines (using same mining methods) have similar ore characteristics and production cost profiles.
- **Model boundaries:** The model covers copper production from mining ore to production of cathodes: from cradle to gate. It does not model the processing of associated mineral and products, but the credits of these copper by-products (such as gold and cobalt) are only accounted for in a stylised manner. In addition, Zambia's industry is thought of as a copper price taker (not a determinant of the price), largely because it accounts for less than 8% of the global copper production. Thus, the copper price is an exogenous input to the model.
- **Capital investments:** Two types of capital investments are considered: ore production capacity and energy efficient motors investments. These investments are mutually exclusive.

### 6.3.3 Framework of a mining firm

A group copper mining firm<sup>15</sup>,  $M_i$ , owns a mine with two types of ore: oxide and sulphide. These ore types are hosted in one mine<sup>16</sup>, where mining of one type leads to the mining of another. Further, the costs of processing each

<sup>13</sup>The life cycle of copper processing from cradle to gate is between four to six weeks

<sup>14</sup>The resource profile of each group category is given in section B.3 of Appendix B.

<sup>15</sup>Based on model aggregation in section 6.3.2 above.

<sup>16</sup>This is a simplification because some mines only have one ore type.

ore type are different and the processes require different inputs. However, because of the way the ore is hosted (in the rock), the firm's profit,  $\Pi_i$ , depends on the profitability of each ore type. The profit varies every time step,  $t$ , and in each time step the firm could make decisions (capital and/or operational decisions) which have implication on current and future profits. The capital investment decisions are long term and have technology lock-in effects while the operational decision are short term and based on the current copper price and production costs.

Under capital investment decisions, there are three investment options: capacity replacement, new capacity (expansion) and efficient electric motor investments. Capacity replacement options focus on sustaining the current capacity stock. Say if the stock had a capacity of one million tonnes of ore per year in time  $t_0$ , this capacity option will ensure that it is maintained at one million tonnes per year through to time  $t_n$ . New capacity development option includes the capacity replacement option plus additional capacity development. An example of capacity expansion would be maintaining the one million tonnes of ore per year plus additional 10% of the current stock in the next  $n$  years. Under the capacity replacement option, as [ore grade](#) reduces the production of copper cathodes also reduces. This is because the quantity of copper in ore reduces. However, under the capacity expansion option, the quantity of copper in ore can reduce, increase or remain constant. The expansion option, therefore, means more capital cost and increased investment risk. Finally, the efficient motor option, focuses on how the firm can reduce its production costs (via energy costs) by increasing the share of efficient electric motors. This can be done through replacement of existing motors if the production capacity stock is maintained or by investing directly in efficient motors if the production capacity stock is expanded.

Under operational decisions, the firm decides whether to maintain or reduce its ore production based on its production capacity stock. The decision is dependent on the profitability of the mining activity. Similar to capital investment decisions, this decision is driven by profitability. How-



ever, the length of time,  $t_T$ , used to calculate profitability is much shorter. This length,  $t_T$ , is dependent on the loss tolerance of the firm (see Equations 6.7 - 6.9 below.).

Further, capital and operational decisions impact each other. For instance, when a firm makes a decision to scale down its ore production in time  $t$ , that firm cannot make a decision to replace or increase its ore production<sup>17</sup> in that time step ( $t$ ). However, because of the project lead time,  $t_L$ , in developing capacity projects (see Equations 6.26 - 6.41), the firm's capacity could increase in time  $t$ . This is because of a technology lock-in mechanism. Another example of the interactions between capital and operational decisions is postponing of a scaling down decision because energy efficient technologies have come online, thus increasing the profitability (via reducing energy costs) even when there is no significant change in the market conditions.

The interactions between these decisions (capital and operational decisions) therefore influence how much ore is produced in each time step  $t$ . A firm's generic ore production function,  $q_t$ , is defined below (detailed description of the function is given in the sections 6.3.4 and 6.3.5 below)

$$q_t = F(Y_t, K_t, Q_t) \quad (6.1)$$

$$Y_t = F(Y_{t-t_L}, IY_{t-t_L}, RY_{t-t_L}) \quad (6.2)$$

$$K_t = F(\Pi_{t-1}, \eta_{t-1}, t_T) \quad (6.3)$$

where,

$q_t$  is the quantity of ore (in tonnes) produced in time  $t$ ,

$F$  is a function defining the relationship between variables,

$t_0$ ,  $t$  and  $t_L$  are initial time, current time step and project lead time respectively,

$Y_t$  is the availability ore production capacity (in tonnes) in time  $t$ ,

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<sup>17</sup>Which will come online in time  $t + t_L$ .

$Y_{t-t_L}$  is the availability ore production capacity (in tonnes) in time  $t-t_L$ ,

$IY_{t-t_L}$  is size of ore production capacity (in tonnes) that the firm invested into in time  $t-t_L$ ,

$RY_{t-t_L}$  is the size of ore production capacity (in tonnes) that is retired between time  $t-t_L$  and  $t$ ,

$K_t$  is the profitability function,

$\Pi_{t-1}$  is the firm's profit in time  $t-1$ ,

$\eta_{t-1}$  is the average energy efficiency of the firm's energy system,

$t_T$  is the firm's loss tolerance time, and

$Q_t$  is the available ore resources (in tonnes) in time  $t$ .

### 6.3.4 Material module

This module describes the processes that copper processing goes through from ore (mining) to cathode (refining).

**Ore resources function:** The size (measured in [tonnes of ore \(tonOre\)](#)) of the available ore resources ( $Q_t$ ) at any time  $t$  is determined by the initial resources ( $Q_{t_0}$ ) minus the sum of all produced ore ([Brennan and Schwartz, 1985](#); [William et al., 2012](#)). Defined below as

$$Q_t = (Q_{t_0} \pm \epsilon_Q) - \sum_{i=t_0}^{t-1} q_i \quad (6.4)$$

with, the physical constraint of  $Q_t \in (0, Q_{t_0})$ ,  $Q_{t_0}$  being the initial ore resources (has a margin of error  $\epsilon_Q$ ) and  $q_i$  being the rate of ore production (extraction) at time  $t_i$ .

**Ore extraction function:** The quantity of ore produced ( $q_t$ ) in time  $t$  is a function of installed capacity, profitability and available ore. The function is defined below

$$q_t = \min(Y_{max,t}, Y_{P,t}, Q_t, Y_{V,t}) \quad (6.5)$$

where,

The physical constraint is  $q_t \in (0, q_{max})$ ,

$Y_{max,t}$  is the installed ore capacity of a firm (measured in **tonOre**). This represents the maximum quantity of ore that a firm can extract at any time  $t$ ,

$Y_{P,t}$  is the maximum quantity of ore (in **tonOre**) that a firm is willing to extract (produce). This is defined in Equations 6.6 - 6.9 below,

$Q_t$  is the available ore resources (in **tonOre**) at any time  $t$  (defined in Equation 6.4 above), and

$Y_{V,t}$  is the available inventory space (in **tonOre**) at any time  $t$ . This is defined in Equations 6.10 - 6.15 below.

**Profitability function:** The firm directly determines the size of the installed capacity through its capital investment decisions (to replace or expand). On the other hand, the maximum quantity of ore a firm is willing to produce ( $Y_P$ ) is determined by the financial position of the firm at any time  $t$ . This represents the endogenous short-term operational decisions that a firm could make to reduce its losses during fluctuations in the market prices. The  $Y_P$  function is defined below

$$Y_{P,t} = Y_{max,t} \times K_t \quad (6.6)$$

$$K_t = \begin{cases} 1 & \text{if } kP_t \leq a_T \\ \frac{(1-kP_t)}{1-a_T} & \text{otherwise} \end{cases} \quad (6.7)$$

$$kP_t = \sum_{i=t-t_T-1}^{t-1} \left( \begin{cases} \frac{PC_i}{RV_i} & \text{if } RV > 0 \\ kP_{ref_i} & \text{otherwise} \end{cases} \right) \quad (6.8)$$

$$kP_{ref} = \frac{PC_{ref}}{RV_{ref}} \quad (6.9)$$

where,

$Y_{max,t}$  is the installed ore capacity (in **tonOre**) of a firm at any time  $t$ ,

$K_t$  is the profitability function,

1 represents normal production patterns,

$a_T$  is the firm's tolerance threshold, that indicates change in the firm's

production patterns due to its financial position,

$t_T$  is the firm's loss tolerance time,

$RV$  is the gross revenue (in US\$) realised from the sales of copper and related by-products (see Equation 6.23 below),

$PC$  is the total costs (in US\$) that are incurred in producing copper and related by-products (see Equation 6.24 below),

$RV_{ref}$  is the gross revenue (in US\$) that would be realised from the sales of copper and related by-products, and

$PC_{ref}$  is the total costs (in US\$) that would be incurred in producing copper and related by-products.

**Inventory function:** The size of inventory space (in tonnes of ore) varies between firms and it is a critical link between ore production capacity ( $Y_{max}$ ) and down-stream capacities such as smelter ( $Y_{smelt}$ ) and refinery ( $Y_{ref}$ ). This link is important because it describes how materials flow from one stage to the next. It is necessary to describe the material flow in details because of the feedback loop in the flow (between stages) and also to enable analysis of how different export policies could affect the production of ore.

The size of the inventory space is determined by the firm's trading strategy<sup>18</sup>. However, in this research, it was assumed that all firms' inventory space is determined by a constant inventory factor ( $\xi$ ). The firm's inventory space ( $Y_V$ ) is described below

$$Y_{V,t} = \frac{V_{St,hydro}}{OG_{t,hydro}} + \frac{V_{St,pyro}}{(OG_{t,pyro} \times CG)} \quad (6.10)$$

$$qC_{t,hydro} = q_t \times v \times OG_{t,hydro} \quad (6.11)$$

$$V_{St,hydro} = \min(qC_{t,hydro}, Y_{t,hydro,cath}) \times (1 + \xi) \quad (6.12)$$

$$qC_{t,pyro} = q_t \times (1 - v) \times OG_{t,pyro} \quad (6.13)$$

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<sup>18</sup>For instance, does the firm stockpile when the price is depressed and for how long does it stockpile?

$$qC_{t,smelt} = qC_{t,pyro} - qC_{t,export} \quad (6.14)$$

$$Vs_{t,pyro} = \min\left(\frac{qC_{t,smelt}}{CG}, Y_{t,smelt}\right) \times (1 + \xi) \quad (6.15)$$

$$qC_t = qC_{t,hydro} + qC_{t,pyro} \quad (6.16)$$

where,

$OG$  is the **ore grade** (measured as **tonnes of contained copper (tonContCu)/tonOre**<sup>19</sup>) in time  $t$  (it can either be ore processed using hydro-metallurgy or pyro-metallurgy),

$CG$  is the constant concentrate grade (measured as **tonContCu/tonnes of copper concentrate (tonConc)**),

$q_t$  is the quantity of ore produced (in **tonOre**) in time  $t$ ,

$v$  is the share ore that follows the hydro-metallurgy route,

$qC_{hydro}$  is the quantity of contained copper that is processed using hydro-metallurgy (in **tonContCu**),

$qC_{pyro}$  is the quantity of contained copper that is processed using pyro-metallurgy (in **tonContCu**),

$qC_{smelt}$  is the quantity of contained copper sent to the smelter (in **tonContCu**),

$qC_{export}$  is the quantity of contained copper exported (in **tonContCu**),

$Vs_{hydro}$  is measured in **tonContCu**,

$Y_{ref,hydro}$  is the installed refinery capacity of electro-winning facility, measured in **tonnes of copper cathodes (tonCath)**,

$Y_{smelt}$  is the installed smelter capacity,

$Vs_{pyro}$  and  $Y_{smelt}$  are measured in **tonConc**,

$\xi$  is the inventory factor, and

$qC_t$  is the total contained copper mined.<sup>20</sup>

<sup>19</sup>**tonOre** is an abbreviation of tonnes of ore.

<sup>20</sup>If there are no process losses (as assumed in this case), then it is the same quantity as copper cathode produced (measured in **tonCath**).

**Ore grade function:** This is an endogenous function that depends on the ore production activities (i.e. the **ore grade** only changes when ore has been produced). The ore reduction model used in this research assumed that firms tend to extract higher **ore grade** first then move to the lower grade ore. An alternative ore reduction model which responds to copper price is presented in Krautkraemer (1988; 1989) and Farrow and Krautkraemer (1989).

Below is the definition of the ore reduction model used in this research

$$OG_{t_0} = (OG_{avg} \pm \epsilon_{OG_{avg}}) \times \gamma \quad (6.17)$$

$$OG_{t_0} > OG_{avg} \quad (6.18)$$

$$OG_t = \begin{cases} OG_{t_0} & \text{if } t = t_0 \\ \frac{AqC_t}{Q_t} \pm \epsilon_{OG_t} & \text{otherwise} \end{cases} \quad (6.19)$$

$$AqC_t = (Q_{t_0} \times [OG_{avg} \pm \epsilon_{OG_{avg}}]) - TqC_t \quad (6.20)$$

$$TqC_t = \sum_{i=t_0}^{t-1} (q_i \times OG_i) \quad (6.21)$$

where,

$OG_{t_0}$  is the initial **ore grade** of the ore resources at time  $t_0$ ,

$OG_{avg}$  is the estimated average **ore grade** of the ore resources (  $Q_{t_0}$ ),

$\epsilon_{OG_{avg}}$  is the average **ore grade** estimation error, and

$\gamma$  is the estimation factor for the initial **ore grade** (relative to the average **ore grade** ( $\gamma > 1$  )),

$AqC_t$  is the available contained copper (in **tonContCu**) in the ore resources (  $Q_t$ ),

$\epsilon_{OG_t}$  represents the uncertainty in the **ore grade** distribution in the ore,

$Q_{t_0}$  is the available ore resources (in **tonOre**) at time  $t_0$ , and

$TqC_t$  is the total mined contained copper from time  $t_0$  to  $t$ .

### 6.3.5 Financial module

This module defines the costs and revenue streams of a firm and it also describes how the firm makes investment decisions.<sup>21</sup>

**Profit function:** This is a cash-flow function of a firm in time  $t$ , and it is driven by copper price, the quantity of cathode copper produced<sup>22</sup> and the production costs. Production costs consist of labour, cost of capital, repair and maintenance, energy, inventory, consumables, mineral royalty tax (MRT) and other on-site costs (as identified in section 3.3.3 above). In this research, the costs of suspending and re-starting operations were not accounted for. Nonetheless, during the period of suspended operations, the firm continues to service the loans of capital (cost of capital). The profit function ( $\Pi$ ) is defined below

$$\Pi_t = RV_t - PC_t \quad (6.22)$$

$$RV_t = qC_t \times P_{t,Cu} \quad (6.23)$$

$$PC_t = \sum_{i=ore} [UC_i]_t \times [q_t] + MRT_t \times qC_t - CC_t \quad (6.24)$$

$$U_{PC_t} = \frac{PC_t}{qC_t} \quad (6.25)$$

where,

$\Pi_t$  is the firms profit in time  $t$ ,

$RV_t$  is the gross revenue (US\$) of a firm at time  $t$ ,

$PC_t$  is the total production costs (US\$) of a firm at time  $t$ ,

$qC_t$  is the total produced cathodes at time  $t$  (see Equation 6.16 above),

$P_{t,Cu}$  is the copper price (in US\$ per [tonCath](#)) at time  $t$ ,

$[UC_i]_t$  is a set containing unit costs (measure in US\$/tonnes<sup>23</sup>) of labour,

<sup>21</sup>See sections D.4 and D.5 below for indicative financial thresholds used by Zambian mining firms when making investment decisions.

<sup>22</sup>If a firm exports its produce, then the revenue is calculated based on the contained copper in the exported quantity.

<sup>23</sup>This tonnage could be measured in [tonOre](#), [tonContCu](#), [tonConc](#) and [tonCath](#) de-

energy, Repair and Maintenance (R&M), consumables etc,

$[q_t]$  is set containing quantities (in tonnes) of ore, concentrates and copper cathodes,

$MRT_t$  is mineral royalty tax (in US\$ per tonCath)<sup>24</sup> at time  $t$ . This is determined by the host government and it changes frequently due to market (copper price changes) and lobbying reasons,

$CC_t$  is the cost of capital (US\$) that a firm is servicing at time  $t$ , and

$U_{PC_t}$  is the unit production cost (US\$ per tonCath) at time  $t$ .

**Capital investment modelling:** Having defined how operational decisions are made (see Equations 6.6 - 6.9 above), this part focuses on modelling how investment decisions (production capacity and electric motor stock) in a firm are made. It considers investment options of replacing retired ore production stock, expanding the available ore production stock and investing in efficient motors. It does not consider retrofitting option because of lack of cost information for retrofitting options. However, the investment process for retrofitting and the new stock is not different except that retrofit options tend to be cheaper in the short term while new stock options tend to be cheaper in the long term.

The replacing option is defined first then the expansion option and finally the efficient motors decision process. The first two options focus on ore production capacity investment options, which are driven by the value of the available mineral resources, the copper price (usually an average of three or five year period<sup>25</sup>) and the obtaining operational status of the firm (determined by the profitability function). Further, it is based on these ore production capacity (upstream) investment decisions that investment decisions for downstream (smelter and refinery) production facilities decisions are made. Investment decision in motors (generally) is based on the installed ore production capacity, as electric motors are supporting equipment. Further, investment in efficient motors is driven by the [energy](#)

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pending on the variable being considered.

<sup>24</sup>This is set as a share of copper price, such as a rate of 6%.

<sup>25</sup>This period is approximately the half life factor of the copper price, see Table E.4.



efficiency gap and the energy price.

All capital stock investments (ore production and electric motors) decisions are determined by specified investment thresholds driven by the financial position of the firm and the equipment economics. These thresholds vary between firms. The use of thresholds (not optimal way of making decisions) in decision making is common place in firms as was found in industry technical reports and literature (see Chapter 4) and also during industry interviews<sup>26</sup>. This approach was used because the firms that were interviewed stated that a positive Net Present Value (NPV) in itself does not mean a positive investment decision. This is contrary to how decisions are modelled in single objective function models, particularly in optimisation models.

Further, whereas in optimisation models the decision maker seeks to find an optimal solution, the results from the interviews and also from literature review show that decision makers in mining firms seek for solutions that are sufficient (which could even be sub-optimal). See Chapter 4 for details of how organisations make strategic investment decisions and also sections 6.2 (above) and D.4 (in Appendix D) for the findings of the industry interviews.

***Ore production capacity investments:*** Ore production capital stock investment decision making are defined in Equations 6.26 to 6.41. Capacity replacement and expansion decisions are expressed as  $IY_{t-t_L,Rep}$  and  $IY_{t-t_L,Exp}$  respectively. The only difference between the replacement and expansion options is the way the size of the proposed project is calculated. If the value of  $ET_t = 0$ , all decisions under this condition are replacement decisions while  $ET > 0$  condition leads to expansion decisions. In this case,  $ET$  is the maximum desired percent increase of copper cathode production based on the current production as described in Equation 6.35.

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<sup>26</sup>Firms operating in Zambia were interviewed on how they make decisions.

$$IY_{t-t_L} = \begin{cases} IY_{t-t_L,Rep} & \text{if } ET = 0 \\ IY_{t-t_L,Exp} & \text{if } ET > 0 \end{cases} \quad (6.26)$$

$$IY_{t-t_L} = \begin{cases} Y_{t-t_L,gap} & \text{if } th_{t-t_L,D} \geq 1 \\ 0 & \text{otherwise} \end{cases} \quad (6.27)$$

$$th_{t-t_L,D} = \frac{th_{t-t_L,Prj}}{th_{t-t_L,I}} \text{ where } th_{t-t_L} \geq 1 \quad (6.28)$$

$$th_{t-t_L,Prj} = \frac{vAqC_t - vPqC_n}{vPqC_n} \quad (6.29)$$

$$Y_{t-t_L,gap} = \max(0, [AfY_{t-t_L} + vPY_n - q_{t-t_L}]) \quad (6.30)$$

$$AfY_{t-t_L} = Y_{t-t_L} - RY_{t_L} \quad (6.31)$$

$$vPY_n = \frac{vPqC_n}{I_{t-t_L}} \quad (6.32)$$

$$vPqC_n = PqC_n \times \hat{P}_{t-t_L,Cu} \quad (6.33)$$

$$PqC_n = (PY_{t-t_L} + RY_{t_L}) \times n \times OG_{t-t_L} \quad (6.34)$$

$$PY_{t-t_L} = \frac{(qC_{t-t_L} \times ET_t)}{OG_{t-t_L}} \quad (6.35)$$

$$vY_t = \frac{vAqC_t}{I_{t-t_L}} \quad (6.36)$$

$$vAqC_t = AqC_t \times \hat{P}_{t-t_L,Cu} \quad (6.37)$$

$$\hat{P}_{t-t_L,Cu} = \exp(\hat{S}_{t-t_L,Cu}) \quad (6.38)$$

$$AqC_t = AqC_{t-t_L} - DqC_{t_L} \quad (6.39)$$

$$AqC_{t-t_L} = Q_{t-t_L} \times OG_{t-t_L} \quad (6.40)$$

$$DqC_{t_L} = q_{t-t_L} \times t_L \times OG_{t-t_L} \quad (6.41)$$

where,

$t$  and  $t_L$  are current time and project lead time respectively,

$n$  is the life span of the stock,

$IY_{t-t_L}$  is the total ore production capacity (in [tonOre](#)) that will be developed,

$ET_t$  is the desired percent increase of copper cathode production based on the current production at time  $t$ . If  $ET = 0$ , this investment option take a form of the capacity replacement option,

$Y_{t-t_L,gap}$  is the available investment capacity gap (in tonnes),

$th_{t-t_L,Prj}$  is the estimated investment threshold of a project,

$th_{t-t_L,I}$  is the investment threshold set by the firm (this could also vary between time steps),

$vAqC_t$  is the total value of contained copper (in [tonContCu](#)) at time  $t$ ,

$Y_{t-t_L}$  is the installed ore production capacity (in [tonOre](#)) at time  $t - t_L$ ,

$RY_{t_L}$  is the ore production capacity (in [tonOre](#)) that will be retired between time  $t - t_L$  and  $t$ . This is calculated endogenously based on the age profile of the stock,

$AY_{t-t_L}$  is the ore production capacity (in [tonOre](#)) that will be available after some capacity has been retired,

$vIY_{t-t_L}$  is the capacity in tonnes of ore ([tonOre](#)) that can be invested in using the value of copper after the project lead time ( $t_L$ ),

$q_{t-t_L}$  is the total maximum possible ore production rate (in [tonOre](#)) in time  $t - t_L$ ,

$vY_{t-t_L}$  is the ore production capacity (in [tonOre](#)) that can be invested in using the value of copper after the lead time ( $t_L$ ),

$I_{t-t_L}$  is the total capital investment cost (US\$) of the capacity at time  $t - t_L$ ,

$AqC_t$  and  $AqC_{t-t_L}$  are the available contained copper (in tonContCu) in the ore resources ( $Q_t$  and  $Q_{t-t_L}$ ) at time  $t$  and  $t - t_L$  respectively,

$\hat{P}_{t-t_L,Cu}$  is the moving average copper price using the half life of price shock (see section 3.3.5 for how this is calculated),

$DqC_{t_L}$  is the estimated contained copper (in tonContCu) that could be produced during the project lead time  $t_L$ , and

$OG$  is the ore grade (as a percentage (%)).

From Equations 6.37, 6.40 and 6.41 it can be seen that the value of the investments options vary between time steps and that it is significantly influenced by the historical movements in the copper price ( $\hat{P}_{t,Cu}$ ), ore grade ( $OG_t$ ), available ore resources ( $Q_t$ ) and the profitability ( $K_t$ ) and inventory ( $Y_{V,t}$ ) feedback loops.

**Electric motor investments:** Similar to the ore capacity investment decisions, investment decisions for energy efficient motors are influenced by investment thresholds. There are two thresholds used for motor investments: profit and project thresholds. The profit threshold determines whether or not a firm would invest if its operation's profit margin is at a certain level. As Prain (1975) observed if a mining firm achieves its set profit margin objective, it seldom invests in efficient technologies to maximise its profits. The project threshold focuses on the economics of efficient motors. It is based on the energy efficiency gap available in the electric motor system of the firm and the electricity price. The energy efficiency gap is the difference between energy demand by the average motor system efficiency of the firm and the efficiency of efficient motors (as defined in Equation 6.52 below). The monetary value of this gap is calculated by multiplying it by the price of electricity ( $P_{t,elec}$ ). A decision maker could decide to invest either in standard or efficient motors. At all times, the firm will have a specified number of motors depending on the ore production capacity (The motor-ore capacity ratio is assumed to remain constant). Further, because

these technologies have a long operational life span, investments in electric motors lead to technology lock-in and path dependence.

The investment decision equations for electric motors are defined below

$$IYm_{t+1} = \begin{cases} EEm & \text{if } th1_t \times th2_t = true \\ Stdm & \text{otherwise} \end{cases} \quad (6.42)$$

$$th2_t = \begin{cases} true & \text{if } th_{t-1,\Pi} \leq th_{t,P} \\ false & \text{otherwise} \end{cases} \quad (6.43)$$

$$th_{t-1,\Pi} = \frac{RV_{t-1} - PC_{t-1}}{PC_{t-1}} \quad (6.44)$$

$$th1_t = \begin{cases} true & \text{if } th_{t,Prj} \geq th_{t,I} \\ false & \text{otherwise} \end{cases} \quad (6.45)$$

$$th_{t,Prj} = \frac{vE_{t,gap} \times \beta_{t,m}}{vIR_{t,m}} \quad (6.46)$$

$$\beta_{t,m} = \frac{RYm_{tL}}{Ym_{t,old} + Ym_{t,exp}} \quad (6.47)$$

$$vE_{t,gap} = E_{t,gap} \times n \times P_{t,elec} \quad (6.48)$$

$$vIR_{t,m} = RYm_{tL} \times I_{t,m} \quad (6.49)$$

$$vI_{t,m,new} = (Ym_{t,old} + Ym_{t,exp}) \times I_{t,m} \quad (6.50)$$

$$E_{t,gap} = E_{t,gap,old} + E_{t,gap,exp} \quad (6.51)$$

$$E_{t,gap,old} = E_{a,t} \times \left( \frac{1}{\eta_{t,avg}} - \frac{1}{\eta_{t,EE}} \right) \quad (6.52)$$

$$E_{t,gap,exp} = E_{a,t,exp} \times \left( \frac{1}{\eta_{t,std}} - \frac{1}{\eta_{t,EE}} \right) \quad (6.53)$$

$$Ym_{t,old} = \frac{Y_{t,max}}{mRq} \quad (6.54)$$

$$Ym_{t,exp} = \frac{IY_{t,exp}}{mRq} \quad (6.55)$$

where,

$IYm_t$  is the total motor capacity that will come online in time  $t + 1$ , this decision is made in time  $t$ ,

$EEm$  and  $Stdm$  are efficient and standard motors respectively,

$th_{t,P}$  is the profit threshold does not require efficient motor investments set by the firm (this could also vary between time steps). It is assumed that the firm has a specified profit target,

$th_{t,I}$  is the threshold for project investment set by the firm (this could also vary between time steps),

$PC_{t-1}$  is the total costs (US\$) that are incurred in producing copper and related by-products in time  $t - 1$ ,

$RV_{t-1}$  is the gross revenue (US\$) realised from the sales of copper and related by-products in time  $t - 1$ ,

$th_{t,Prj}$  is the estimated investment threshold of a project,

$vE_{t,gap}$  is the estimated total value of energy saving (in US\$) if the gap is immediately<sup>27</sup> eliminated by efficient motors,

$RYm_{tL}$  is the motor capacity (number of motors) that will retire in time  $t + tL$ ,

$I_{t,m}$  is the capital investment cost (US\$) of the capacity in time  $t$ ,

$Ym_t$  is the total capacity of the motor system (number of motors) in time  $t$ ,

$E_{t,gap}$  is the total **energy efficiency gap** (in kWh) that exists in the firm's motor system in time  $t$ ,

$n$  is the life span of the stock,

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<sup>27</sup>However, because of technology lock-in, the gap cannot be eliminated in an instance.

$P_{t,elec}$  is the current electricity price (US\$ per kWh) in time  $t$ . This assumption implies that investments in standard motors is incentivised,

$E_{a,t}$  is the total energy consumed by electric motors (in kWh) in time  $t$ ,

$\eta_{t,avg}$  is the dynamic average energy efficiency of the motor system in time  $t$ ,

$\eta_{t,EE}$  is the energy efficiency of the efficient motors in time  $t$ ,

$Y_{t,max}$  is the total installed production capacity (in tonOre) in time  $t$ , and

$mRq$  is the required motors per tonne of installed capacity.

## 6.4 Method for SD model analysis

Section 3.1.3 identified two types of uncertainty (parametric and structural) in models, this section builds on that and focuses on identifying the most influential inputs and feedbacks loop in SD models. Influential inputs and feedback loops are those inputs/loops that significantly impact the output of the model. These (inputs and loops) are however difficult to quantify or know before-hand (Ford and Flynn, 2005; Ford, 1999). Thus, in order to understand system behaviour over time, statistical screening is used.<sup>28</sup>

Taylor et al. (2010) describe statistical screening as a rich method for identifying and quantifying model parameters' influence on system behaviour throughout the course of the simulation. This method also helps in understanding how the impact of exogenous parameters on the system behaviour changes over time. Central to this method is the use of Pearson correlation coefficients (defined in Equation 6.56 below) for determination of the strength of the linear relationship between two model variables<sup>29</sup>

<sup>28</sup>See section 7.2.2 below for the application of the statistical screening method in the identification of key drivers of the model.

<sup>29</sup>Latin Hypercube Sampling (LHS) technique was used when sampling values of input parameters. This is because the technique is efficient and also gives a better representation of value from the sample space (Mckay et al., 1979; Welch et al., 1992).

(Ford and Flynn, 2005).

$$\rho_{X,Y} = \frac{\text{cov}(X, Y)}{\sigma_X \sigma_Y} \quad (6.56)$$

where  $\text{cov}(X, Y)$  is the covariance between  $X$  and  $Y$  variables and  $\sigma_X$  and  $\sigma_Y$  are the standard deviations for variables  $X$  and  $Y$  respectively.

The method (statistical screening) involves six steps (adapted from Taylor et al. (2010)), which are described below:

1. Select a specific set of exogenous model parameters (inputs) and a performance variable (output) for analysis. Select ranges of possible exogenous parameter values based on an understanding of the real system.
2. Perform statistical screening of the model to calculate correlation coefficients for the selected exogenous model parameters (as described in Equation 6.56). Plot both the correlation coefficients and the behaviour of the performance variable over time.
3. Select a time period for analysis by examining time series of the performance variable and the correlation coefficients.
4. Create a list of most influential parameters. Most influential parameters are the parameters with the highest absolute correlation coefficient values during the selected time period.
5. Identify the most influential model structure(s) for each parameter identified in step 4 as those that are directly connected to the most influential parameter. If multiple parameters from step 4 are directly connected to the same model structure, add each parameter set to the list.
6. Use additional structure–behaviour analysis methods (such as verbal reasoning, scenario analysis, behavioural analysis etc)<sup>30</sup> to explain

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<sup>30</sup>Such as the one described in Ford (1999).



how each parameter or set of parameters and the structures they influence drive the behaviour of the system.

## 6.5 Chapter summary

In this chapter, processes used to study how strategic investment decisions are made in Zambia's mining sector were described. Key decision variables and rules were identified and defined. The chapter also identified endogenous (such as how ore production leads to the reduction of [ore grade](#)) and exogenous (such as how fluctuations in copper markets impact the firm's profitability) interactions that could impact decision making in mining firms were defined. Identification of key decision variables, rules and interactions was necessary in order to explore how Zambia's mining sector would grow. The chapter then discussed and described the method used to analyse the mining model that was developed as part of this research.



# Chapter 7

## Results and discussion

This chapter presents and discusses the main findings of this research. It has four sections: section 7.1 presents and discusses the results of the energy models ([LEAP \(Heaps, 2016\)](#) and [OSeMOSYS \(Howells et al., 2011\)](#) models for demand and supply modelling respectively) described in Chapter 5 while section 7.2 presents and discusses the results of the mining model (described in Chapter 6), a model which was built on a Vensim platform ([Ventana, 2015](#)). Section 7.3 gives a discussion summary of the findings. Finally, section 7.4 gives a summary of the results and highlights the main findings. The results output of both the energy and mining models were analysed using [R Core Team \(2017\)](#).

### 7.1 Energy system results

This section addresses the first research question: How would Zambia's energy sector evolve by 2050? and its related sub-questions given in Chapter 5. This question focuses on understanding how changes in energy demand would impact investments in supply technology stock and the electricity price (via the average generation cost). Demand and supply scenarios are described in section 5.3. A range of sensitivity tests were applied to the supply model to check for factors that have the most impact. Results for

sensitivity tests are given in section 7.1.3 below.

### 7.1.1 Energy demand

Having argued the importance of correctly modelling energy demand in section 3.2.5 (Chapter 3) and the impact that fuel switching would have on the development of the energy system in section 5.1.1 (Chapter 5), this subsection presents and discusses the results of the demand model described in Chapter 5. Three key dimensions of energy demand are presented: total energy demand, total electricity demand and total forest cover which would be lost<sup>1</sup> due to use of wood and charcoal for each demand scenario. In-depth results of the residential sector are then given. Residential sector results focus on the impact that increasing access to [clean energy](#) and fuel switching would have on the sector's electricity demand.

Figure 7.1 shows the total final energy demand (all sectors) for each scenario. Energy demand is projected to grow from 162 PJ<sup>2</sup> in 2010 to between 370 and 466 PJ in 2050, depending on the scenario considered<sup>3</sup>. The variance in total energy demand by 2050 is a result of the use of different economic growth rates, energy access rates and fuel transition assumptions. For instance, the rate of economic growth has a direct bearing on the total

<sup>1</sup>Forest re-growth through regeneration was considered, reforestation was not.

<sup>2</sup>The 162 PJ figure is estimated based on the calibrated model (using data from [IEA \(2012\)](#), [ZESCO \(2013\)](#) and [CSO \(1994; 1996; 2003; 2005; 2012\)](#)), however, [IEA \(2012\)](#) estimates it to have been 230 PJ in 2010. The main difference between the calibrated value and the [IEA](#) value was in the wood and charcoal values.

<sup>3</sup>Demand scenarios:

Scenario 1: considers a slow economic and electrification growth, with low mining output. The national average share of households (of those connected to electricity) using electricity for cooking and heating is 75%.

Scenario 2: considers slow economic and electrification growth, with high mining output. The national average share of households (of those connected to electricity) using electricity for cooking and heating is 75%.

Scenario 3: considers slow economic growth but with fast electrification growth and high mining output. The national average share of households (of those connected to electricity) using electricity for cooking and heating is 75%.

Scenario 4: considers fast economic and electrification growth and high mining output. The national average share of households (of those connected to electricity) using electricity for cooking and heating is 50% because of the introduction of gas as a cooking fuel. Gas displaced both electricity and traditional fuels.

Scenario 5: considers fast economic and electrification growth and high mining output. The national average share of households (of those connected to electricity) using electricity for cooking and heating is 100%.

– see section 5.3 of Chapter 5 for details.

energy demand in the transport, services and other sectors. However, it also has an indirect impact on residential energy demand via household income (See section C.4). Energy access and fuel transition assumptions directly impact the level of energy demand in the residential sector. For example, if energy access is low and most households continue using traditional fuels (charcoal and wood), the total energy demand would be high because technologies that consume traditional fuels are energy inefficient.

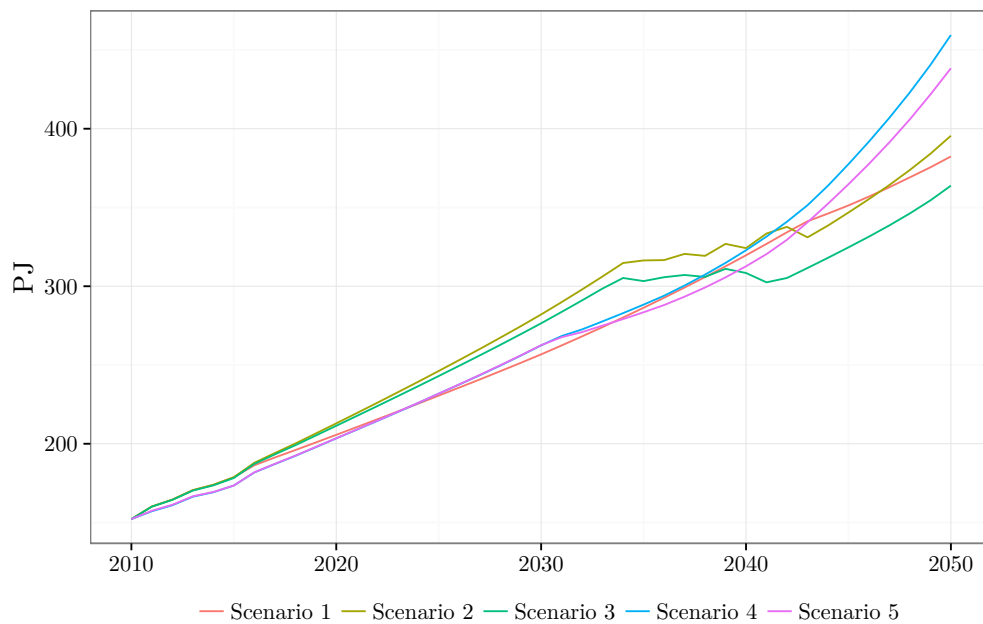


Figure 7.1: Projected total final energy demand at scenario level

Of the five demand scenarios, scenario 4 has the highest total energy demand due to increased energy demand from economic sectors as a result of high economic growth (6%) and also because of the increase from the residential sector due to increase in household income and fuel switching from electricity to gas, gas being a less energy efficient fuel for cooking and heating service. Scenario 4 explores a situation where the government targets to increase access to [clean energy](#) by deploying off-grid solutions for lighting service and gas fuel (a clean fuel) for cooking and heating service.<sup>4</sup> The total demand in scenario 4 increased from 162 PJ in 2010 to a maximum of 466 PJ in 2050.

<sup>4</sup>An example of such a policy move is in the Republic of Ghana. Their government incentivised residential consumers to switch from traditional fuels as a source for cooking and heating to [LPG](#) (MOP, 2016).

As mentioned in Chapter 5, the energy demand from the mining sector was estimated using the mining model (presented in section 7.2) and not the LEAP model. Initial energy demand from the mining sector was estimated by considering demands from three cathode production outputs (based on the maximum growth rates of production capacity) at constant energy prices: maintaining, increasing (double) and high production<sup>5</sup> outputs. These demands were then used as input in the OSeMOSYS (supply) model to estimate the energy prices (via average generation cost). These estimated prices were then used as initial non-constant inputs (making energy prices variable, from constant) in the mining model (SD model). This process and iterations between the OSeMOSYS and mining models was repeated<sup>6</sup> until there was insignificant change in demand and prices between models. Thus, because each demand scenario<sup>7</sup> had its own energy price, energy demand from the mining sector was different for each scenario.<sup>8</sup> Section 7.2 below discusses the mining model in details, with sub-section 7.2.1 discussing the iteration process further.

A detailed energy demand (all sectors) projection is given in Figure 7.2. This figure shows energy demand by sectors and also by fuels. From the graph, it can be seen that the residential sector continues to be a significant consumer of final energy and that oil, electricity and traditional fuels have the largest uncertainty. The uncertainty in oil demand is largely due to the linkage between economic output (particularly in the transport sector) and the *energy intensity*. To better understand uncertainty in oil demand, detailed modelling would be required. However, this was not the focus of this research. On the other hand, the uncertainty in electricity (and

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<sup>5</sup>See section 7.2.1 below for an explanation of the use of high production output.

<sup>6</sup>After the initial OSeMOSYS run, high production output demand was dropped because this scenario was not the focus (the maximum mining output was more than 2 million tonnes, above the maximum targeted production of 1.9 million). Hence, the iterations were only done for maintaining (targeted output of 0.9 million tonnes) and increasing (targeted output of 1.9 million tonnes) copper production growth rates.

<sup>7</sup>Of the five scenarios, maintaining production regime has one energy scenario (scenario 1) while increasing production regime had four energy scenarios (scenarios 2 to 5), as described in section 5.3 above.

<sup>8</sup>See Figure E.1 in Appendix E for the mining sector energy demand of the final iterations.

consequently, traditional fuels) demand<sup>9</sup> (which was one of the foci of the research) is a result of various compounding factors such as population growth, increased energy access and copper production, among others.

As discussed in section 5.1.1, the projections of transport, services and other sectors are solely determined by the assumed sectoral growth rate. Thus, energy projections from these three sectors can be explained relative to the economic growth rate assumption, that is, there are no other interactions that drive energy demand within the model. However, energy demand in mining and residential sectors is driven by a multiple of factors. In the residential sector, these factors are population growth, household income, fuel switching and energy access<sup>10</sup>; while in the mining sector factors such as reduction in ore grade, mining method and ore type influence demand. Detailed results for these two sectors are given and discussed below.

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<sup>9</sup>See Figure E.3 in Appendix for the projected electricity, charcoal and wood demand for each scenario.

<sup>10</sup>See section C.4 and Appendix C for the assumptions.

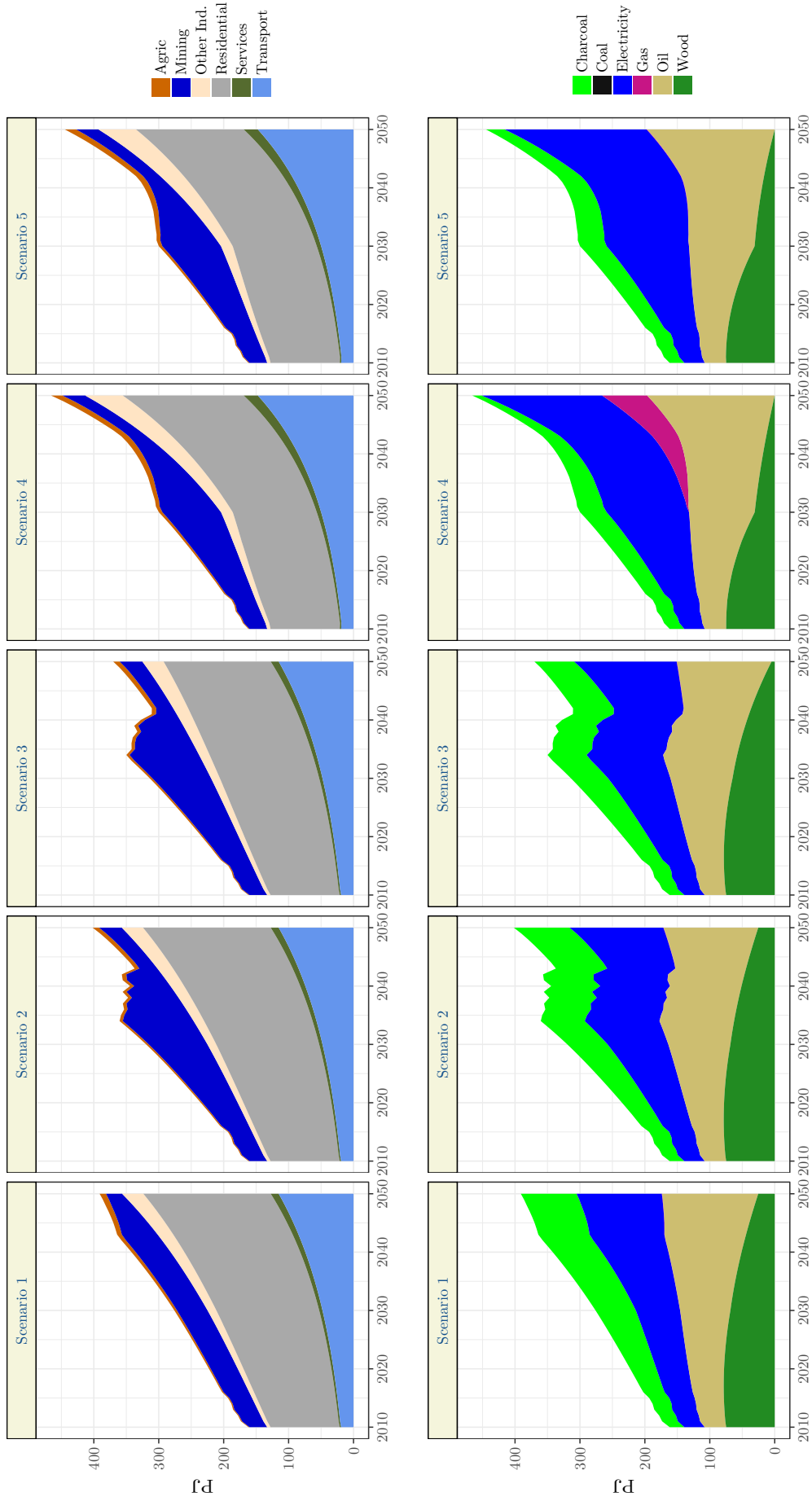


Figure 7.2: Projected total final energy demand by sector and fuels



In scenario 1<sup>11</sup>, it was assumed<sup>12</sup> that electricity access rate in the residential sector increased to 70% (by 2050) and that 75% of the households which had access to electricity also used it for their cooking and heating services. Under this scenario, total residential energy demand grew from 106.7 PJ (in 2010) to 195.8 PJ (in 2050) and final electricity demand also grew from 8.8 PJ to 84.5 PJ during this same period as shown in Figure 7.3 below. To put it into context, residential electricity demand is projected (by 2050) to be twice as much the value of the country's total electricity demand of 2010 (which was 39 PJ).

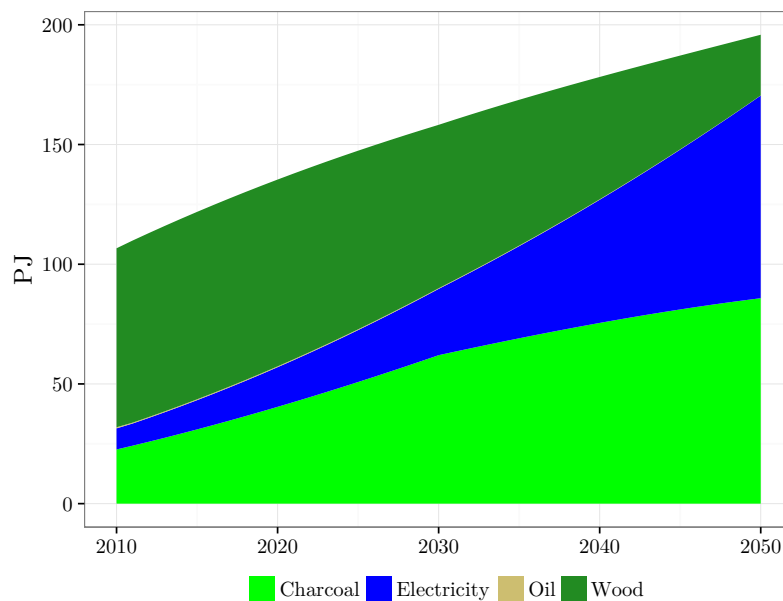


Figure 7.3: Residential energy demand projection for scenario 1

Electricity growth was driven by increased population<sup>13</sup>, access to electricity and household income relative to the base year (2010). With population increase of 270%, electricity demand would increase by 23.5 PJ (by 2050) if all things are held constant; because the total number of households needing electricity would have increased. Increased access to electricity also leads to cooking and heating fuel transition (from wood and charcoal to electricity), as could be seen in Figure 7.4a, while increase in household income (from US\$ 850 in 2010 to US\$ 1,600 in 2050) enabled households

<sup>11</sup>All the key scenario drivers were loosely based on GRZ (2006), see the scenarios description in section 5.3

<sup>12</sup>See section 5.1.1 of Chapter 5 for the current energy use patterns in Zambia.

<sup>13</sup>The household size was kept constant throughout the time horizon.

to acquire and use other electrical appliances (such as refrigerators and air-conditioners). The impact that increase in energy access and household income have on final energy use in the sector is shown in Figure 7.5.<sup>14</sup> Further, during this time horizon (2010-2050), it is projected that the use of charcoal and wood as a cooking and heating fuel would lead to a total loss of 52, 000 square kilometres of forest cover<sup>15,16</sup>. This translates to about 12% of Zambia’s total forest cover. The fuel transition in the sector and resultant deforestation is given in Figures 7.4a and 7.4b respectively below. From Figure 7.4 it can be seen that even though the share of electricity increases significantly, deforestation does not correspondingly reduce. This is because the share of charcoal increases; whose production process efficiency (from wood to charcoal) is about 40% (IEA, 2012) and technologies that consumed charcoal have an estimated efficiency of 24%.

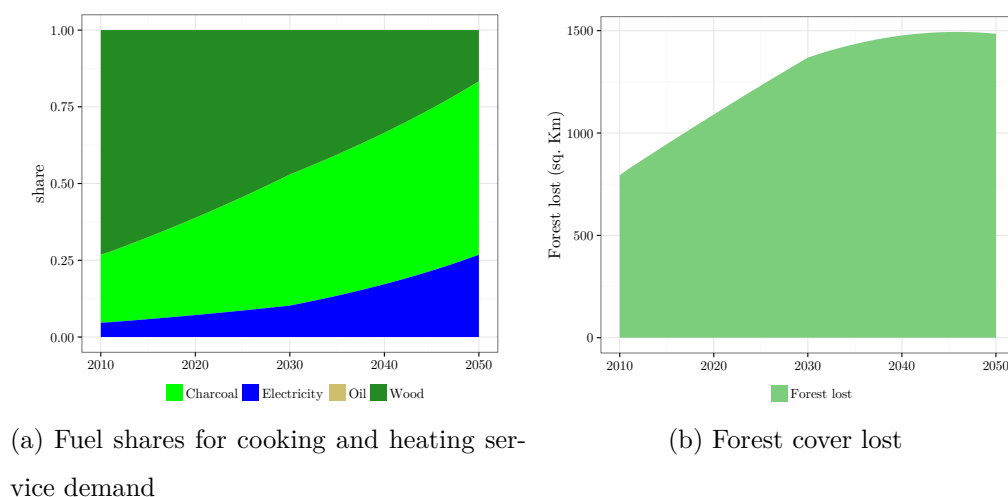


Figure 7.4: Fuel-switching and deforestation for Scenario 1

Changes in final energy demand patterns are given in Figure 7.5. From the figure, it can be seen that cooking and heating service continues to dominate final energy demand in the residential sector (i.e. the “Energy Use” graph). This is because of continued reliance on traditional fuels

<sup>14</sup>Both the impacts of increased access and household income on demand are described in the model structure assumptions, see section 5.1.1.

<sup>15</sup>Taking forest regeneration rate of 1% per annual, this regeneration rate is estimated based on Chidumayo (1991) and Hibajene and Kalumiana (2003).

<sup>16</sup>Using data from CSO (2007), it was estimated that one MJ (of energy) from wood leads to an equivalent of 0.5975 hectares of forest cover loss.

(wood and charcoal) as can be seen in Figure 7.4a above. In addition, the results (shown in the “Electricity Use” graph of Figure 7.5) suggests that as household income and energy access increase, energy demand for Other Uses would grow significantly and so would the total household electricity demand. It is therefore important that as the economy grows, so should investments in supply infrastructure, in order to avoid supply shortage.

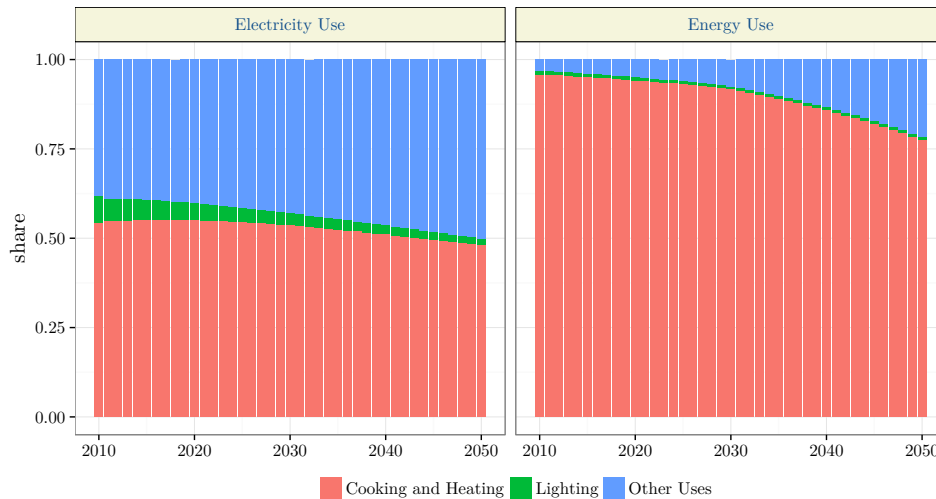


Figure 7.5: Residential final energy services demand for scenario 1

### Energy demand for scenarios 2 to 5

Table 7.1 below shows the relative total cumulative energy demand from the residential sector for scenarios 2 through 5 (relative to scenario 1).<sup>17</sup> The table also shows the relative levels of deforestation for each scenario. From the table, scenario 2 shows that increasing copper revenue<sup>18</sup> (assuming the constant copper price but increasing production) does not lead to significant increase in residential sector electricity demand. However, if there is a fuel transition in cooking and heating fuels to electricity, as shown in scenario 3<sup>19</sup> (where all households with access to electricity also use it for their cooking and heating service by 2050), an additional 177 PJ would need to be produced. The impact of increasing household income on electricity

<sup>17</sup>Residential energy demand projection for scenarios 2 - 5 can be seen in Figure E.4 of Appendix E.

<sup>18</sup>Which also has an impact on household income, through increase in GDP per capita – see section C.3 for linkage between household income and copper industry GDP.

<sup>19</sup>This scenario assumes same access rates as scenarios 1 and 2.

demand is given in scenario 4, while scenario 5 shows the impact that household income, access and fuel transition assumptions would have on residential final energy demand.

Table 7.1: Cumulative residential energy demand and deforestation over the time horizon relative to Scenario 1

	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Electricity (PJ)	10.62	176.92	759.31	1067.79
Gas (PJ)	0	0	643.98	0
Charcoal (PJ)	0	-321.27	-1101.77	-960.0
Wood (PJ)	0	-221.39	-965.35	-939.10
Total Energy Saved (PJ)	-10.62	365.74	663.84	831.29
Forest cover saved ( $km^2$ )	0	6307	21049	20489

The least deforestation occurs under scenario 4 (with only 31, 000 square kilometres of forest cover being lost), because of the 50% penetration of gas as a cooking and heating fuel by 2050. This scenario focused on understanding the impact that introduction of a new [clean energy](#) source would have on the electricity system and also on the mining sector. It takes into account a situation where a decision maker or the government wants to understand what it would take to achieve high electrification access (in this case, 100% urban and 70% rural) but with lower penetration of electricity as a cooking and heating fuel. One such situation would be high deployment of off-grid technologies (such as solar and mini-hydro technologies) to provide electricity for lighting and other uses services and yet increase access to clean cooking fuel which is not electricity, such as [LPG](#) and biogas. The down-side of the strategy (as in scenario 4) is that there would be considerable increase in energy import dependence (for [LPG](#) or biogas) since Zambia does not have local crude oil and gas resources. On the other hand, the upside of this would be reduced negative impact on the copper

industry (as discussed in section [7.2.3](#) below).

### **Uncertainty in electricity demand**

The aggregated mining energy demand for scenarios 1 - 5 (taking a constant copper price of US\$7, 000 per tonne) are given in Figure [7.6](#) below. Energy demand for scenario 1 reduces towards the end of the simulation as production from North-Western open pit becomes less profitable. Further, despite having the same expansion target, energy demand for scenarios 2 to 5 varies because of each scenario is exposed to a different energy price (price that is driven by both endogenous and exogenous activities to the mining sector). The reduction in diesel consumption (in scenarios 2 - 5) after 2040 was because production from North-Western open pit had significantly reduced. A discussion on the disaggregated behaviour of the mining model is given section [7.2](#) below.

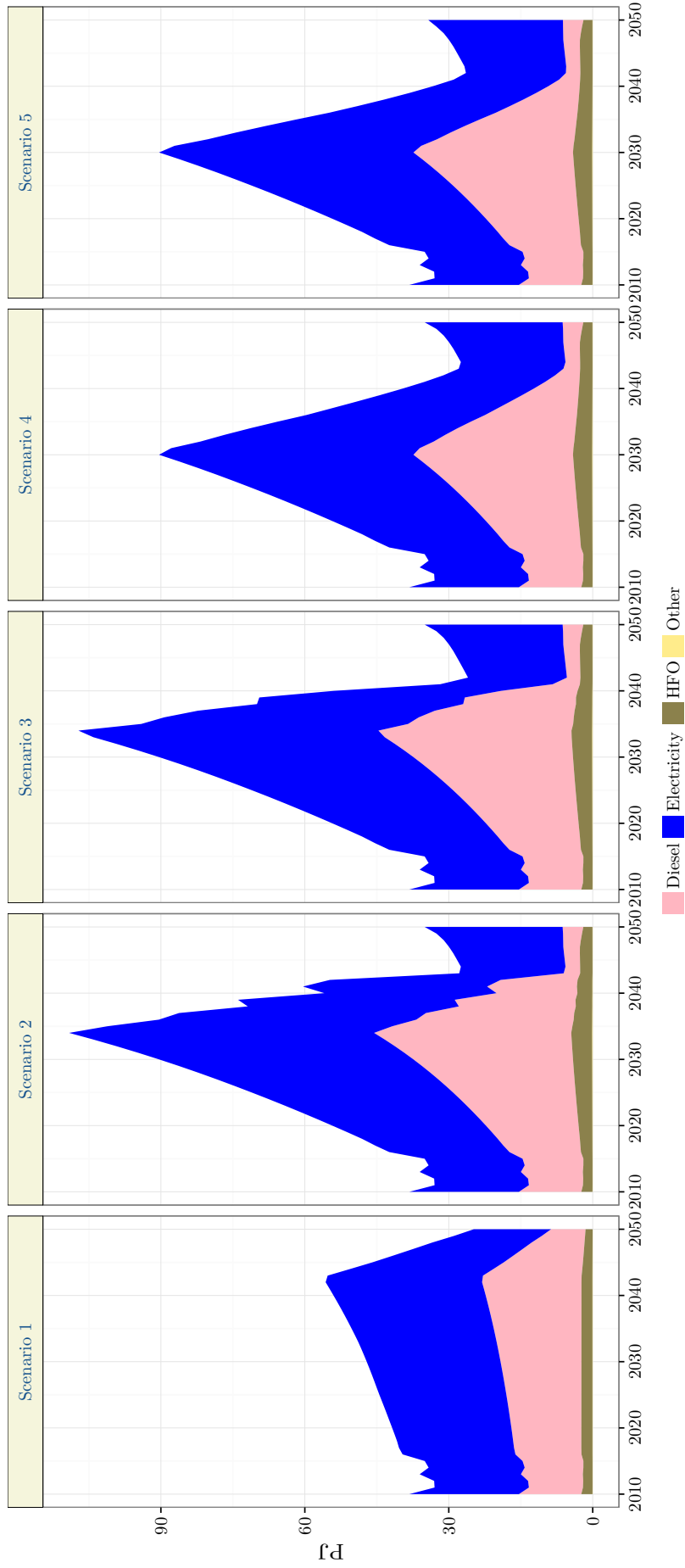


Figure 7.6: Mining energy demand projections (after iterations)

The difference between the maximum and minimum electricity demand for the residential and mining sectors is given in Figure 7.7 below. Depending on Zambia’s economic growth and government energy access targets, the outlook of the residential electricity demand could vary by over 50 PJ in 2050. This variance is about five times the variance of mining demand in 2050. However, because of the nature of production drivers in the mining sector, maximum variance in electricity demand (in the model) occurs as early as 2034; a variance of 35 PJ<sup>20</sup>. This variance is lower than the maximum variance in the residential sector. Therefore, analysing government’s residential energy-related policies (such as increasing access to [clean energy](#)) is essential because these policies could have a greater impact on the country’s energy system than increasing copper production. Besides, when government’s plans are considered as a whole ([GRZ, 2006; 2011; MOF, 2016](#)), increasing energy access has potential to limit economic growth of energy-intensive sectors (such as the mining sector<sup>21</sup>) because it would lead to higher energy prices and also increase competition for energy supply (from other sectors).

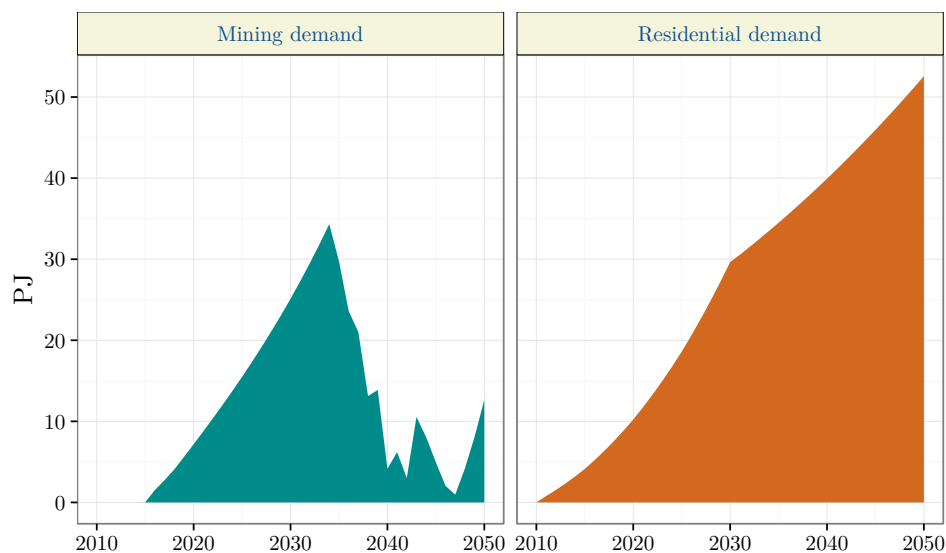


Figure 7.7: Electricity demand uncertainty in the residential and mining sectors

<sup>20</sup>This variance could be higher or lower if the price of copper increases or reduces respectively.

<sup>21</sup>The mining sector analysis is given in section [7.2.3](#) below.

### 7.1.2 Energy supply

This sub-section presents and discusses the results of the supply infrastructure that would be required to meet the electricity demand presented in section 7.1.1 above. It first gives the snapshot of estimated levelised cost of generating electricity (LCoE) using 2010 cost estimates (See section C.5 of Appendix C for the input data and section E.2 for the LCoE of grid-connected Solar PV with reducing capital investment cost.) for each of the potential (additional) technologies that could be used to meet the demand. It then presents the least cost results of the OSeMOSYS model and finally presents a trade-off analysis between electrification and deforestation.

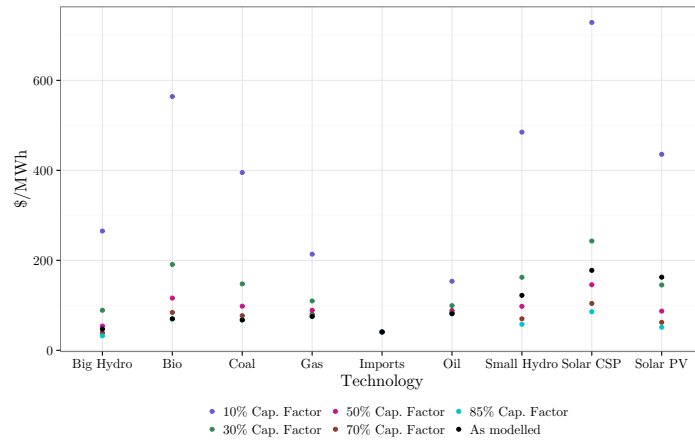
Figure 7.8 below shows the LCoE for different technologies. From Figure 7.8a it can be seen that all things kept constant, it could be cost effective to import electricity, use oil and gas plants to meet peak demand because of their lower LCoE at lower capacity factors. Importation of electricity would be ideal in a situation where the SAPP<sup>22</sup> grid is fully integrated and the price is constant. However, because of the limited available electricity on the SAPP regional market and with the projected increase in price, a better strategy would be to build oil and gas plants to serve as peaking plants, or better still, build more new large hydro plants and become a net exporter in the region. Building of hydro plants would be better on two fronts: it would reduce the total carbon emissions in the energy system and it would also enhance security of supply in the energy system (since Zambia relies on imports for its oil and gas needs)<sup>23</sup>.

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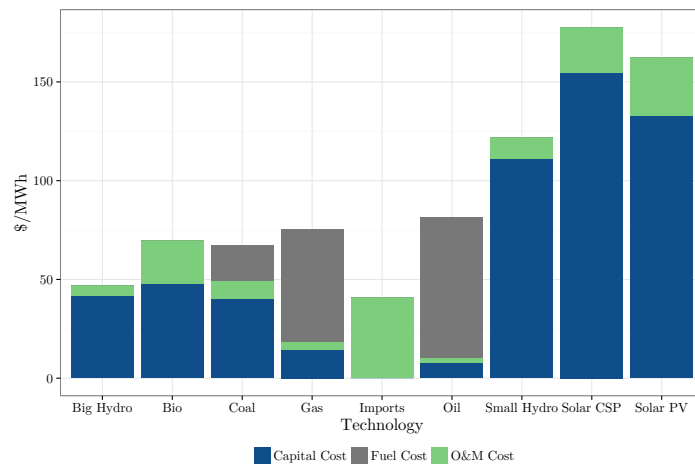
<sup>22</sup>Southern Africa Power Pool.

<sup>23</sup>This was also Barrett et al. (2008)'s argument that reduced share of oil and gas technologies in the energy mix help to minimise the impact of fuel price shocks on the energy system.





(a) LCoE at various plant capacity factors



(b) LCoE with capacity factors as in the model

Figure 7.8: Levelised cost of electricity (LCoE) for all potential supply technologies using 2010 cost estimates

Further, as can be seen in Figure 7.8b, electricity imports, oil and gas plants are more susceptible to price shocks. Thus, increasing the share of these options reduces security of supply. Furthermore, on the other hand, technologies such as hydro, bio, coal and solar require significant upfront investment costs. Development of these technologies would, therefore, be limited if the government has limited financial resources and/or has limited access to external infrastructure development funding.

The least cost optimal results<sup>24</sup> for all the five demand scenarios are presented below. Results for scenario 1 are discussed first then relative

<sup>24</sup>See section C.5 of Appendix C for the input data.

results (to scenario 1) are presented and discussed. These results consider the total developed capacity, the type of technology developed, production of electricity from each technology, average generation cost (LCoE) and the total carbon emissions.

Figure 7.9 shows the total supply capacity for scenario 1. The generation capacity development is projected to grow from 1,900 MW (in 2010) to 10,100 MW (in 2050). As expected (building up from Figure 7.8) the capacity development is dominated by hydro technologies because they have a lower LCoE. After all the hydro potential is exhausted, biomass technology is developed (to a maximum of 500 MW) thereafter, capacity development is dominated by coal technology. As a result, the carbon intensity of Zambia's electricity system is projected to increase to about  $300 \text{ gCO}_{2eq}/kWh$  by 2050, from  $4.25 \text{ gCO}_{2eq}/kWh$  in 2010. The total carbon emission during this time horizon is 145 Mt of  $CO_{2eq}$ .

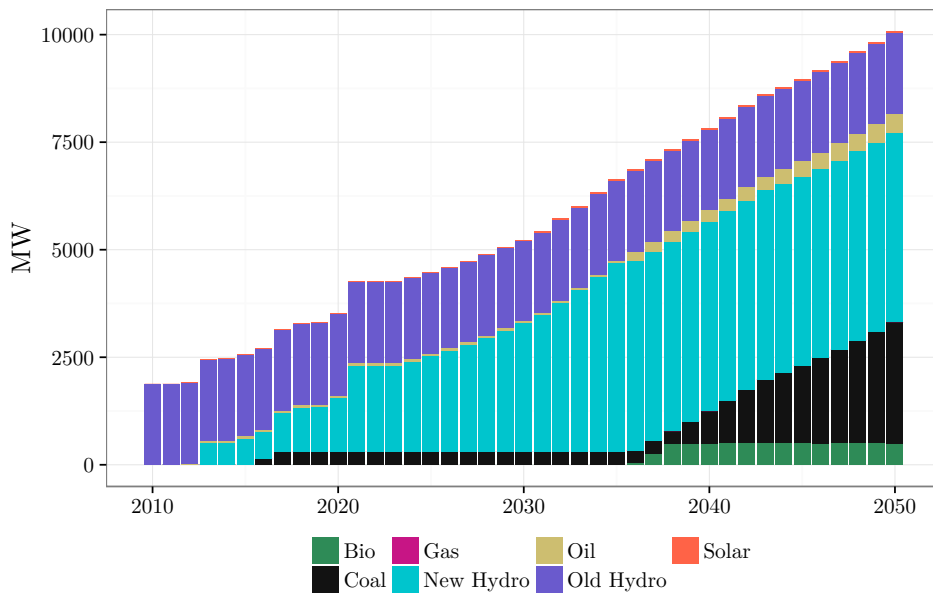


Figure 7.9: Least cost capacity mix for scenario 1

The required total capital investment cost for the scenario (over the time horizon) is US\$ 35 billion. This on average (per year) translates to 3.4% of Zambia's total GDP. The quantity of electricity generated by each technology has a similar profile as that of capacity development, with total production increasing from 12,000 GWh (in 2010) to 59,000 GWh (in 2050) as can be seen in Figure 7.10.

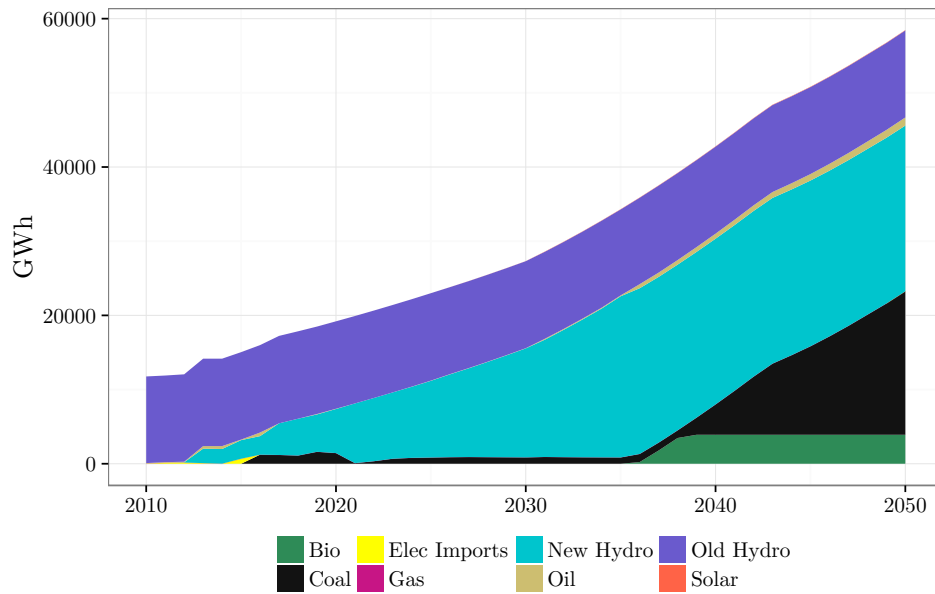


Figure 7.10: Total electricity generation by technology in scenario 1

Generation technology utilisation over the time horizon can be seen in Figure 7.11. Technology utilisation is defined as the quantity of electricity that a technology produces in a particular year divided by the maximum quantity of electricity that a technology could produce in a year, if ran throughout the year.<sup>25</sup> From the graph, it can be seen that even though oil technology capacity was developed, its utilisation rate was low. Further, despite having already installed capacity (of oil technology that is), it was desirable to build new capacity of bio and coal technologies. This proved cost effective because oil technology has high operating costs. The utilisation rate of solar was constant but on the low side, this is because solar has a low capacity factor and cannot be used to generate electricity after sunset.<sup>26</sup>

As explained above, the increasingly significant role that coal technology plays in electricity generation can also be seen in the figure. Coal technology utilisation rate increases from 39% (in 2038) to 82% (in 2050). This means that should the Zambian government adopt a zero emissions policy (or other carbon emission reduction related policies), development of coal, oil

<sup>25</sup>Estimated monthly electricity production output profiles from three of Zambia's largest hydro power plants can be seen in Figure E.5 of Appendix E.

<sup>26</sup>The participation and role of RE technologies (such as solar) is likely to change depending on the developments in energy storage technologies, see Spataru et al. (2015) for a discussion.

and gas technologies could be affected. Thus, considering the available technologies in the energy system, Zambia could only have solar technology and electricity importation as options for covering its supply deficit. This is because both the available hydro and biomass technologies potential could have been fully developed.

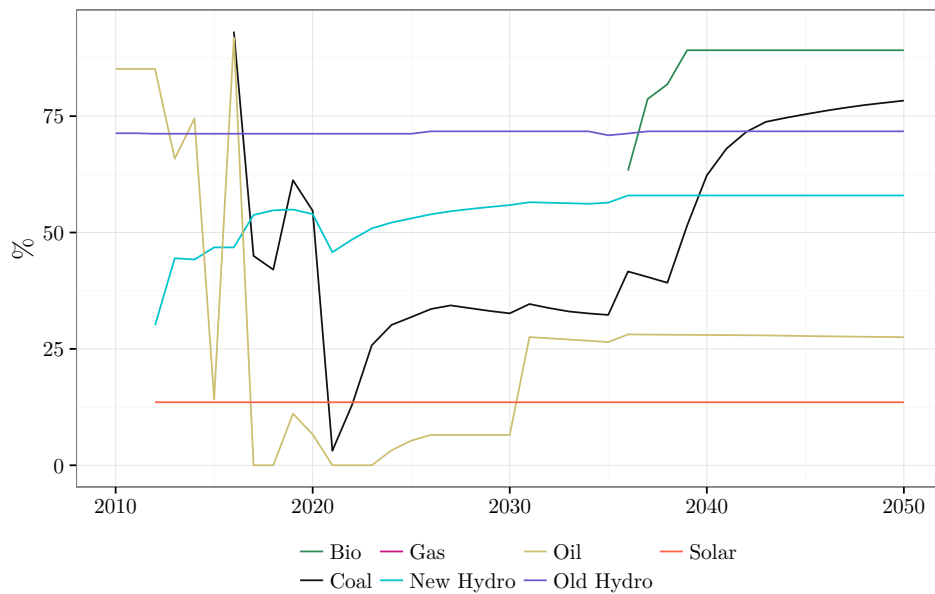


Figure 7.11: Technology utilisation in scenario 1

The stacked system costs (capital and operating<sup>27</sup> costs) and the average generation cost are given Figure 7.12. The average generation cost increase from US\$ 4/MWh<sup>28</sup> (in 2010) to US\$ 29/MWh (in 2050). From the graph, it can be seen that increased share of operating costs tends to lead to increase in generating cost. This increase in operating costs is largely driven by the increase in fuel costs as can be seen from Figure 7.11 where sharp increase in generation costs coincide with increases in utilisation rates of oil and coal technologies. Furthermore, the generation cost is fairly flat between 2020 and 2035, this is because electricity production was dominated by hydro technologies (which have high capital cost but low operating costs, as can be seen in Figure 7.8).

<sup>27</sup>Operating costs in this graph include fuel and O&M costs.

<sup>28</sup>See section A.1.1 of Appendix A for a brief description of the energy market in Zambia. Basically, this LCoE of US\$4/MWh above does not include the capital cost of the current generating stock (as of 2010) because it is almost fully amortised – having been built in the 1960s and 1970s.

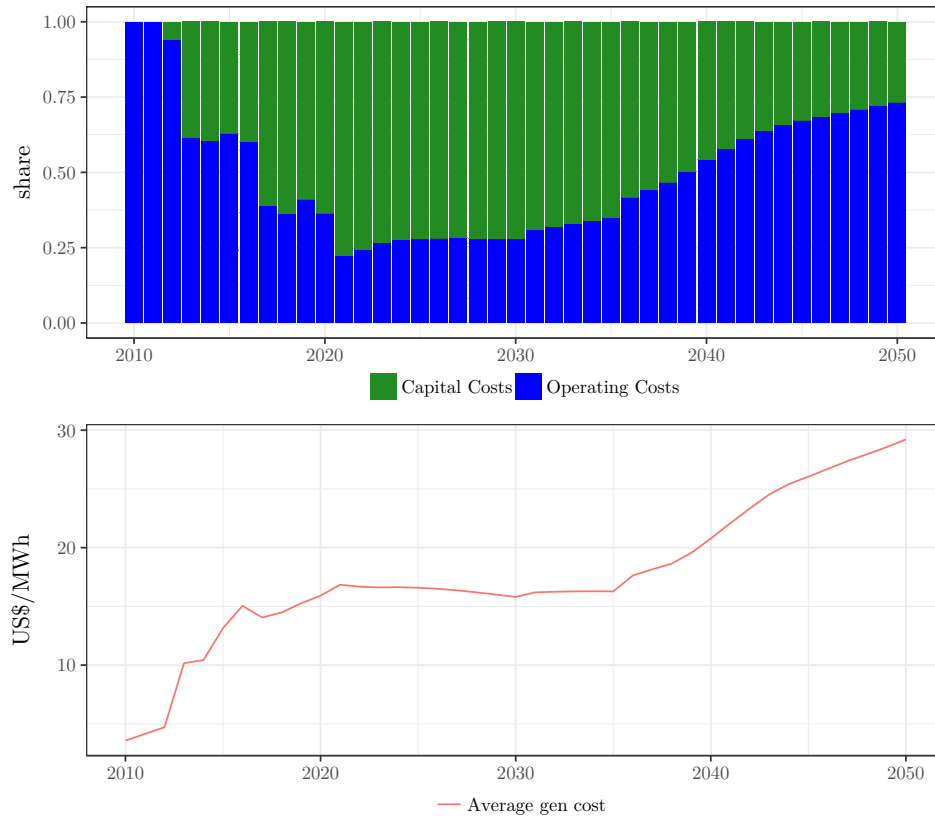


Figure 7.12: System costs and average generating cost in scenario 1

Figure 7.13 displays the changes in least cost generation capacity (of scenario 1) that would be required to meet demand in scenarios 2 to 5. By 2050, it is projected that capacity of 500 MW would be added in scenario 2 (which considers the impact that increasing copper production would have on electricity demand). Capacity development in this scenario is largely dominated by early development of hydro, bio and coal technologies (though coal technology development is de-emphasised in the early to mid-2040s), like in all other later scenarios. An additional capacity of 1, 400 MW would be needed in scenarios 3 (relative to scenario 1). This increase in capacity of 900 MW relative to scenario 2 is solely as a result of fuel switching, increasing the share of households using electricity for their cooking and heating service from 75% to 100% (among households with access to electricity) by 2050. This shows the significant impact that achieving access to [clean energy](#) would have on the energy system, the electricity system in particular.

The impact of economic growth and increase in access to electricity

(with reduced number of households using electricity for their cooking and heating service) is given in scenario 4. An additional capacity of 3, 050 MW would be required (relative to scenario 1). However, the significance of increasing the number of households using electricity for their cooking and heating under high rates of access to electricity is emphasised in a comparison between scenarios 4 and 5. An additional 2, 950 MW (relative to scenario 4) would be required by 2050 to meet cooking and heating service demand under high electricity access rate. Therefore, increasing access to electricity at the same time as increasing the share of households using electricity for their cooking and heating service would prove to be a significant investment challenge.

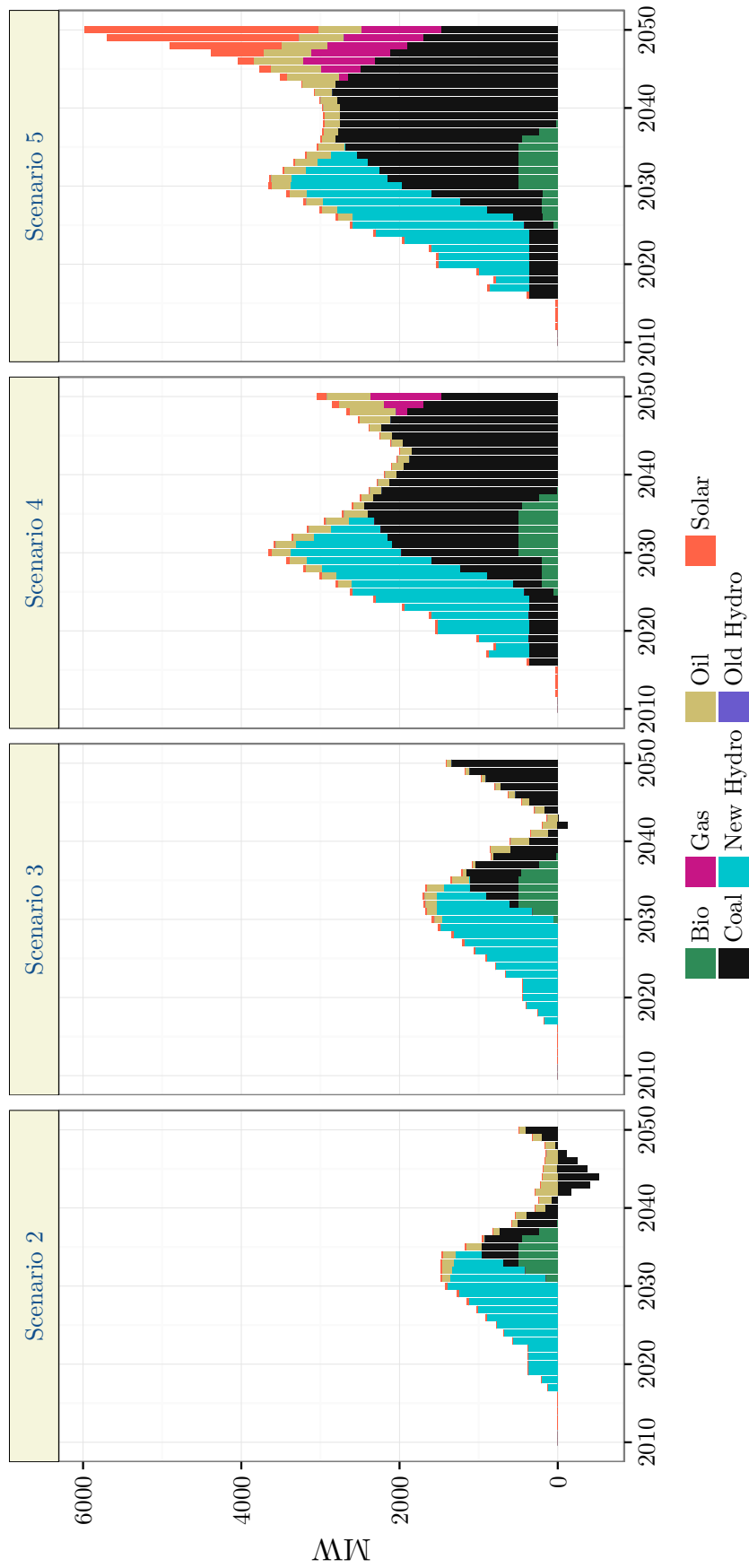


Figure 7.13: Relative additional capacity for least cost capacity mix in scenarios 2 to 5

Furthermore, it can be seen from Figure 7.13 that the quantity of available potential (in MW) and the timing of when it can be exploited, significantly impacts the outlook of capacity development. For instance, although biomass technology is more cost effective than coal technology, coal capacity was built before biomass technology. This is because biomass technology was scheduled to be available much later, in 2020, while coal was available in 2016. Apart from the timing of when a technology would be available, the size of what capacity could be exploited is also important. This means that a detailed energy resource assessment for Zambia would be essential in order to effectively plan developments in the energy system.

From both Figures 7.9 and 7.13 solar technology development are low and only come (significantly) into the mix after all the other available resources have been exploited (as is the case in scenario 5).<sup>29</sup> This shows the challenge that deployment of solar technology would have in Zambia when technology investments are only evaluated based on techno-economic dimension. This is so because Zambia has many other cheaper options for capacity development. See section 7.1.3 for the impact that technology learning would have on solar technology deployment and section E.2 for a LCoE analysis of why there is limited diffusion of Solar PV in Zambia's energy system.

Finally, total additional capital investment costs (relative to scenario 1) that would be required to develop capacity for scenarios 2, 3, 4 and 5 are US\$ 4.5 billion, US\$ 7.5 billion, US\$ 21.8 billion and US\$ 24.7 billion respectively. The impact of this on the average generation cost, among others, is shown in Figure 7.14.

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<sup>29</sup>Section E.2 gives a LCoE analysis that shows that despite the projected reduction in capital investment cost of electricity in Solar PV, diffusion of grid-connected solar would still be limited.



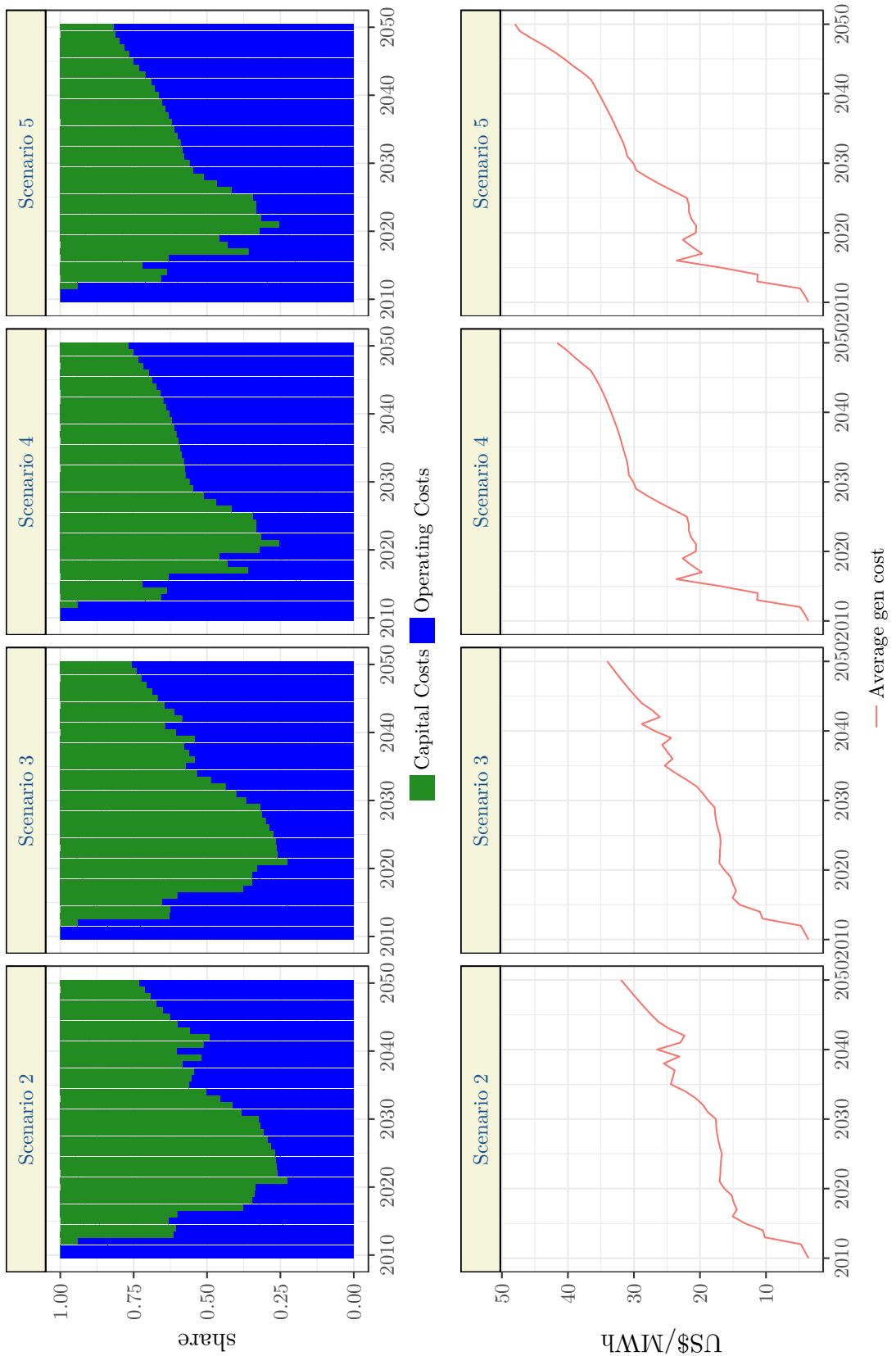


Figure 7.14: System costs and average generating cost in scenarios 2 to 5

Figure 7.15 shows technology utilisation in scenarios 2 to 5. A utilisation rate that decreases over times (for instance, the behaviour of the oil technology in all the graphs) implies that it is more expensive to produce from that particular technology than to develop capacity for another technology and operate it. An example of this, is the development and utilisation of gas technology in scenario 4 over already existing oil technology. The total associated carbon emissions due to the utilisation of these technologies for scenarios 2, 3, 4 and 5 are 172 Mt, 221 Mt, 469 Mt and 557 Mt of  $CO_{2eq}$  respectively.

In Figures 7.14 and 7.15 it can be seen that the average generation costs tend to be higher when technology utilisation rates for coal, oil and gas technologies and also when the share of operating costs are high. The average generation cost in 2050 vary from 9.4% (US\$ 2.74/MWh) to 64.4% (US\$ 18.80/MWh) relative to that of scenario 1. Similarly, both total generation capacity and total electricity production<sup>30</sup> in 2050 vary from 5.0% to 59.3% and 6.7% to 57.0% respectively to that of scenario 1.

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<sup>30</sup>See Figure E.6 of Appendix E shows the electricity production.

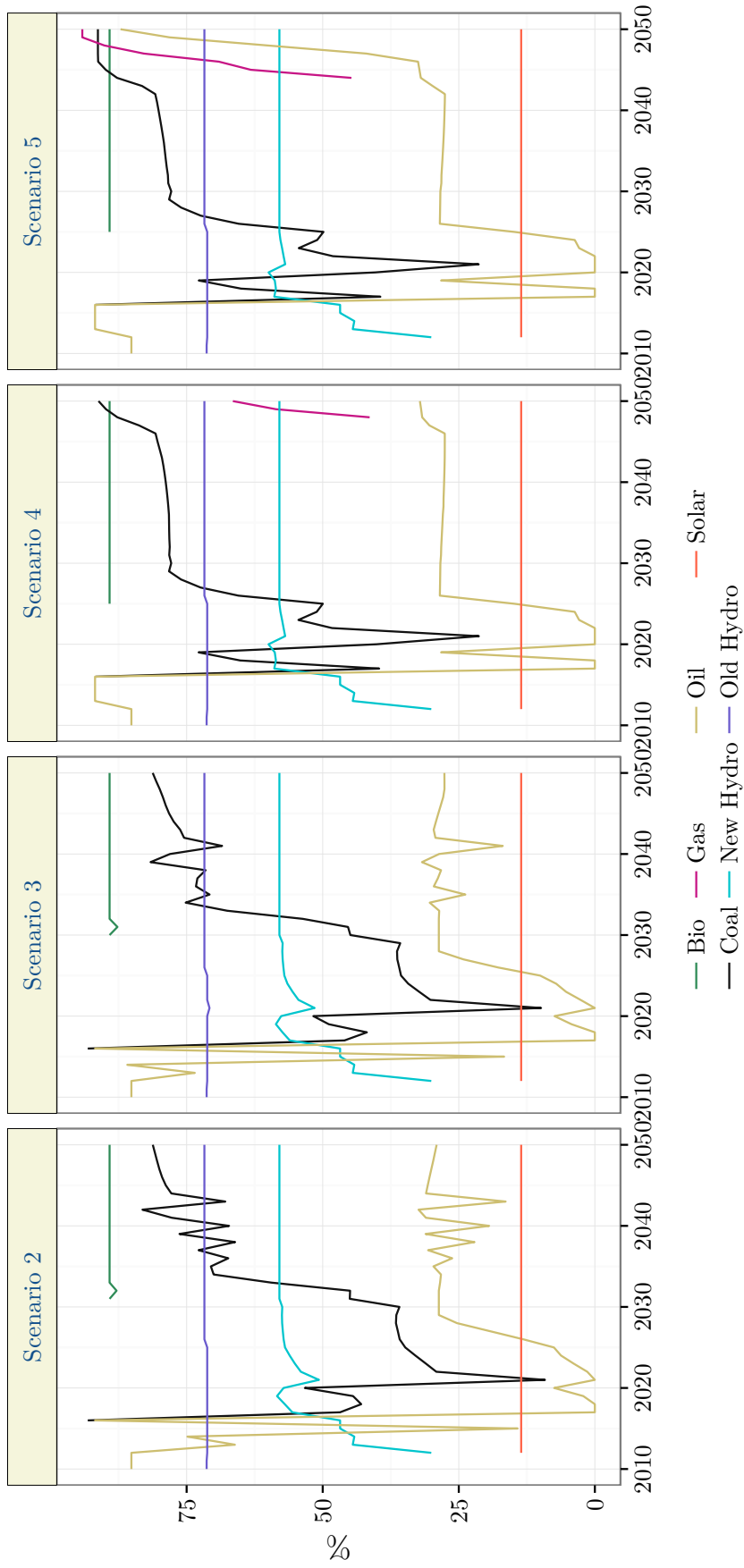


Figure 7.15: Technology utilisation in scenarios 2 to 5

### Deforestation vs electrification trade-off analysis

A trade-off analysis on costs and benefits of conserving forests for carbon storage and sequestration, as framed in the REDD+ initiative, was done.<sup>31</sup> The analysis<sup>32</sup> compares the estimated values of revenue that Zambia would get by avoiding deforestation and the costs that Zambia would incur in order to electrify its population (thereby avoiding deforestation through usage of electricity for cooking and heating service instead of traditional fuels)<sup>33</sup>. The revenue that would be realised by avoiding deforestation is a product of  $tCO_{2eq}$  stored in the forest per hectare and the opportunity cost (US\$ per  $tCO_{2eq}$ ), while the value of costs incurred is a quotient of total system costs incurred in order to electrify households (US\$) and forest cover saved as a results of electrification (in hectares).

Using the estimates from Zambia's forest carbon storage and unit opportunity costs, realised revenue ranges from US\$ 62 to US\$ 5, 100 per hectare.<sup>34</sup> Whereas considering the difference in the increase in total system costs and the saved forest cover between scenarios 2 and 3<sup>35</sup> gives a minimum unit cost of US\$ 6, 800 per hectare. Therefore, from this analysis, it would not make financial sense for Zambia to avoid deforestation by increasing access to electricity for cooking and heating service.<sup>36</sup> However, because this analysis is sensitive to both the opportunity cost (US\$ per  $tCO_{2eq}$ ) and energy systems costs, a thorough analysis would be required before a firm policy recommendation could be made.

#### 7.1.3 Sensitivity analysis on the supply model

The sensitivity analysis sought to identify factors that have the largest impact on total investment capital cost, average generation cost, solar capacity development and carbon emissions over the time horizon. The reference

<sup>31</sup>See section 5.2 above.

<sup>32</sup>Data used in the analysis can be found in section E.1 of Appendix E.

<sup>33</sup>See Cacho et al. (2014); Damnyag et al. (2011); Kalaba et al. (2013); Lupala et al. (2014); Summers et al. (2015) for similar analyses.

<sup>34</sup>The value is sensitivity to the value of the opportunity cost.

<sup>35</sup>Find the description in section 5.3 above.

<sup>36</sup>If the only purpose of increasing access is to reduce the rate of deforestation.

case (REF) that was used has the same data has demand scenario 1. All the scenarios (given on left of Figures 7.16, 7.17, 7.18 and 7.19) and their data details used in the sensitivity analyses are given in section C.6 below.

Figure 7.16 shows the impact that various factors have on total investment capital cost relative to the reference case scenario. The relative impact was calculated using the difference between a particular scenario's value (on the left side of the figure) and the reference case value divided by the reference case value. From the figure, it can be seen that electricity demand followed by capital cost and discount rate have the biggest impact on investment capital cost.

A disaggregated analysis of demand shows that residential and mining demands are the most significant demands. This means that it is essential to carefully quantify future demand as it is the most important driver of total investment capital of the system. Further, in spite of a significant reduction in solar technology investment cost globally (due to technology learning, which is captured under the Tech. Learning RE Cost scenario), there was no significant reduction in total capital cost. This could be because of low solar technology deployment in the energy system (of about 8%).<sup>37</sup> This, therefore, implies that the arguments that claim that as technology's capital cost reduce (due to technology learning), countries that invest more of solar technology (and other renewable energy technologies) would have significantly lower capital expenditure requirements do not hold in certain contexts (such as the Zambian context). This is because there would be better options for reducing capital expenditure requirements such as reducing energy demand. In the Zambian context, reducing energy demand (by 10%) could offset over 13% of the required investment capital whereas reducing investment capital cost of solar technology by 62% (between 2010 and 2050) only offsets about 2% of required investment capital. Furthermore, this also means that more uncertainty in projected energy demand would lead to more uncertainty in estimating the required capital investment.

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<sup>37</sup>As was observed by Barrett and Spataru (2013), the potential role of any technology needs to be analysed within a context of the whole energy system.

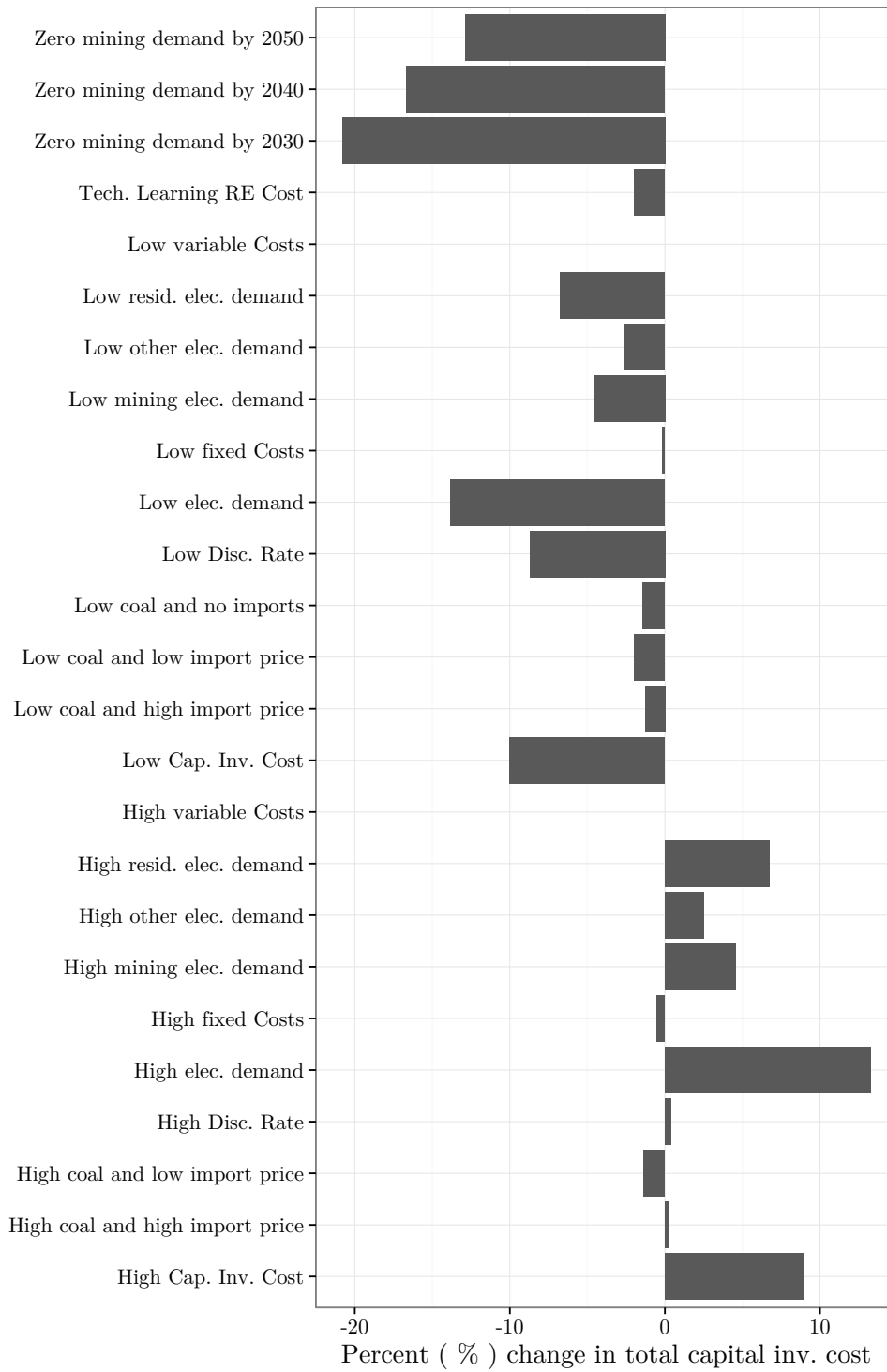


Figure 7.16: Effects on total capital investment relative to the REF case

Figure 7.17 presents the impact that various factors have on the average generation cost relative to the reference case scenario. It can be seen that average generation cost is mainly driven by the discount rate (a variance of over 30%) followed by capital investment cost (7% variance) and energy demand (6.5% variance). Whereas technology learning did not have a significant impact on the system's total investment capital requirement <sup>38</sup> (see Figure 7.16), it had a considerable effect on reducing the average generation cost of the system (reduced it by about 4.8%). In addition, adopting a policy<sup>39</sup> that limits electricity production from coal technology would have a noticeable impact on the average generation cost (ranging from 2.8% to 4.5%).

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<sup>38</sup>Section E.2 gives a LCoE analysis that shows that despite the projected reduction in capital investment cost of electricity in Solar PV, diffusion of grid-connected solar would still be limited.

<sup>39</sup>Such as local coal and no imports, local coal and low import price and local coal and high import price scenarios.

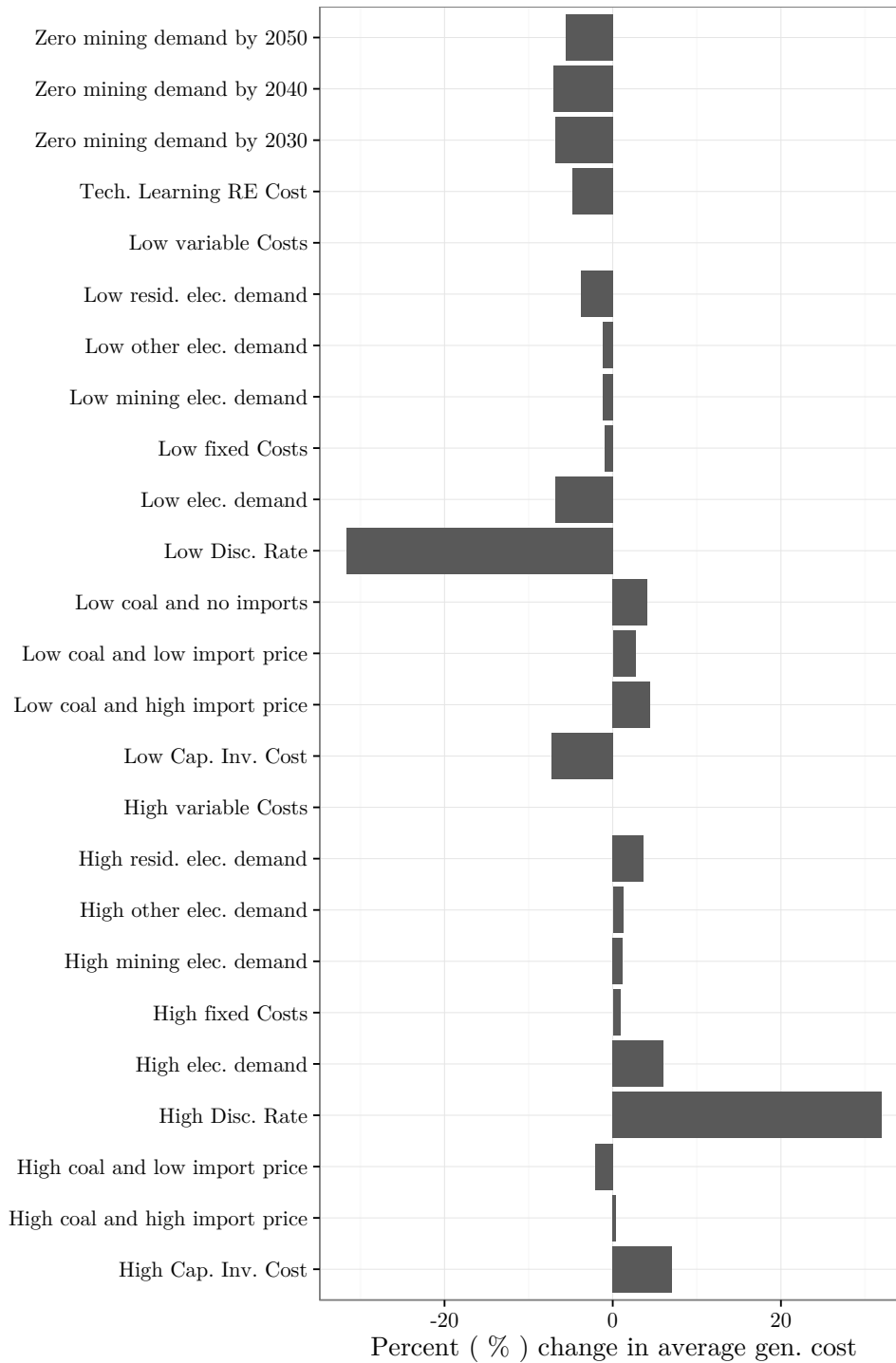


Figure 7.17: Effects on average generation cost relative to the REF case

Figure 7.18 displays the impact that various factors have on solar deployment relative to the reference case scenario. As anticipated, the drivers for increased solar deployment into the energy system are technology learning (reducing investment capital cost) followed by low production from coal



technology and restricted importation scenarios<sup>40</sup> and low discount rate. On the contrary, increasing production from coal technology, low electricity import price and low energy demand do not incentivise deployment of more solar technologies.

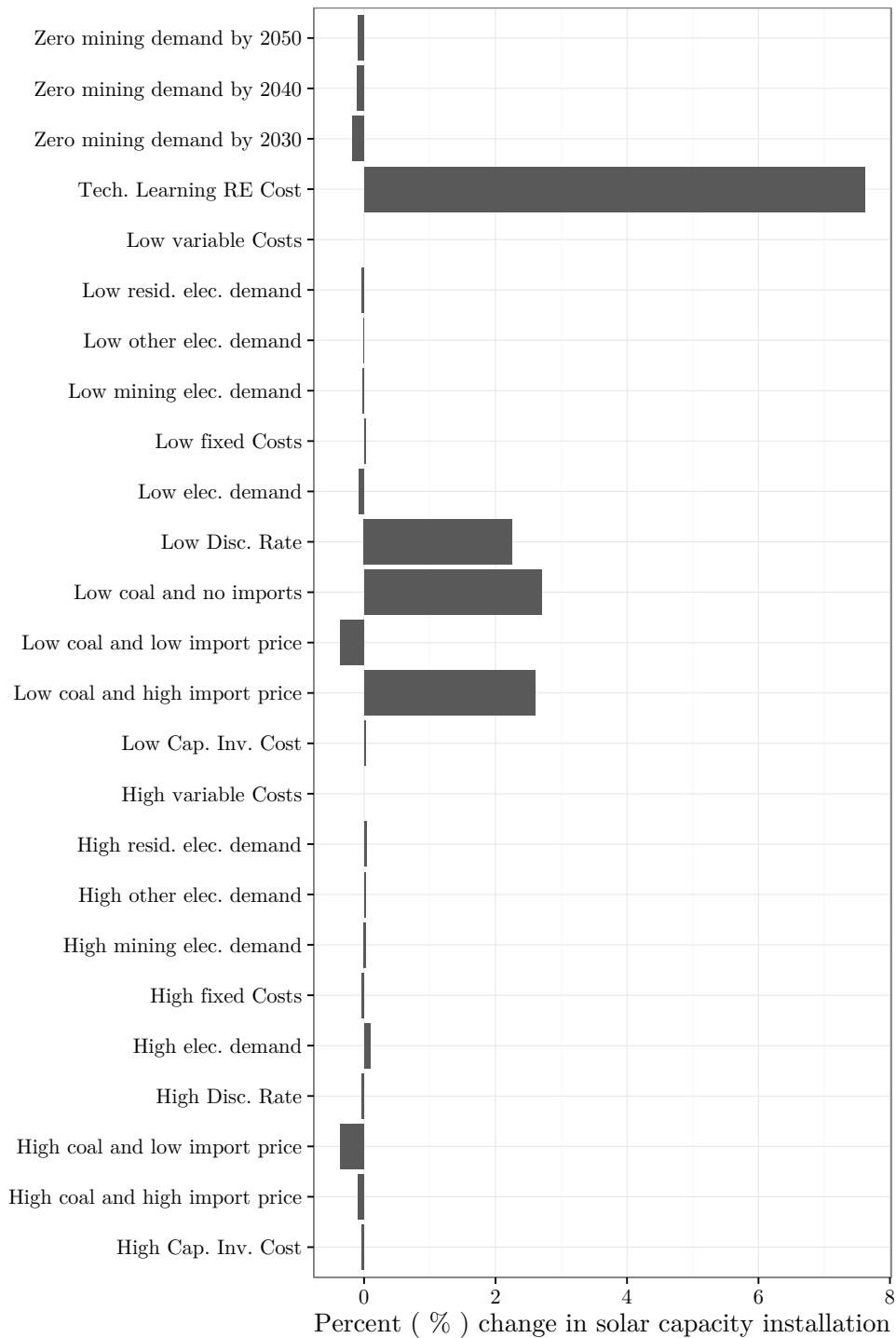


Figure 7.18: Effects on solar capacity deployment relative to the REF case

<sup>40</sup>Namely low coal and no imports and low coal and high import price scenarios.

Figure 7.19 gives the impact that various factors have on total carbon emissions relative to the reference case scenario. It can be seen that the easiest way to reduce carbon emissions from Zambia's electricity system is by importing electricity. However, the largest exporter of electricity in the SAPP regional market is South Africa, whose electricity production is dominated by coal technology. For that reason, using imported electricity to reduce emissions would not be the best option. Besides that, there is a shortage of electricity in the SAPP region. There are, therefore, three other ways to reduce carbon emissions: reducing demand, limit production from coal technology and deploy more solar technology (as the investment capital cost reduces). Conversely, increasing energy demand increases carbon emissions.

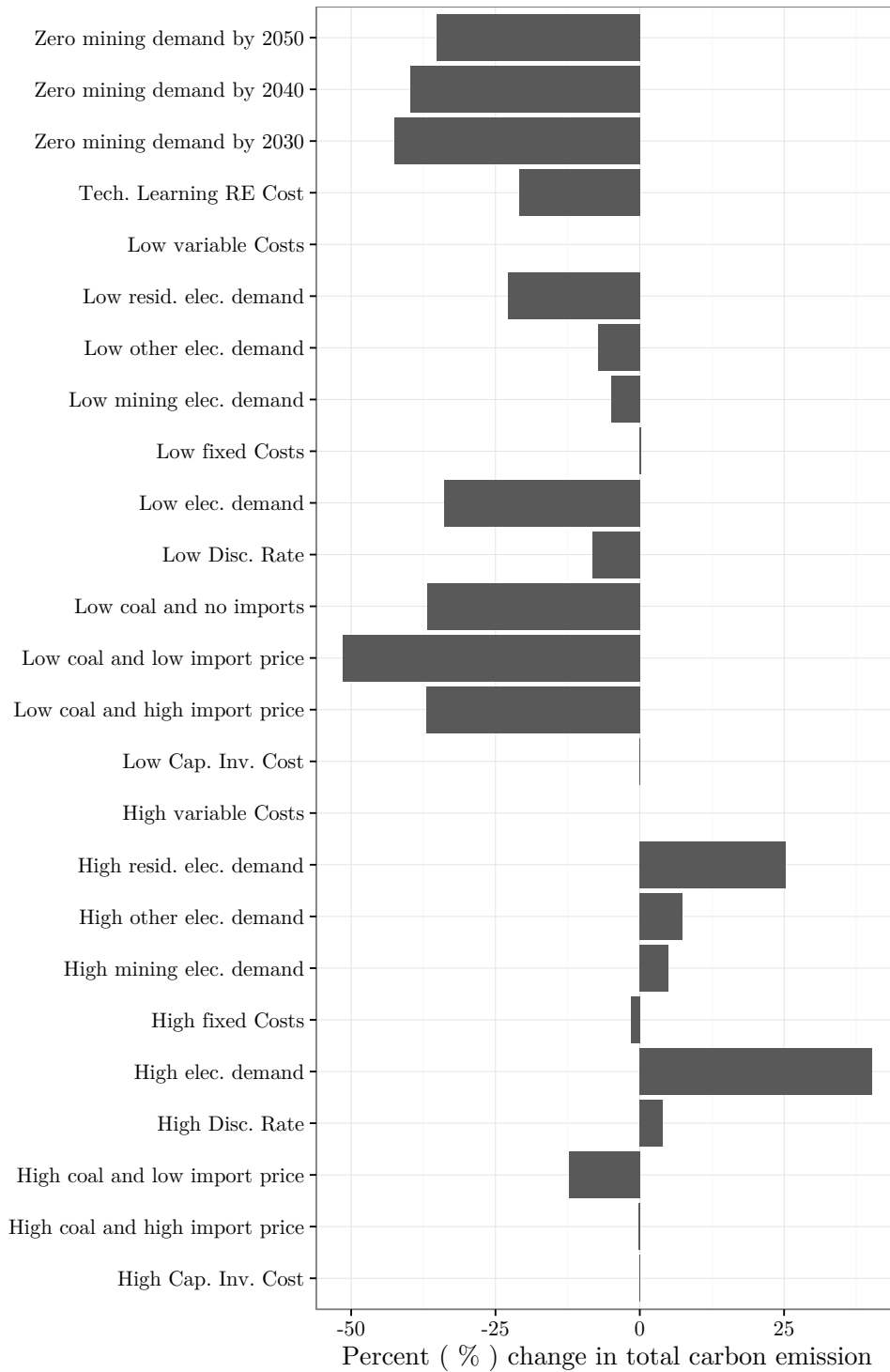


Figure 7.19: Effects on total carbon emissions relative to the REF case

In summary, energy demand is the most significant factor in the supply model. This is followed by discount rate and state of coal technology participation (to produce or not) in the energy system. The impact of energy demand (in planning energy systems) is also confirmed in literature

by Rosnes and Vennemo (2012). This (impact of demand on supply model) emphasises the importance of using appropriate methods when estimating future energy demand, which was done in this research. Further, some of the results presented in this sub-section seem trivial and obvious, but for completeness, it is important that these results are presented.

## 7.2 Mining model results

Having looked at how Zambia's energy system could evolve in the above section and considered how mining firms make decisions in Zambia, this section sought to address the research question: What impact does increasing access to clean energy have on mining sector's profitability? Further, building on from the research findings above, this section also provides an analysis which helps to identify decision variables that are most significant in Zambia's mining industry (based on the mining model). The methods used to develop and analyse the model are described in Chapter 6.

### 7.2.1 Indicative production scenarios

In this sub-section, the discussion focuses on a range of possible (from 1200 simulation runs) copper production outputs (based on copper production growth rates), selection of outputs to focus on for further analysis and describes how electricity prices to use in the mining model were estimated. The initial simulated production outputs consider different industry's production capacity growth rates<sup>41</sup>, the uncertainty in ore grade, available ore resources and copper price. It assumes that mineral royalty tax, energy prices and all other inputs remain constant. This stylised approach was used in order to establish the possible extremes of copper production at industry level, particularly the maximum production output. It was important to establish the technically feasible maximum production output, as this production statistic was useful for estimating maximum energy

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<sup>41</sup>Capacity expansion was done independently at firm level, in this case, NW-OP, CB-OP and CB-UG level, see section 7.2.5 for a detailed description.

demand from the industry. As discussed in section 7.1.3 above, energy demand significantly influences the energy system's total investment cost, carbon emissions and energy price. In section 7.1.1, I briefly discussed how mining energy demand was estimated. Those copper production outputs (based on the maximum growth rates of production capacity) used in that section (maintaining, increasing and high production outputs) were picked from a range of possible production outputs, as is shown in Figure 7.20.

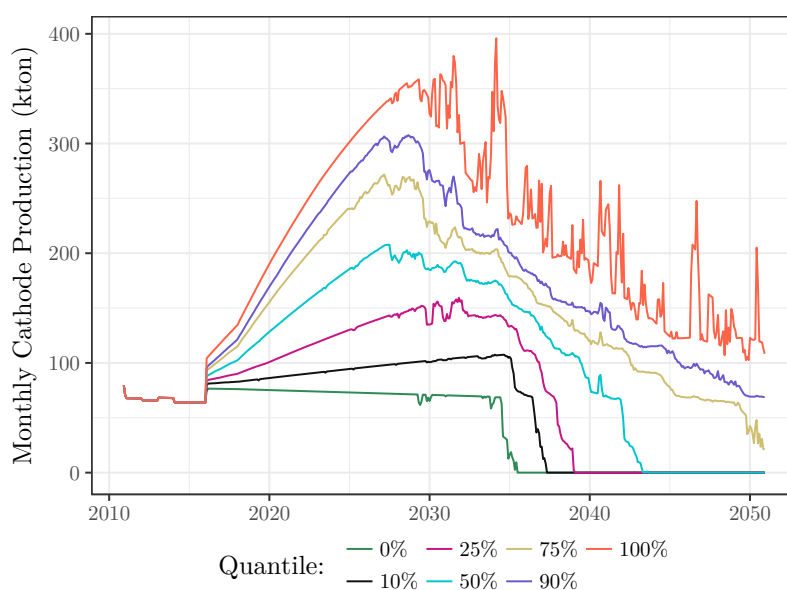


Figure 7.20: Range of possible copper cathode production scenarios

After establishing the possible production outputs (given in Figure 7.20), three copper capacity production growth rates<sup>42</sup> and their corresponding energy demands (shown in Figure 7.22) were selected, with energy demand used as initial inputs into the OSeMOSYS model (as explained on page 188 above). The selected capacity production growth rates representing maximum possible production output<sup>43</sup> under maintaining, increasing (double) and high outputs are shown in Figure 7.21 below.<sup>44</sup> These three growth rates were used to sketch out how the industry's production behaviour would change over time and were also used to estimate the initial energy demand (which were energy inputs of the OSeMOSYS model). The

<sup>42</sup>Representing maximum possible production output under maintaining, increasing (double) and high outputs.

<sup>43</sup>Note that the actual production output is endogenously determined in the SD model.

<sup>44</sup>See section 5.3 above for the detailed description of the scenarios.

capacity production (maximum) growth rate of 0.25% per month (i.e. under the maintaining production regime) captures a system that maintains production at 2010's industry level, of 80, 000 tonnes of copper per month. Under the increasing production regime (with a maximum capacity growth rate of 0.55% per month.), copper production increases to a maximum of 160, 000 tonnes per month by 2038 then decreases to an average of 90, 000 tonnes per month thereafter. This decrease is driven by the reduction in [ore grade](#) which led to increase in production costs and made some production activities infeasible (activities at the North-Western province site).

The high production regime (with a maximum capacity growth rate of 2% per month.) captures a fast industry growth scenario (doubling copper production capacity every three years). The high production regime is extreme (and unrealistic); which is used here to illustrate that Zambia has limited resource from which to produce (the industry cannot keep growing forever even under the best investment environment). From Figures 7.21 and 7.22, it can be seen that increased production leads to increased energy demand and also early closure of mining sites. The sub-sections below gives details of system behaviour of these scenarios at a disaggregated level (by mining group sites).

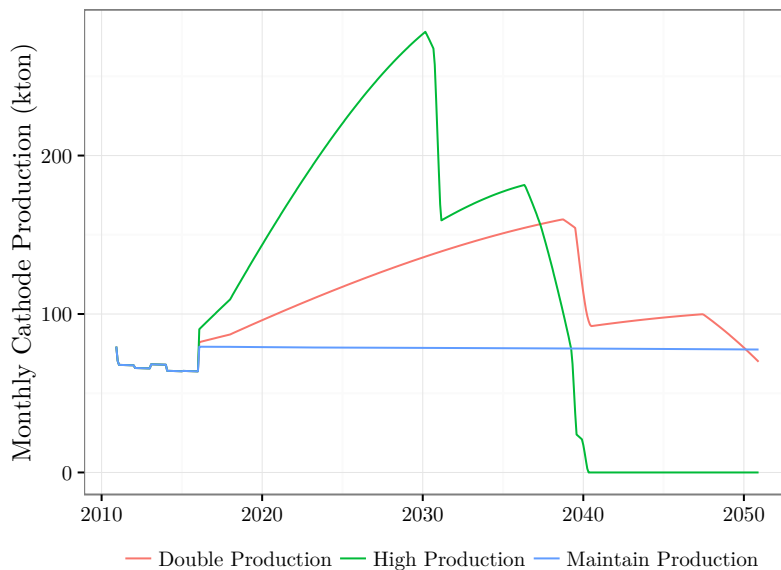


Figure 7.21: Selected copper cathode prod. regimes (before iterations)

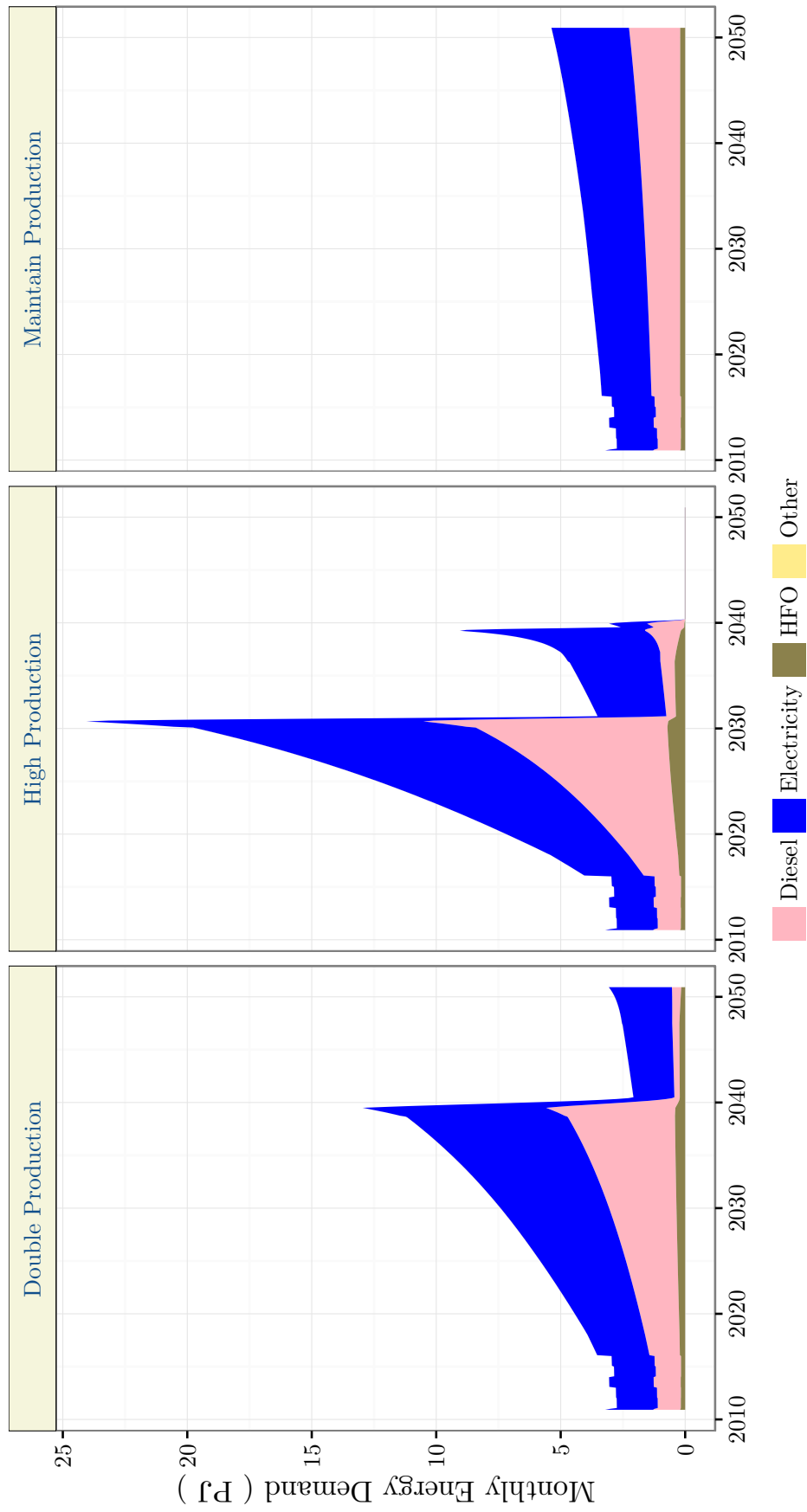


Figure 7.22: Initial energy demand for selected prod. regimes (before iterations)

The OSeMOSYS model was then run with these initial energy demands in order to estimate the electricity price (via average generation cost) for each of the production regime. The SD model (mining model) was then run with the newly estimated electricity prices for each of the five energy scenarios. Maintaining production regime has one energy scenario (scenario 1) while increasing production regime had four energy scenarios (scenarios 2 to 5), as described in section 5.3 above. The high production regime was used to estimate the first back-stop energy price<sup>45</sup> (this production regime was however not included in the iteration process).<sup>46</sup> The iteration process between the OSeMOSYS model (for energy prices) and SD model (for energy demands) was repeated until the model output converged (i.e. no change in energy demand and price between iterations). Figure 7.23 below shows the annual average electricity generation cost and electricity demand for all the five demand scenarios for selected iterations runs.<sup>47</sup>

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<sup>45</sup>The second back-stop energy price assumes a production regime higher than that of high production regime – thus it is higher than the first back-stop price. It is calculated by multiplying the first back-stop price by a factor.

<sup>46</sup>See Figure E.2 for mining production outputs of the initial (under constant energy prices) and final iterations for each scenario.

<sup>47</sup>See Figure E.1 for the mining sector energy demand (by fuels) of the final iterations.



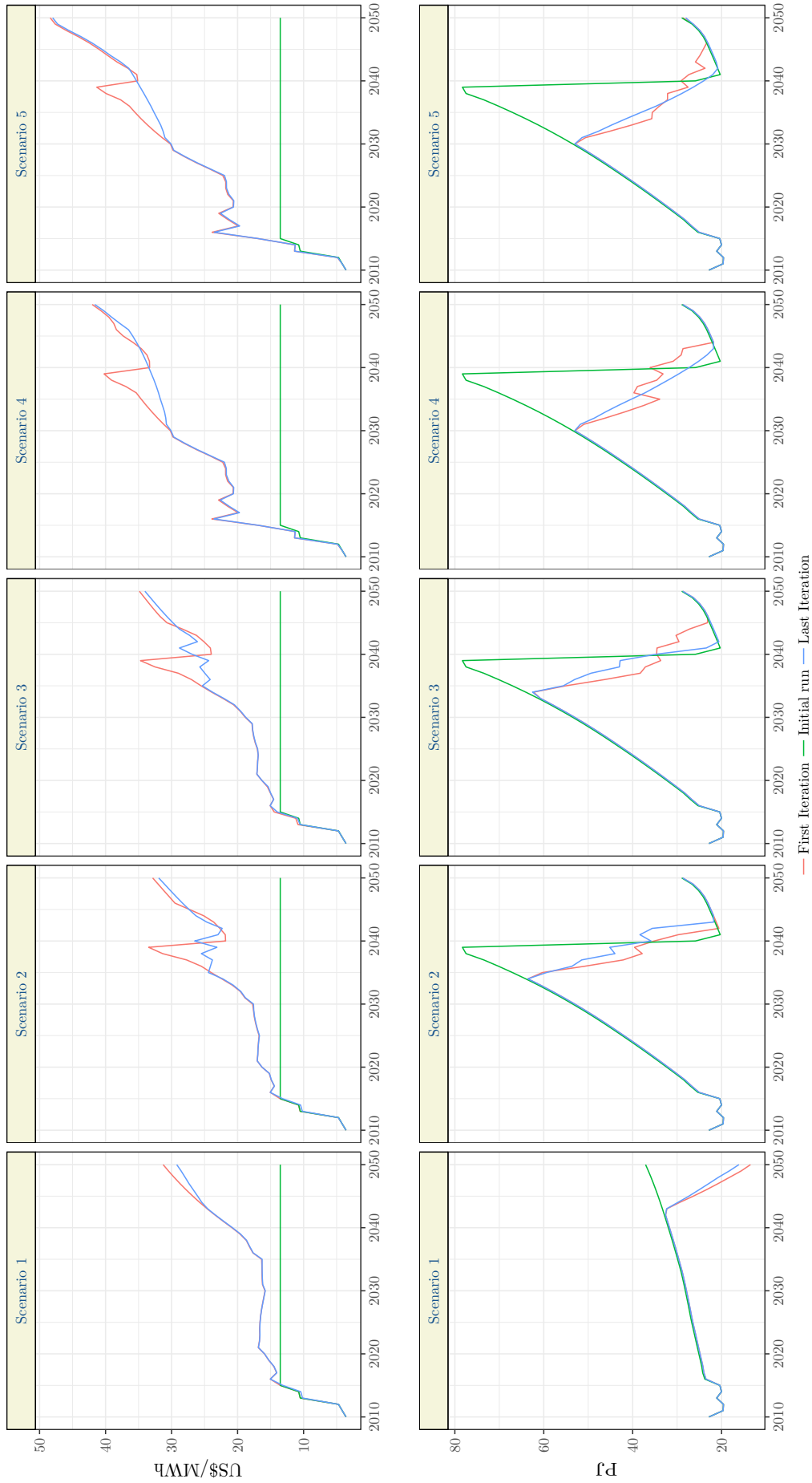


Figure 7.23: Average generation cost and electricity demand for selected iterations

The electricity prices were estimated by relating the known electricity prices<sup>48</sup>, from 2010 to 2015, and the estimated average generation cost (from the model) for the same period. Then by keeping this relationship constant, the future price was estimated based on the profile of the generation costs for each energy demand scenario. This approach was used because there was no solid analytic basis of understanding how electricity prices in Zambia are estimated. This is because electricity price in Zambia is a negotiated price (through the regulator<sup>49</sup>), not a cost reflective price. Thus, using a marginal cost approach would grossly over-estimate the price. Detailed results (after the models had converged) of the energy model are given in section 7.1 above.

## 7.2.2 Identification and impacts of key drivers

Having earlier (in section 7.2.1 above) assumed that mineral royalty tax, energy prices and all other inputs remain constant, this sub-section relaxes this assumption and considers a range of different values for variables. This was done to enable identification of variables and relationships that significantly impact copper cathode production in the model.<sup>50</sup> A total of 1200 simulation runs were done and an analysis of the same is given below. These runs also helped identify inputs that influence the unit cost of production. A total of 77 inputs<sup>51</sup> were varied, see section D.5 in Appendix D for details.

Figures 7.24 - 7.27 below shows a summary of all the 1200 runs at site level. Under same copper and energy prices, the production behaviour and profitability of each mining site vary. This, therefore, suggests that while factors that influence production and profitability are the same, their

<sup>48</sup>See Table A.1 in Appendix A for the historical electricity prices.

<sup>49</sup>ZESCO (the public utility) applies for price adjustments to the regulator (ERB), who (ERB) then invites comments from the public. The main focus from public and ERB is usually the current business performance of the utility, as ERB only uses a max of six-year economic outlook of the country and the impact that the proposed price would have on it.

<sup>50</sup>See section 6.4 for an approach that is used in the identification process of key variables and relationships in this mining model.

<sup>51</sup>Ranging from energy intensities, energy prices, capital cost, operational costs, expansion strategies, ore resource quality and quantity.

impact on mining sites are heterogeneous. The heterogeneity is largely due to the characteristics of a mine, such as mining methods, ore mix (split between oxide and sulphide ore), ore resource and [ore grade](#) of the mine. For instance, a site with high [ore grade](#) (such as Copperbelt open pit) is generally more profitable (via profit margin) than that with low [ore grade](#) (such as North-Western open pit).<sup>52</sup>

In all three mining sites, it can be seen from Figures [7.26](#) and [7.27](#) that despite reducing profit margins and [ore grade](#) in the early years, ore production increased. This implies that conditions for increased ore production capacity investments were still present. This is expected as production investments are determined using thresholds (as explained in Chapters [4](#) and [6](#) above) and not just increase in operation's profitability.

In addition, Figure [7.25](#) shows that North-Western open pit has a higher unit production cost than the Copperbelt mines. This is because it has lower [ore grade](#), as can be seen in Figure [7.26](#). The effects of [ore grade](#) on production costs are discussed in details below.

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<sup>52</sup>See section [E.5](#) for the impact that [ore grade](#), ore mix of reserve and copper price have on cathode production at industry level.

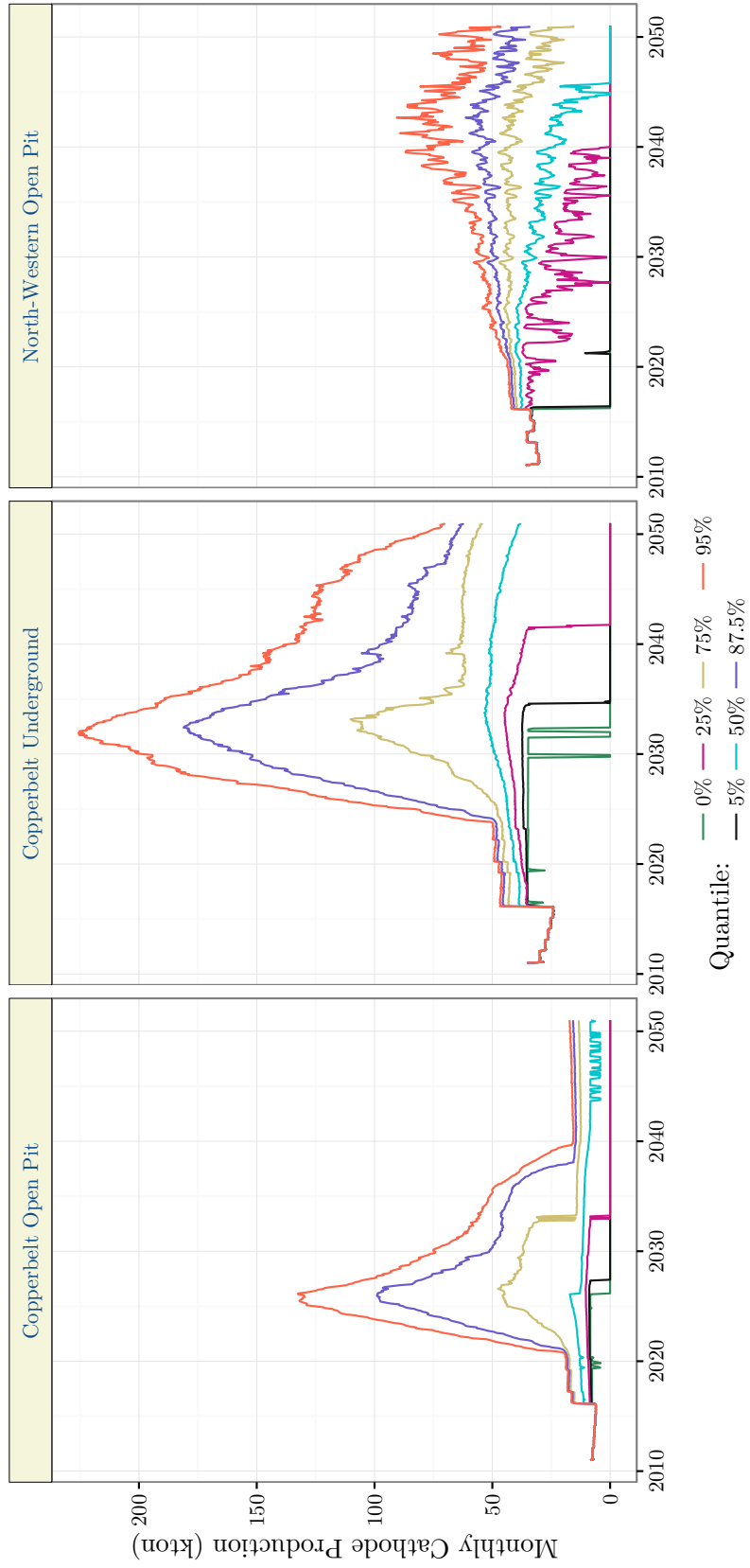


Figure 7.24: Monthly cathode production at mining site level

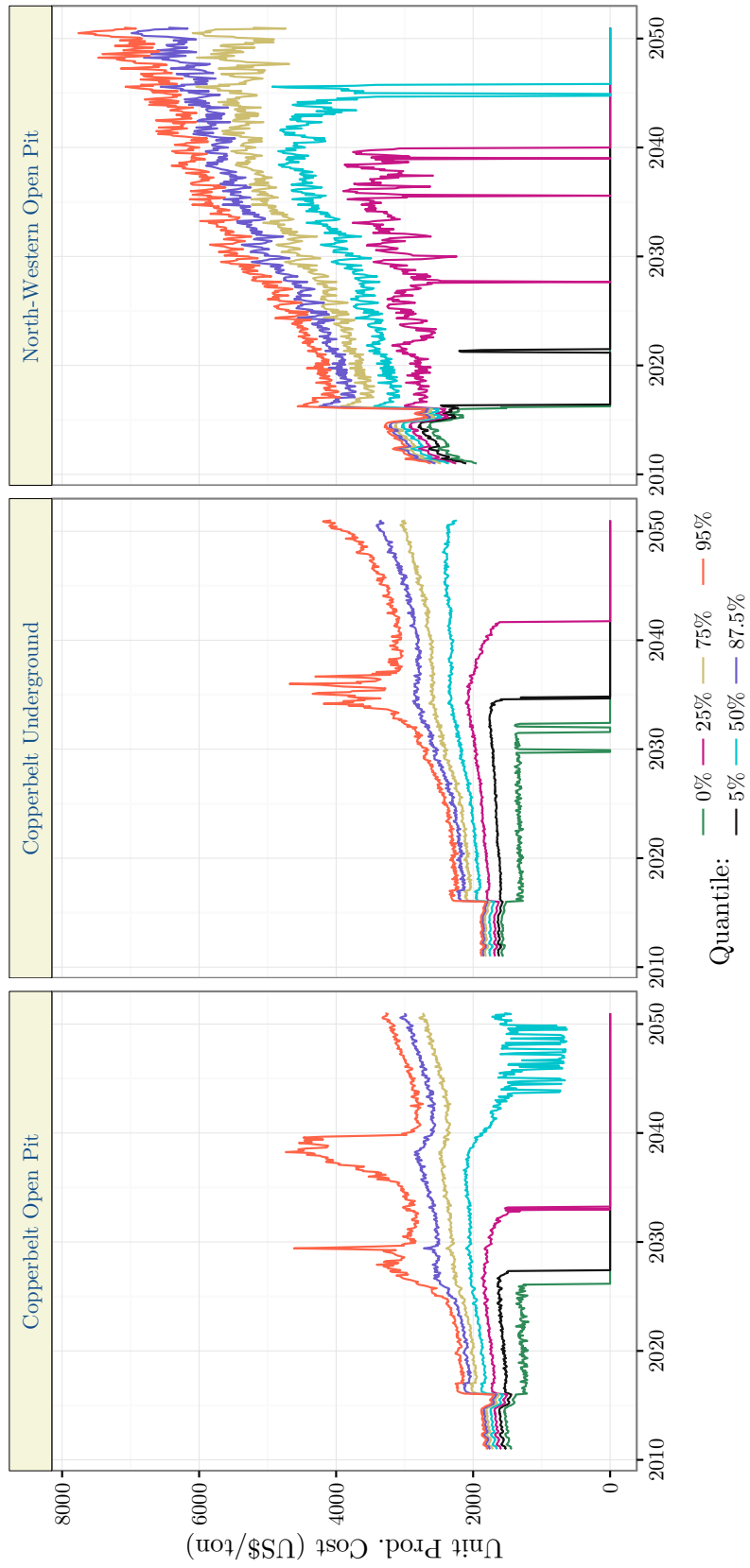


Figure 7.25: Unit production cost at mining site level

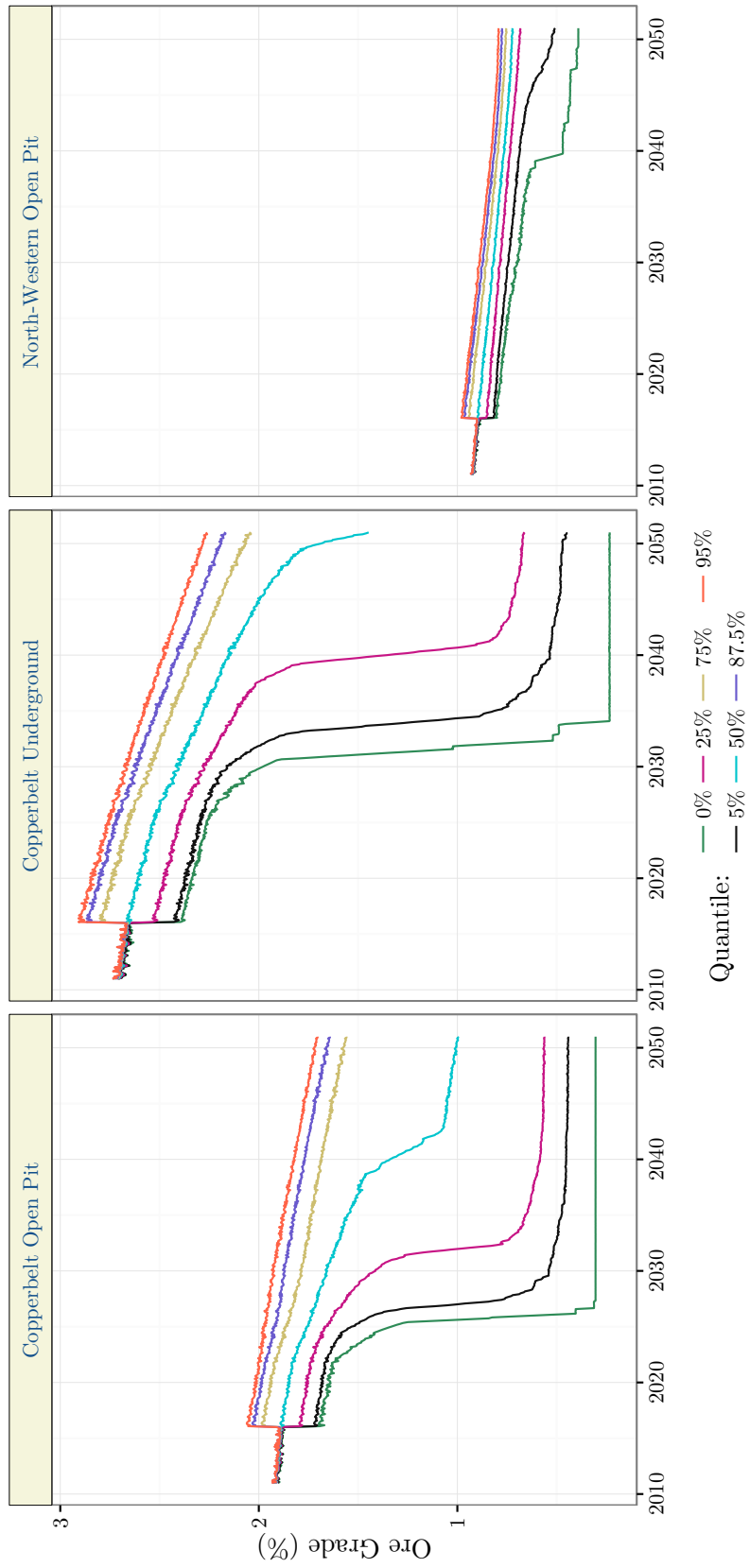


Figure 7.26: Ore grade at mining site level

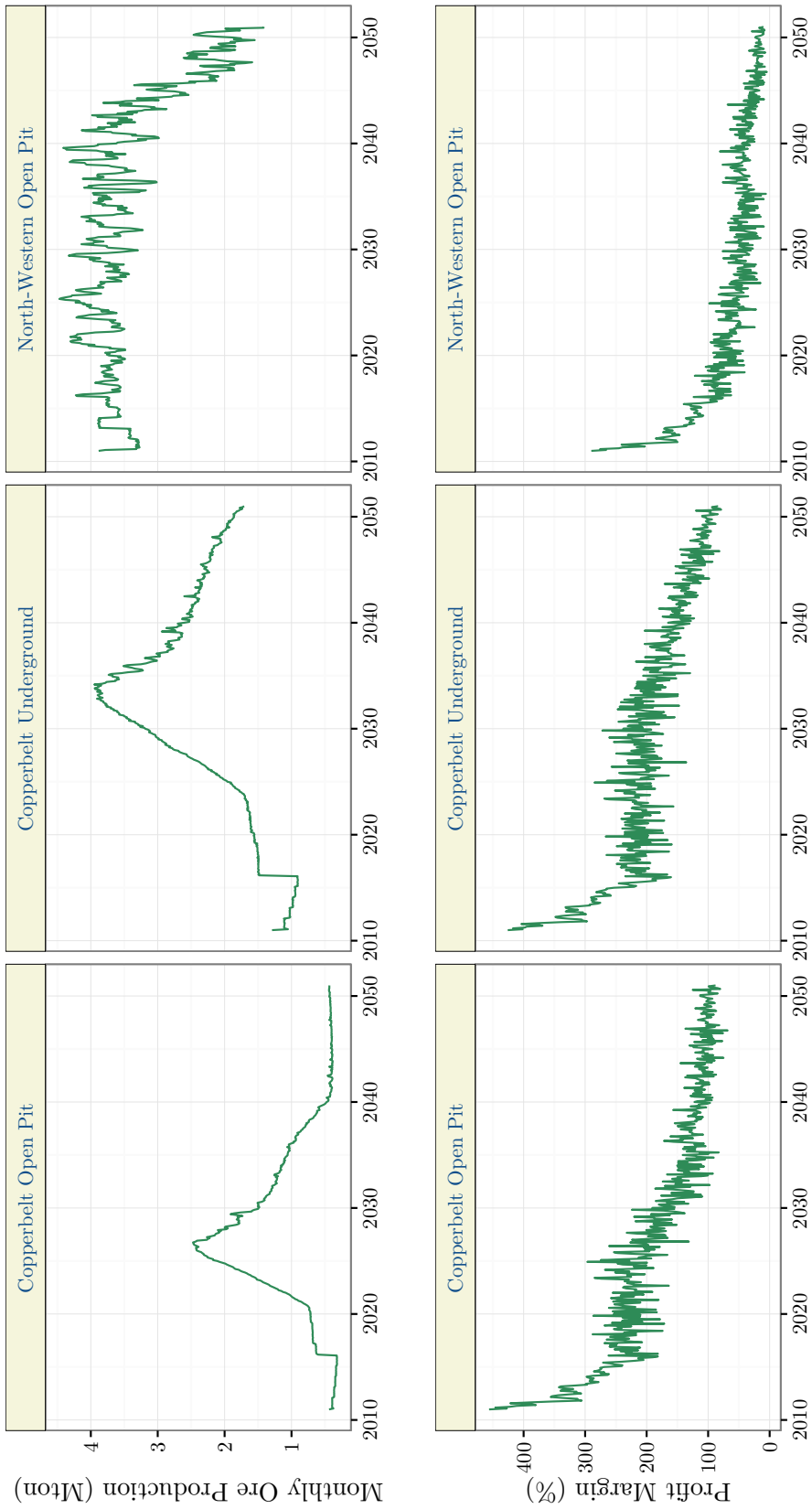


Figure 7.27: Average monthly ore production and profit margin at mining site level

From literature and also in practice, copper cathode production is largely determined by the energy supply capacity<sup>53</sup>, ore production capacity, available ore, ore grade and profitability of an operation. The energy supply capacity, in the model, is not explicitly expressed except through the energy prices (which were estimated as explained above)<sup>54</sup>. The impact of energy prices is given in section 7.2.3 below. However, the ore production capacity, ore grade, available ore and profitability are explicitly captured endogenously. Thus, based on the model structure, ore production capacity, available ore and profitability<sup>55</sup> could be said to be drivers of ore production.<sup>56</sup> Further, ore grade influences ore production through profitability. Apart from that, cathode production is a function of produced ore and ore grade<sup>57</sup>.

Figure 7.28 shows the correlation<sup>58</sup> (based on the 1, 200 simulation runs described in the first paragraph of this sub-section) between ore production and its drivers. This correlation can be explained as follows: “0” means no relationship, “+1” means a strong limiting influence and “-1” means a weak limiting influence (i.e. enhance more ore production). It can be seen that there is a strong correlation between ore production and profitability capacity; this shows the strong influence that copper price has on production. The profitability capacity<sup>59</sup> is a function of revenue and production costs<sup>60</sup>, with time delays<sup>61</sup>. For Copperbelt sites, installed capacity also has a strong correlation in earlier years but the relationship tails off later. This is expected as can be seen from the figure that production and in-

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<sup>53</sup>The quantity of energy and energy capacity available to support copper production process.

<sup>54</sup>Because the focus the research was to estimate the size of supply capacity that would need to be developed in order to meet demand, it was assumed that all required energy would be met at a price.

<sup>55</sup>The profitability function is defined in Equations 6.7 – 6.9 and 6.22 – 6.25 above.

<sup>56</sup>There are many more factors that drive ore production in actual copper industry such as adopted business strategy, lobbying tactics and industry politics.

<sup>57</sup>See Figure E.12 (Appendix E) for the graph on average ore grade, ore and cathode production of 1200 simulation runs.

<sup>58</sup>Correlation (defined in Equation 6.56) was calculated using the statistical screening methods which are described on page 182 above.

<sup>59</sup>See Equations 6.9 - 6.6 for a definition.

<sup>60</sup>Ore grade has an indirect effect on production costs.

<sup>61</sup>The time delay in the prof. capacity is the same as the loss tolerance time ( $t_r$ ).



stalled capacity gap grows in later years. In the North-Western open pit, there is a weak relationship between ore production and installed capacity, this is because the site is a marginal cost mine. Further, because all sites have substantial ore resources, the impact of available ore on production is insignificant though it slightly increases towards the end of the simulation for Copperbelt sites<sup>62</sup>. This is because of ore resource depletion.

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<sup>62</sup>See Figure E.13 (Appendix E) for the gap between available ore, mined ore and ore production capacities.

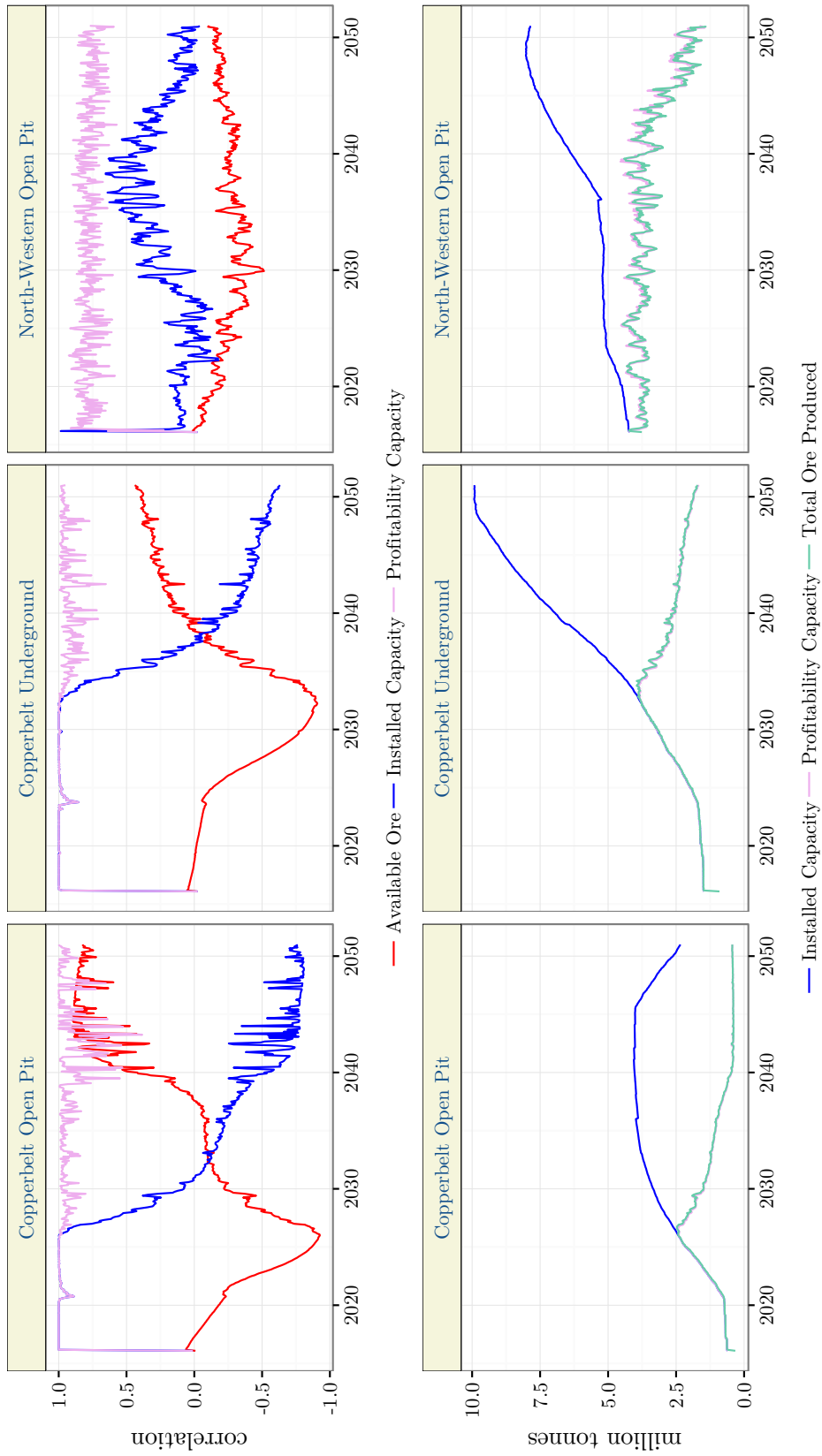


Figure 7.28: Correlation of ore production and prod. capacities (above) and average ore production versus prod. capacities (below)

While change in **ore grade** is driven by production (an endogenous factor), dynamics of profitability are driven by both exogenous factors (copper price, mineral royalty tax and input costs) and endogenous factors (**ore grade** and loss tolerance time) to the mining firm. It is, therefore, important to understand how this loop (production–ore grade–profitability loop) re-enforces itself.

The impact of the firm's loss tolerance time<sup>63</sup>,  $t_r$ , (defined in Equation 6.8) on ore production is given in Figure 7.29. It can be seen that the shorter the loss tolerance time, the more variance there is in production from one period to the next. This behaviour is more pronounced in marginal mining operations such as the North-Western open pit, which try to protect themselves from losses over an extended time period.

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<sup>63</sup>Loss tolerance time is the duration a firm is willing to keep its operation going while in a loss making position (where copper price is less than the unit production cost).

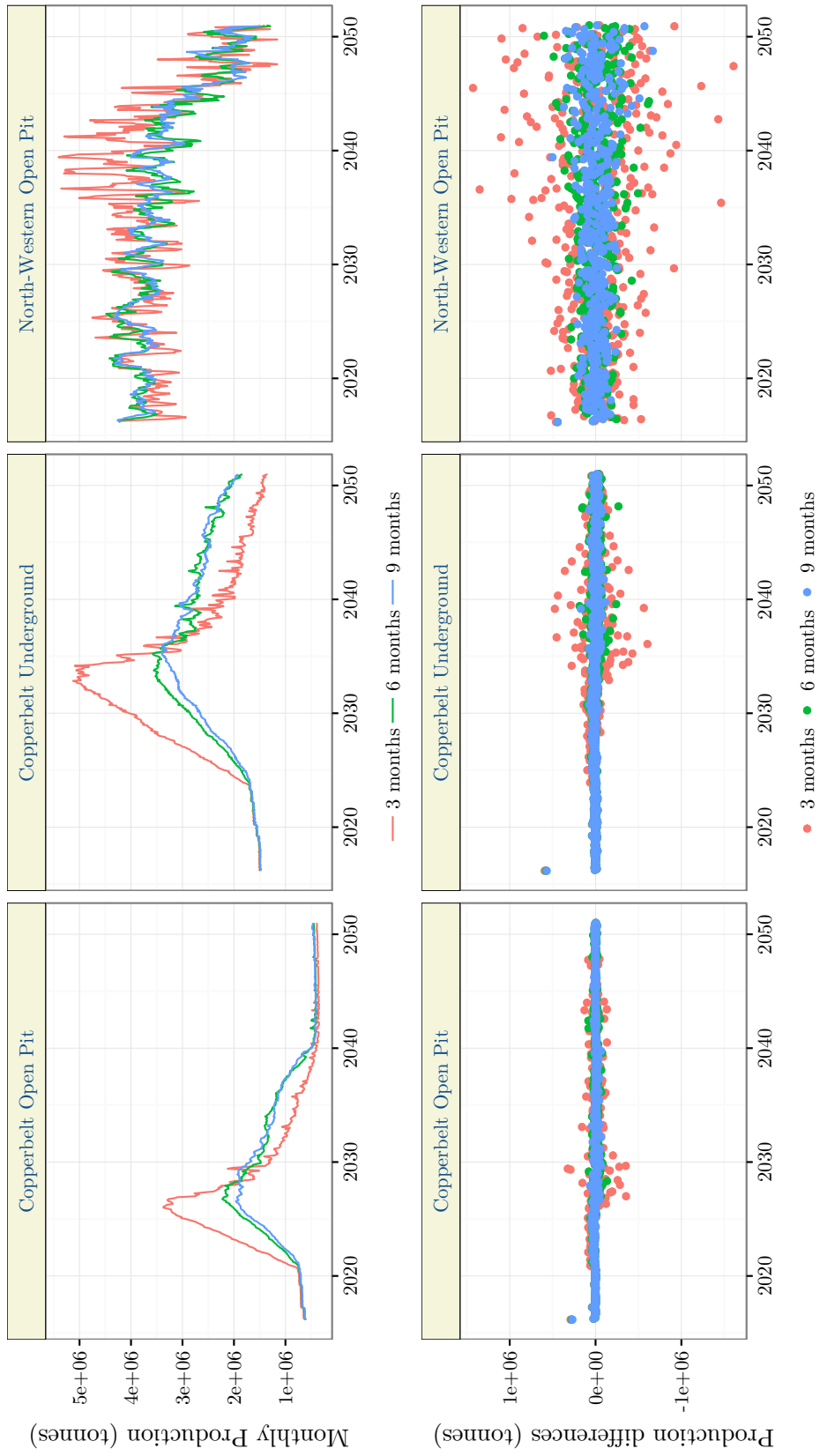


Figure 7.29: The impact loss tolerance time on ore production

Being a function of total revenue and total production costs, profitability can be expressed and analysed in terms of copper price and unit production cost. The components of unit production cost<sup>64</sup> are given in Figure 7.30. It can be seen that other production costs<sup>65</sup> (which is disaggregated in Figure 7.31 below) is the biggest share. This is followed by the by-products credits, which play a significant role in reducing the unit cost of production in the North-Western open pit. The share of mineral royalty tax is similar in all three sites because it is applied at cathode level. Hence, it is not affected by *ore grade*. Furthermore, because the new capital investment cost is amortised over a life span of the capacity (15 years for electric motors and 25 years for all other mining equipment), the impact of loan repayments relative to other costs is insignificant.<sup>66</sup> However, should the mine halt its operations, the mining firm would have to service the loan accrued to facilitate capacity investment. There is, therefore, a tendency in the mining industry to use a shorter pay-back period when amortising their capital investments in order to avoid servicing loans when the mine halts its operation.

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<sup>64</sup>The correlation between total production costs and ore production is shown in Figure E.15 (Appendix E).

<sup>65</sup>This includes labour, energy, transport and other operating costs.

<sup>66</sup>Apart from using loans to finance investment into new capacity, a firm could also use its financial resources as was the case in this model.

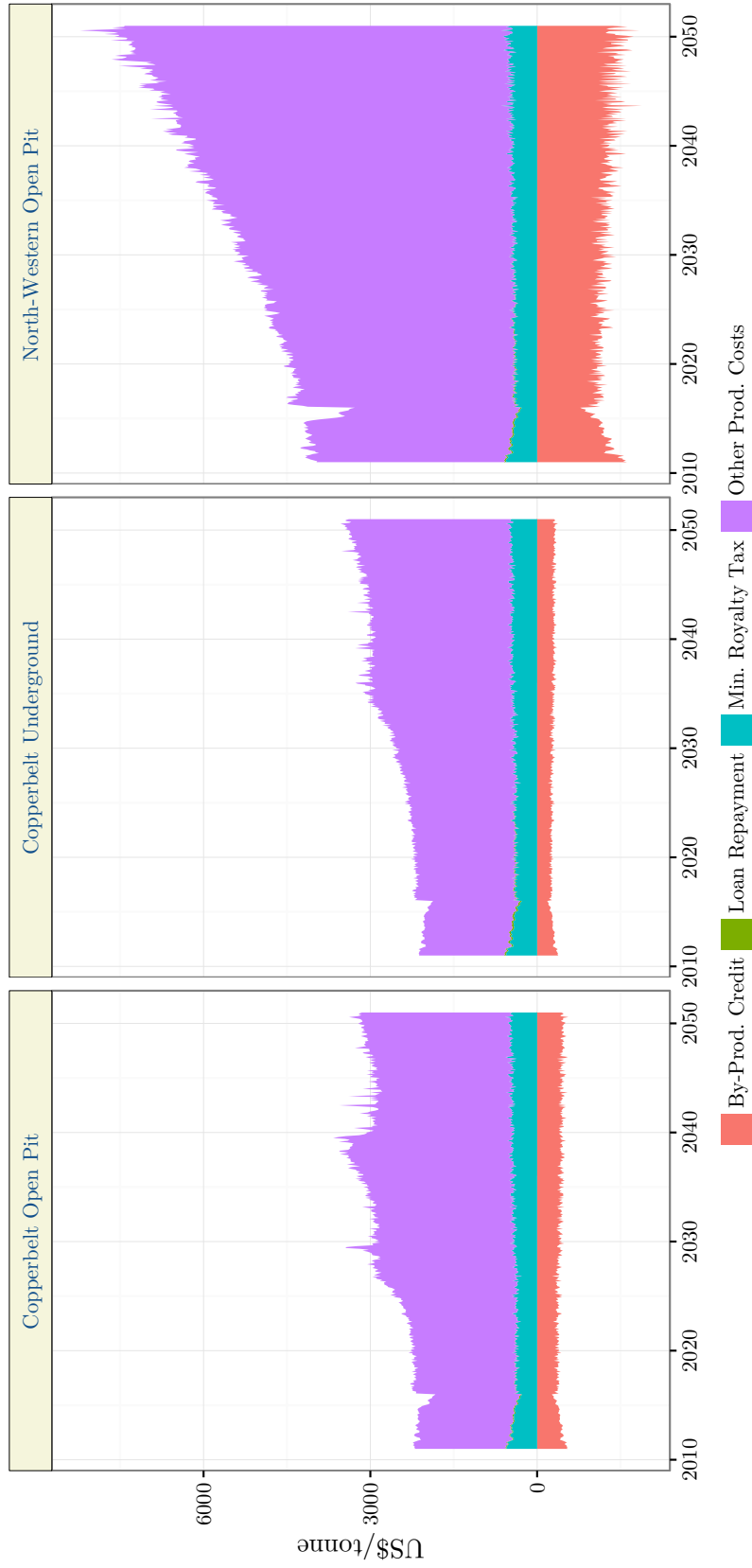


Figure 7.30: Components of unit production cost per tonne of cathode produced

Of these four components, only the other production costs are affected by changes in the endogenous factors. Mineral royalty tax is set by the host country and is therefore subject to negotiations and lobbying, by-products credit is an ore characteristic that is known with some level of certainty at exploration stage, and investment capital costs and interest rates are determined by equipment manufacturers and loan financiers respectively. The shares of other production costs components are displayed in Figure 7.31.

With projected increase in electricity price, it can be seen that the electricity cost would have a significant impact on the production costs for all the mining sites. The three main factors that drive electricity costs are: electricity price, intensity and [ore grade](#). Electricity price is driven by activities within the mining sector and also by growth in demand from sectors outside the mining sector, such as increasing electricity access rates in the residential sector. A detailed analysis of the impact of electricity price on mining output is given in section 7.2.3 below. While electricity intensity can be estimated within reasonable bounds based on the equipment used and the process involved, its value will change throughout the time horizon depending on the changes in the [ore grade](#) (a key driver). Further, because intensity is calculated based on the unit tonne of ore, as [ore grade](#) reduces, the amount of electricity required to produce one tonne of copper cathode will increase.

Figure 7.31 also shows that the price of oil (fuels) would play a significant role in the unit cost since the share of fuels costs increases over time for both the Copperbelt and North-Western open pits. The fuel unit cost for North-Western open pit is higher than that of Copperbelt pit because of the difference in strip ratio<sup>67</sup> (see section D.5 of Appendix D for all the model data input). Overall, the underground site is more sensitive to consumables, other and Repair and Maintenance (R&M), electricity and labour costs, while open pits sites are more sensitive to consumables, other and R&M, electricity and fuel costs.

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<sup>67</sup>Strip ratio is an index used to compare the volume of waste material from a mine for every one tonne of ore that is extracted.

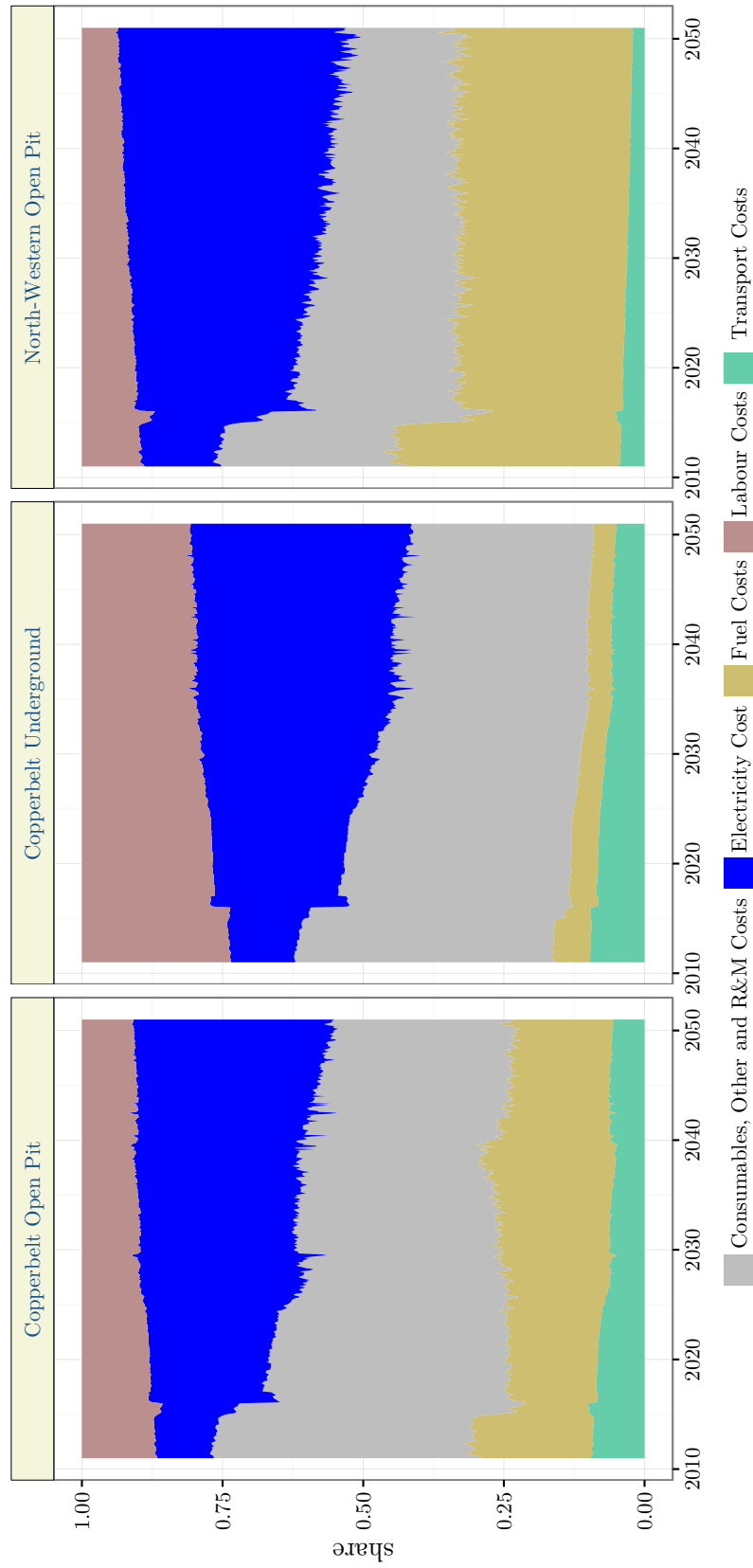


Figure 7.31: Components of Other Production Costs per tonne of cathode produced



In summary, cathode production is determined by available ore production capacity, [ore grade](#) and profitability.<sup>68</sup> The interactions of these three factors and also taking into account time delays<sup>69</sup> within the production process affect how much copper cathode is produced in a particular time-step. Exogenous factors such as mineral royalty tax, energy prices and raw input costs impact the unit cost of production. This unit cost is further significantly impacted by the [ore grade](#) (an endogenous factor). When the unit cost of production is considered in the light of copper price (an exogenous factor), profitability of a mining activity can be calculated. By considering profitability, a mining firm can decide whether to produce or not and also on whether to invest in more ore production capacity.

### 7.2.3 Impact of increasing access to clean energy

The analysis in this sub-section and also in sub-sections [7.2.4](#) and [7.2.5](#) focus on the five scenarios that are described in section [5.3](#). This was done in order to give easy to understand context and analysis. This sub-section presents and discusses results of the impact that increasing access to [clean energy](#) would have on the mining firm's total cathode production and profit. It considers price increase relative to that constant electricity price (that was used to simulate production in [Figure 7.20](#)) and the estimated prices of the five energy demand scenarios, described in section [5.3](#).<sup>70</sup> The impact was estimated by taking the difference between the total cumulative sum of a scenario (say scenario 1) and that of the scenario with constant electricity price and dividing it with the total cumulative sum of the scenario with constant electricity price.

Taking a constant copper price of US\$7, 000 per tonne, [Figure 7.32](#)

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<sup>68</sup>There are many more factors that could impact ore production and capacity investments in the actual copper industry such as the firm's adopted business strategy, lobbying tactics, industrial relations and other industry politics. However, these were not analysed because the focus of the research was on how increasing access to clean energy in residential sector would impact the copper industry and also because there would not have been enough time during the PhD process to address all these other drivers.

<sup>69</sup>Such as loss tolerance time and the firm's tolerance threshold defined in [Eq. 6.7](#).

<sup>70</sup>The constant price is the price of the Initial run while the estimated price is the price of the Last Iteration as shown in [Figure 7.23](#) above.

shows the effect that different electricity prices have on cathode production at mining site level. While cathode production patterns do not significantly change relative to the initial scenario (with the constant electricity price) across energy scenarios for Copperbelt mining sites, increasing access to [clean energy](#) affects North-Western mines considerably. This is because of the low [ore grade](#) that North-Western open pit has (see the discussion in section [7.2.2](#) above). Thus, marginal mining firms, such as the North-Western mines, would be the most impacted by policies that target increasing access to clean electricity.

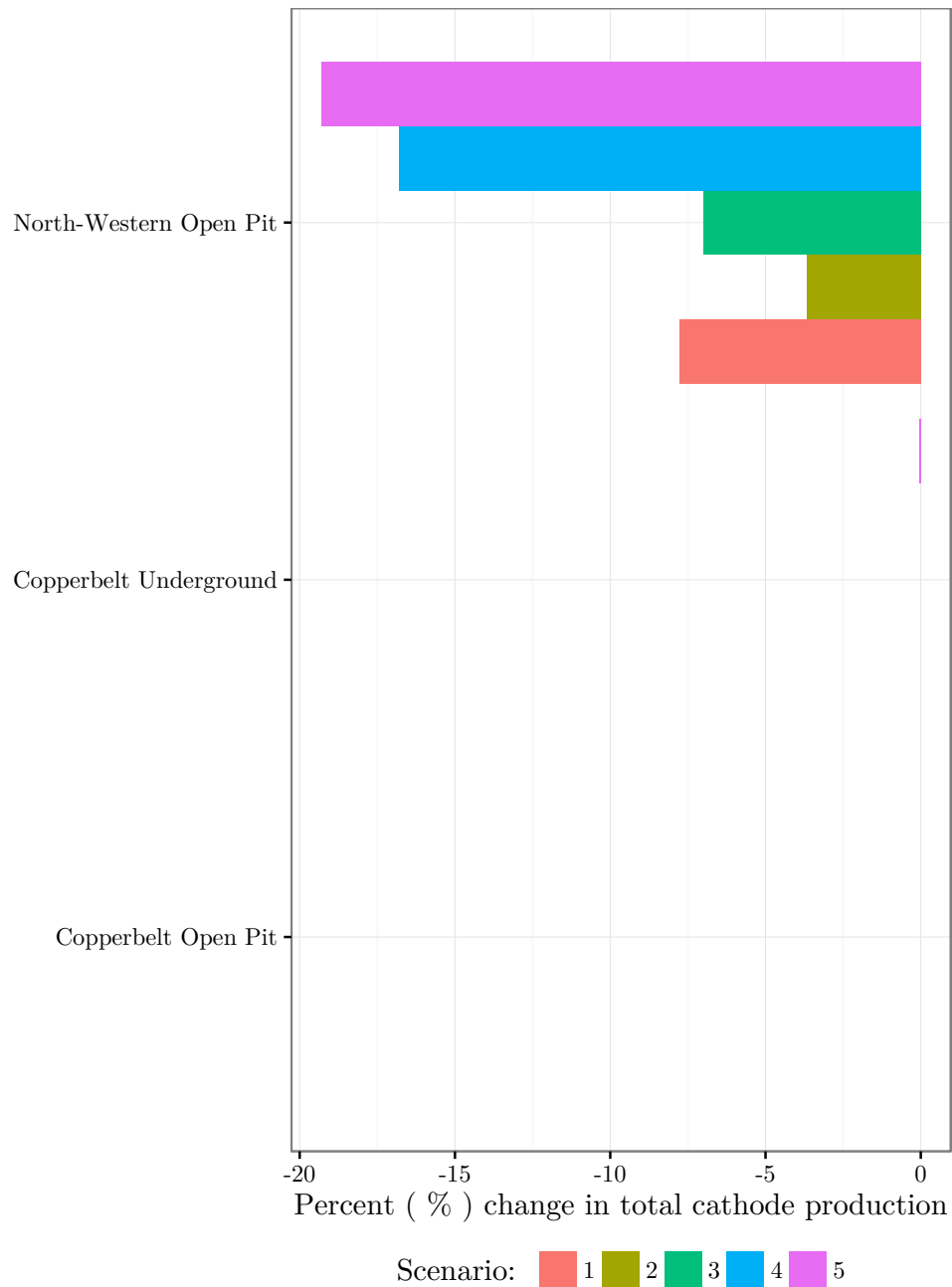


Figure 7.32: Impact of electricity price on cathode production

The impact of increasing access to clean cooking fuel (from 75% to 100% among households that are electrified) on cathode production can be seen by comparing scenarios 2 and 3. In North-Western mines, this impact reduces production by 3.32% (production in scenario 3 reduced). The impact of introducing gas as an option for clean cooking fuel can be seen by comparing scenarios 4 and 5. Cathode production in North-Western mines increases by 2.50% as a result of introducing gas (scenario

4) in residential sector. This implies that adoption of a non-electricity based policy for increasing access to clean cooking fuel would minimise the barriers to industrial growth in Zambia.

Figure 7.33 shows the impact of electricity price changes on total profits. It can be seen that increasing electricity price reduce the profits of all mining sites. However, reducing profits does not translate into reducing cathode production (compare with Figure 7.32, except for North-Western mines), because even with reducing profits, a mining firm could still remain profitable to continue producing and also invest in production capacity. On the other hand, this means that it would take longer for a mining firm to break-even on its investment. Furthermore, for marginal mining firms, it could lead to a reduction in their production.

For instance, taking the Copperbelt underground mines (the most electricity intensive operations), under scenario 1, increase in electricity price led to an impact of 15% on total profit. However, because low ore grade leads to increased *energy intensity*, the impact of the same increase in electricity price led to a profit reduction of 30% in North-Western open pit (even though open pits are less electricity-intensive compared to underground operations). Thus, it would be essential for policy makers to consider the heterogeneity of mining operations when formulating energy pricing policies. Other non-energy related policies could be used to cushion the impact of increasing electricity prices on the mining industry.

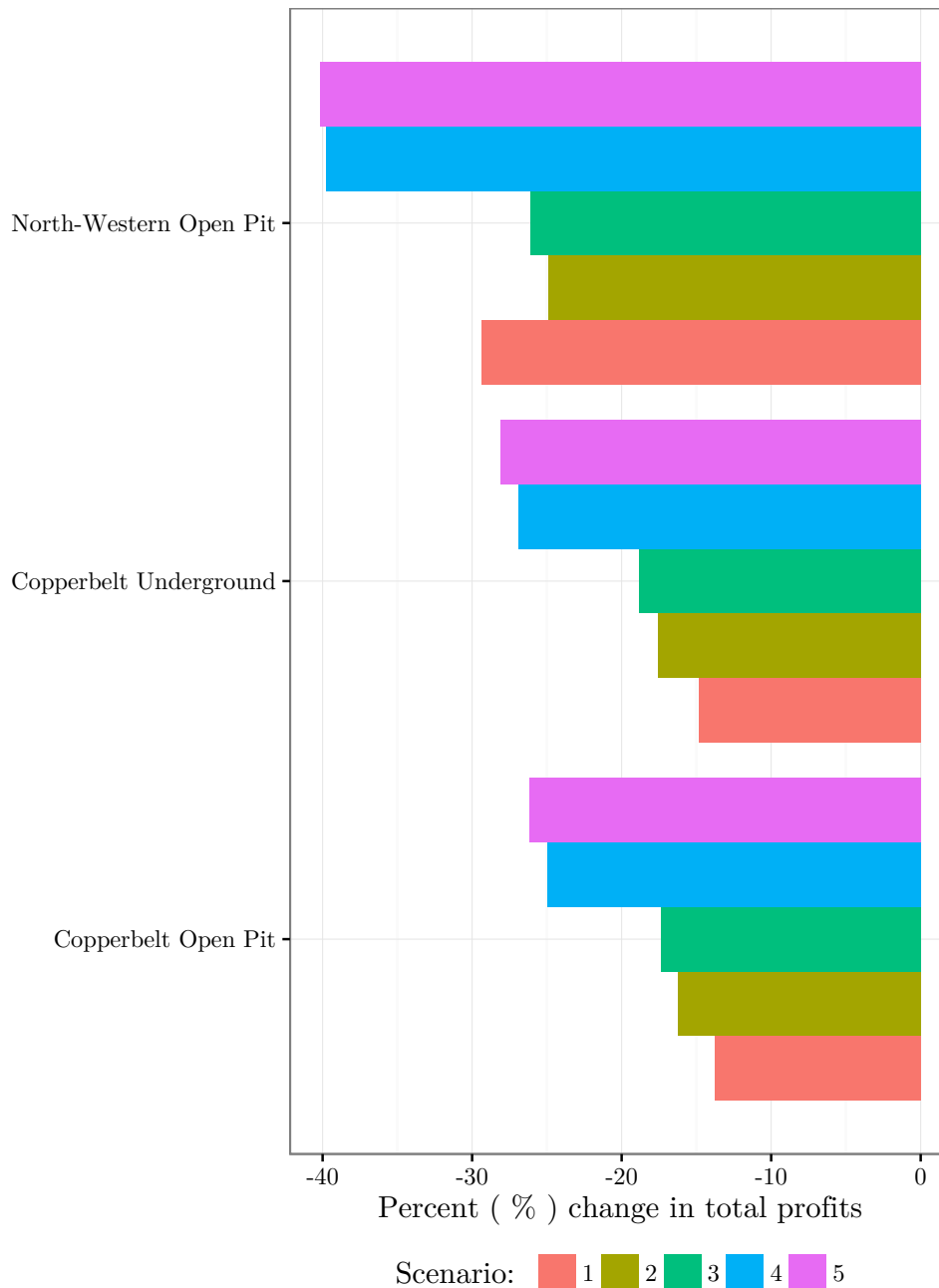


Figure 7.33: Impact of electricity price on total profits

#### 7.2.4 Impact of energy efficiency investments

This sub-section presents results of the impact of increased energy efficiency investments<sup>71</sup> in the mining industry. In Chapter 3, I argued that past energy efficiency studies took a narrow view of how investments in energy efficiency measures and technologies are made. These studies also

<sup>71</sup>See section D.5 Appendix D for the data used in the model

presented the energy cost as being significant such that investing in efficient measures and technologies would alter the production and profitability of the industry. Further, because they found that despite investment opportunities being available but with limited investments happening, they then focused on recommendations of how to overcome these investment barriers.

In line with the observation by Haglund (2010), I argued that past energy efficiency investments studies did not capture the broad spectrum of investment options that a firm could use to reduce its production cost. And based on the interviews' findings, I further argued that some of the factors considered as investment barriers may not be barriers in themselves. This is because as Prain (1975) observed that mining firms investments are driven by the firm's desired investment and profit margin threshold. That is, a firm that achieves its desired profit margins would not invest in technology that could help it to further increase its margins. Thus, I argued, some energy efficient opportunities would go untapped.

Figure 7.34, 7.35 and 7.36 below shows the cumulative impact of solely investing in standard motors and efficient motors on total cathode production, total profits and total electricity demand respectively.<sup>72</sup> From these three Figures, it can be seen that while solely investing in efficient motors would lead to increased total profits (and investing in standard motors would reduce total profits); the overall impact on production is only noticeable in North-Western open pits. Furthermore, if a marginal mine (such as North-Western open pit) overlooks investing in energy efficient measure and technologies, its operational life could be reduced as can be inferred from Figures 7.34 and 7.36. On the whole, comparing the impacts of increase in electricity price (due to increase in access to clean energy) and increase in energy efficient investment, the impact of price would be significant. This could explain why interviewed mining firms were more concerned about electricity price than on mitigation options (such as investing in efficient technologies). Furthermore, these Figures confirmed my argument that in-

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<sup>72</sup>The impact was estimated by taking the difference between the total cumulative sum of the normal motor investment rule and that of either standard motor investment only rule or efficient motor investment only rule and dividing it with the total cumulative sum of the normal motor investment rule.

vesting in efficient measures and technologies does not lead to significant changes in a firm's profits and production patterns, in the Zambian copper industry.

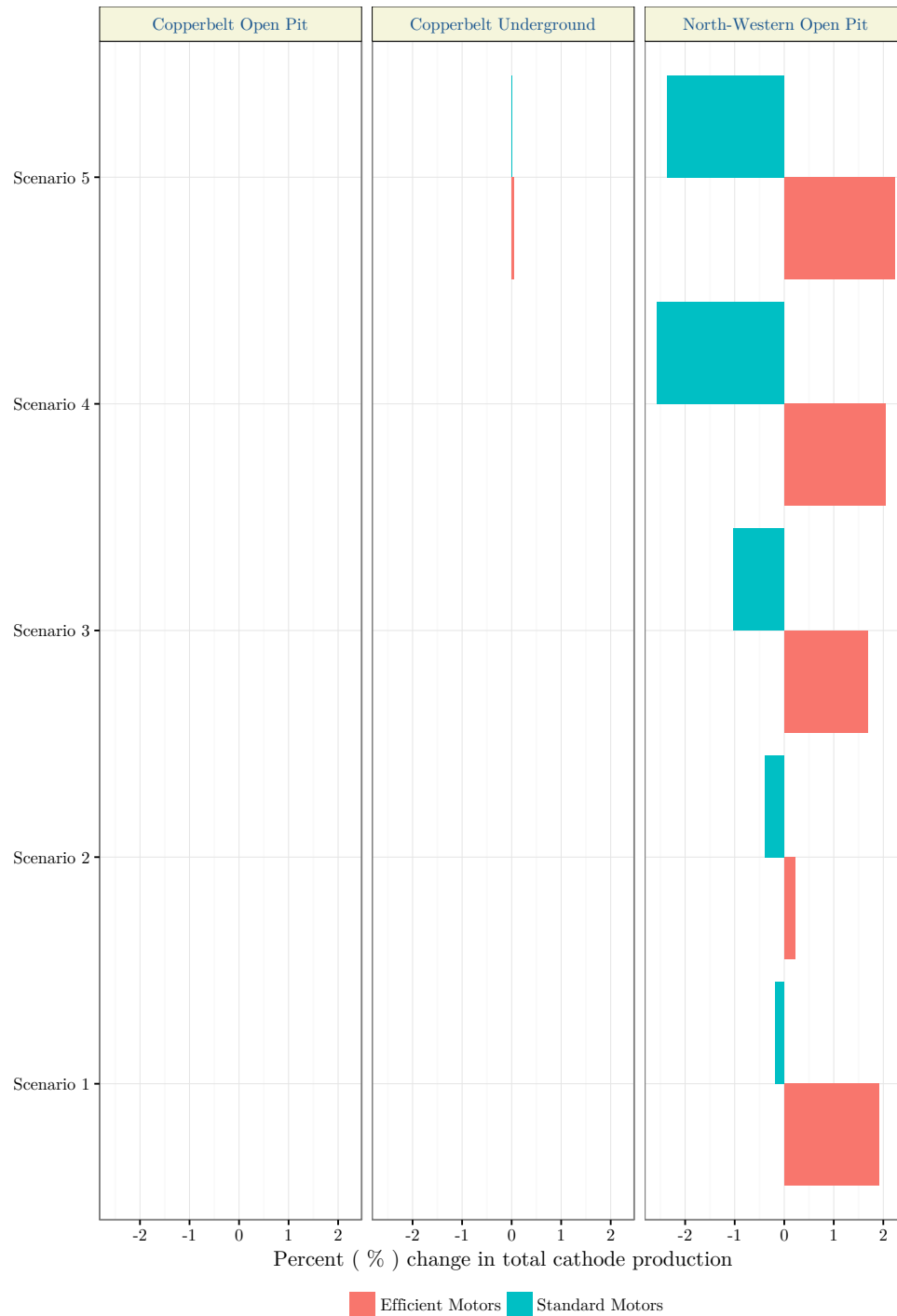


Figure 7.34: Impact of energy efficiency investment on total cathode production

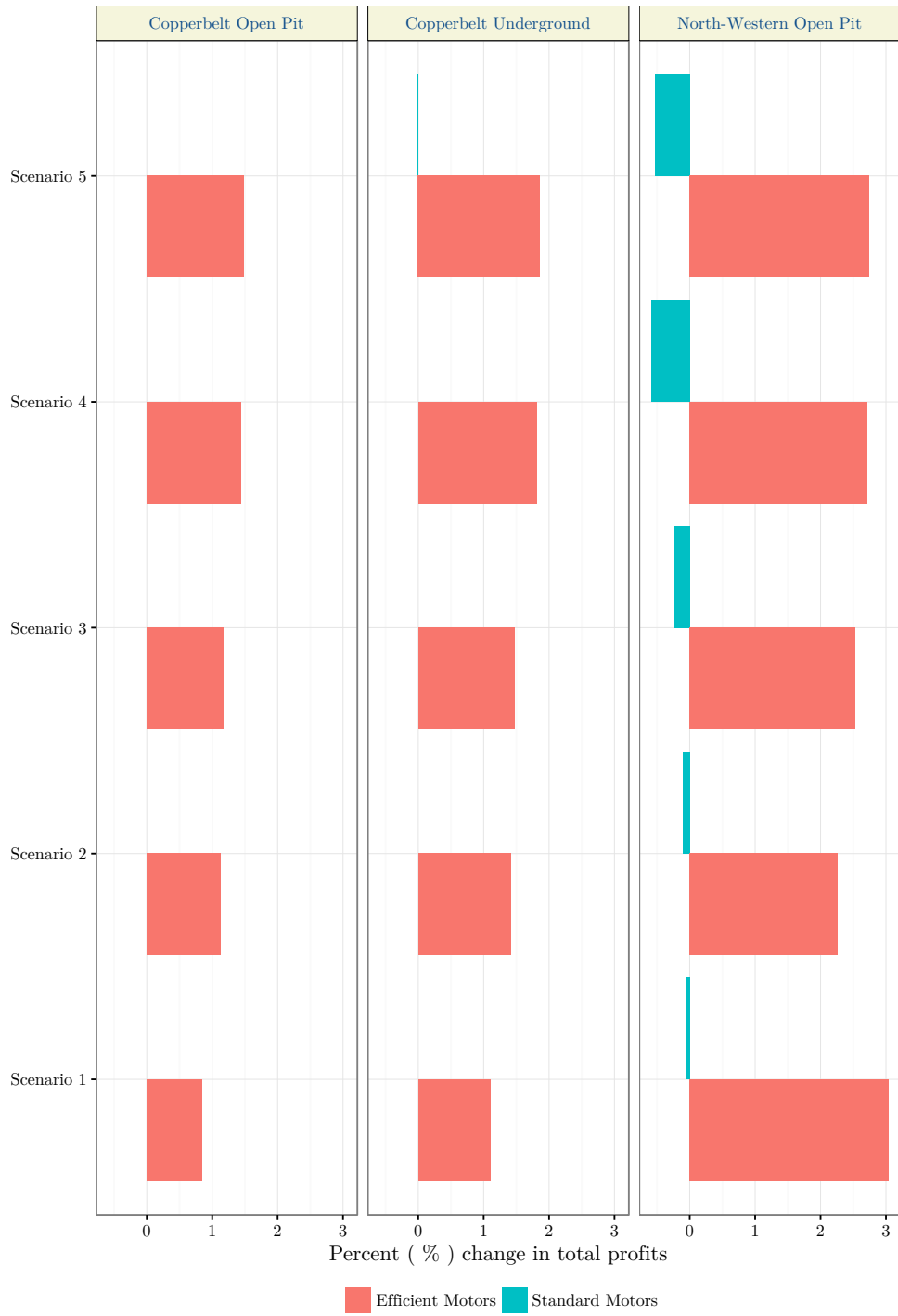


Figure 7.35: Impact of energy efficiency investment on total profits





Figure 7.36: Impact of energy efficiency investment on total electricity demand

### 7.2.5 The impact of expansion strategies on the outlook of the industry

As shown in section 7.2.1, the production output could vary enormously based solely on the expansion strategy adopted by the industry. In this sub-section, two expansion strategies were considered: the market-share and profit-share expansion strategies. The market-share strategy (used in section 7.2.1) is based on the firm's independent expansion planning decisions. It considers a firm that desires to grow at a certain rate based on its own profitability and available copper ore. For instance, a firm that wants to grow its cathode production at a maximum of 10% every year in order to increase its market share<sup>73</sup>.

The profit-share strategy, on the other hand, considers a coordinated expansion plan. The rate of expansion is driven by the desired industry level output (not firm level) and the firm with the largest profit margin is allocated the largest share of the proposed expansion. The strategy assumes that the planner has full knowledge of the profitability of all the firms that operate in the industry and plans their expansion in a way that maximises the profit of the industry (in a particular time step). Similar to the market-share strategy, a firm will expand (use up its allocated space) based on the projected profitability of the expansion and the available ore.

Assuming a constant copper price of US\$7, 000 per tonne, Figure 7.37 shows the cathode production at site level based on the expansion strategies. From the Figure, it can be seen that if expansion is done based on profit-share strategy, the industry produces more from Copperbelt open pit in early years and de-emphasises production from North-Western open pit until in later years. This behaviour confirms the initial position that North-Western open pit is a high cost mine. Further, it can also be seen that under a profit-share strategy, the longevity of the industry (particularly for Copperbelt mines) could be shortened. Thus, if mining is to play a

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<sup>73</sup>Within Zambia, because of different levels of firms' profits, the rate of actual expansion (not desired rate) will vary which in turn would lead to fluctuations in market share.

key role in socio-economic development as planned, it would be imperative that growth strategies used in the industry are understood so as not to miss key opportunities.

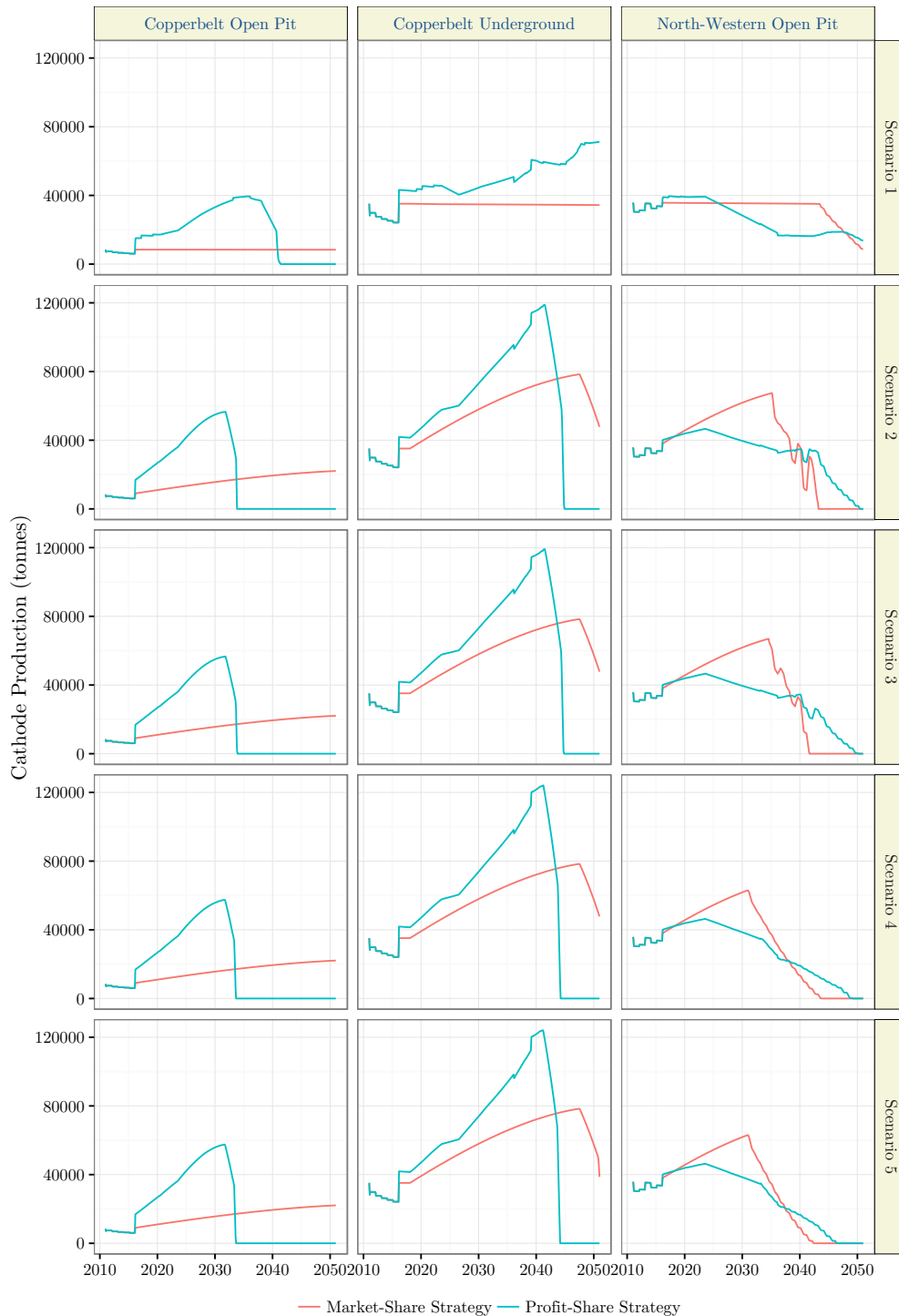


Figure 7.37: Production based on expansion strategies prices at mining site level

Under scenario 1 (which targets to keep cathode production output at a maximum of 80, 000 tonnes per month), it can be seen that if the profit-share strategy is used, it could be difficult to maintain the same level of production through the simulation time horizon. This is because of the difference in project lead time between underground (7 years) and open pit (4 years) infrastructure development. Also, because the ore grades for each mining site differ, if ore production capacity is developed in a site that has high [ore grade](#), then cathode production (at industry level) would increase. More so, if the production gap was estimated based on a low [ore grade](#) mining site.

### 7.2.6 Insights from the mining model analysis

From the sub-sections above, it is clear that there are various factors that affect copper production and in turn decision making in the industry. Some of these factors can be quantified (such as [ore grade](#), copper and electricity prices) while others are more qualitative in nature, such as the firm's strategic interactions with the host government and industrial labour relations. This sub-section gives insights on operational and investment behaviours of a mining firm. It considers combinations of five critical drivers in a mine operation: [ore grade](#), copper price, labour costs, energy costs and mineral taxes.

From the research findings, copper price is the strongest predictor of the state of a mining operation (to operate or not and to invest or not).<sup>74</sup> That is, a high copper price always favours copper production. For instance, if a scenario where [ore grade](#) continues to reduce but mineral tax, copper price, energy prices and labour costs increase is considered. The mining firm will almost always continue to produce and invest in production capacity, because the copper price is increasing. However, the level to change in [ore grade](#), mineral tax, energy price and labour costs would be of interest to the decision maker.

In a scenario where the copper price reduces together with the ore grade,

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<sup>74</sup>While [ore grade](#) is a good predictor of unit production cost.

the decision maker would need to re-evaluate the firm's planned investments. This is because such a scenario has two critical drivers indicating a negative trend. On one hand, the reduction in [ore grade](#) implies increase in the firm's production costs while on the other hand, reduction in copper price means further reduction in a mining operation's profitability. For a firm to continue operating and investing in such a situation, it could be important that the firm takes mitigation actions such as investing in energy efficiency measures or technologies (to reduce the energy cost). Another option would be for the firm to strategically engage the host government, in order for the government to re-look at the drivers (mineral royalty tax and energy prices) under its control. This engagement is common practice in Zambia's industry as was also revealed from the interviews (see [section D.4](#) in [Appendix D](#)).

Whereas profitability of a mining operation is directly impacted by the changes in any of the critical drivers, production patterns, on the other hand, do not change linearly relative to the drivers. For instance, a change in copper price does not always lead to a change in production levels. This is because production is controlled by thresholds that determine the operational behaviour of a mining firm.<sup>75</sup> An example of such thresholds could be, if the firm is making a profit margin of 20% or more, the firm continues to operate normally regardless of the copper price; if the profit margin is below 20% but above 10%, reduce production by 30% otherwise suspend operations. Further, because a mining operation is a large and discrete investment, reducing production linearly would lead to increase in production costs.

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<sup>75</sup>The behaviour is more like a step function (*a mathematical term*).

### 7.3 Discussion summary

This section discusses the findings (from literature and the two sections above) of the research as a whole and shows how parts of the research are linked.

From the reviewed literature, it was found that while most of the arguments on energy demand and projections are around lack of statistics (parametric uncertainty), little attention has been given to correct modelling of energy demand in developing countries' residential sector. Thus, because of this incorrect modelling of demand, most energy research informing policy (in developing countries) has been of little effect; because it is vulnerable to conceptualisation errors (structural uncertainty). Two categories of conceptualisation errors were identified: definition error and key energy drivers.

Definition error has two parts: the definition of what electrification is and the categorisation of types of energy use. Literature that has been reviewed defined electrification in terms of getting access to electricity for lighting service, when electrification is much more than lighting. This narrow definition was partly because some of the countries studied (see [Komatsu et al., 2011](#)) already had access to [clean energy](#) (such as [LPG](#) and natural gas) for their cooking and heating service. The other reason was plainly just lack of knowledge of energy systems and how energy is used in developing countries, particularly sub-Saharan Africa (see [Rosnes and Vennemo, 2012](#); [Zeyringer et al., 2015](#)). As a result, optimal solutions for lighting service (such as off-grid solar systems) were presented as optimal solutions for electrification (which covers cooking and heating, lighting and other uses services). These studies failed to distinguish energy services that can be met by different types of off-grid and grid solutions.

The other conceptualisation error was identification of key energy drivers in the residential sector. Growth in energy demand was modelled as being largely influenced by household income (see [Rosnes and Vennemo, 2012](#); [Zeyringer et al., 2015](#)) rather than government policy intervention. This is because, one would suppose, of the desire to make energy use sustainable.

The challenges of increasing access to [clean energy](#) and electrification in a sustainable way were studied by [Barnes and Floor \(1996\)](#). It has generally been acknowledged that increasing of access to [clean energy](#) through government policy intervention is unsustainable, as government would need to heavily subsidise energy use in order to keep the prices low. This, notwithstanding, has continued to the case in many African countries (government policy intervention); the importance of government intervention in facilitating fuel transition was argued in [Hosier and Dowd \(1987\)](#). In addition, if energy demand is modelled as driven by household income, not only will it grossly underestimate the required energy infrastructure investment efforts but also signal that electricity and other [clean energy](#) forms demand will grow at a slow pace. This is because household income increases at a slow pace considering that it is a function of economic and population growth.

In the light of these identified conceptual limitations, this study used a bottom-up method when estimating energy demand. Not only is this method able to capture energy use at end-use level, possible government policy interventions were captured and analysed. The energy demand scenarios considered<sup>76</sup> looked at how much energy could be needed if certain energy access targets were met. It was important that energy demand projections were properly estimated, as literature ([Rosnes and Vennemo, 2012](#)) as well as this study found that energy demand projections have the largest impact on the supply model (estimations of required capital investment). In addition, by capturing energy use at end-use service level, it was possible to model the transition from an inferior fuel to a superior fuel (as described in the energy ladder literature).

It was also found that although there has been considerable research on energy ladder (fuel transition), these studies assumed that the decision maker had access to an array of energy fuels to choose from. This type of research focused on understanding which factors were key influencers of energy transition; which inevitably ended up focusing on the economics of the household. However, it was found that while many rural households in

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<sup>76</sup>See section [5.3](#) of Chapter [5](#).

Zambia could afford to use electricity (based on their income, see Chapter 5), most households did not have access to electricity because it was not available. It was, therefore, essential that energy use that is driven by availability, and not only affordability, was also captured (this was facilitated by the bottom-up method). This is the other reason why considering government policy intervention when analysing increasing energy access is important.

The energy demand model that was developed for this study found that apart from economic growth, income, access and fuel transition assumptions being important in the final energy projection estimates, population growth assumptions were also impactful. It also found that although final energy demand is projected to increase by at least 120% by 2050, electricity demand, on the other hand, is expected to increase by at least 450%. In contrast to the findings of [Rosnes and Vennemo \(2012\)](#), who found that main driver of electricity demand in sub-Saharan African was economic growth, this study found that growth in electricity demand in Zambia was significantly influenced by the residential sector. This difference (of which drivers are important) was as a result of different demand estimation methods: [Rosnes and Vennemo \(2012\)](#) used an econometric method (a top-down approach) while in this thesis end-use method (a bottom-up approach) was used which best captures the specifics of energy system in developing countries ([Bhattacharyya and Timilsina, 2010](#); [Pandey, 2002](#)). This difference further shows the impact that different modelling methods could have on policy recommendations.

Having isolated the residential sector as a key player in future electricity demand, an analysis that looked at the benefits of reduced deforestation as a result of increased access to [clean energy](#) was undertaken. This analysis is important because Zambia has in the past entered into agreements for prevention of forest cover losses (under [REDD+](#) initiative) on the premise that it would reduce deforestation by increasing access to electricity. The analysis found that such a premise is weak because Zambia would incur a minimum cost of US\$ 6, 800 per hectare while reaping maximum ben-



efits of US\$ 5, 100 per hectare. This analysis, however, did not consider other important benefits that come with the use of [clean energy](#) such as reduced energy-related health illness (see [Javadi et al., 2013](#)). Therefore, it would be important that further analysis is carried out before a firm policy recommendation could be made.

Two other important findings on the supply side were that coal technology is projected to play a key role in electricity generation and that technology learning for solar does not lead to significant penetration of solar technology in the energy supply mix. The impact of technology learning is limited because there were other cheaper supply options available to choose from (such as hydro technologies). On the other hand, because coal technology is expected to play a significant role, implementation of carbon emissions reduction targeted policies would have a noticeable impact on the average generation costs but a positive impact on deployment of solar technology.<sup>77</sup>

From the mining model analysis, it was found that increased electricity price (due to increase in access to [clean energy](#)), would lead to reduced total profits in all the mining firms. However, apart from the North-Western open pit (a marginal cost mine), production patterns and investment behaviour of the firms were not expected to change significantly. This is because firms would still be enjoying healthy profit margins. This is in agreement with [Prain \(1975\)](#) who noted that production behaviour of firms is driven by the set objective and not maximisation of profits.

Furthermore, it was found that for marginal mines, the best way to keep them profitable would be by introducing non-electricity based clean fuels (such as [LPG](#)) in the residential sector. Such a decision would help reduce the impact of electricity price on the mining sector. This is important because not only would mining firms save on their energy costs but also growth of this sector is expected to enhance growth in other sectors in Zambia (see [Chapter 1](#)). In addition, such a measure would also help cushion the impact of electricity price on the profitability of all economic

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<sup>77</sup>See sections [C.5](#) and [C.6](#) in [Appendix C](#) for the input assumptions.

sectors and also on the affordability of electricity in the residential sector. The level of cushion would vary depending on the specifics of the sector being analysed.

Whereas electricity prices do not significantly change the production patterns of the industry, production growth rates do, as can be seen in both Figures 7.20 and 7.32 above. This implies that firms could derive more benefits from their investments if the government focuses more on reducing bottlenecks of industry growth rather than focusing on keeping the electricity prices low. In the model, these industry bottlenecks (such as the development of human capacity, better policies and regulations, rail and road infrastructure) were represented by the production growth rate.

However, because growth and profitability of the sector are not solely driven by the price of electricity, it was important that the decision making process that leads to growth and profitable operations in the sector was understood. It was found, in literature and during the fieldwork, that firms have concrete guidelines on how strategic decisions should be made. As part of the decision process, the firms use Discounted Cash Flow (DCF) when evaluating investment options. This method (DCF) is the industry standard, as was confirmed in literature, industry reports and by the mining firms and experts that were interviewed during my fieldwork. Further, the interviewed mining firms noted that the use of stochastic methods as an evaluation method was not common. This could be in part because final investment decisions are made at the firms' headquarters (only personnel based in Zambia were interviewed). At headquarters, the submitted proposed investment opportunities are further analysed relative to opportunities from other countries, then final decisions are made. While these decisions are informed by analytic assessments, it was found that the judgement of the final decision maker is critical in the process.

In order to effectively simulate copper production and growth of the mining sector in Zambia, the guidelines used in the decision process were implemented in a system dynamics (SD) model (see section 4.3). These guidelines were formulated in form of thresholds, such as all opportunities

with a minimum of 15% RoI on technology assessment and when the firm's profit margin is less than 30% leads to a positive decision. This approach (usage of simple decision rules – thresholds) was found to be a better representation (than using an optimisation model) of how real decision makers make decisions. This is what was found in literature (see Chapter 4) and also during my fieldwork.

## 7.4 Chapter summary

This chapter presented and discussed the results of the energy and mining models. The energy systems analysis found that total final energy demand by 2050 would increase by between 120% to 190%, with residential sector continuing to dominate energy demand. It also found that an increase of 450% in electricity demand would lead to about 700% increase in average generating costs relative to 2010 value (of US\$4/MWh).

Analysis of the semi-structured interviews (which were also used as inputs into the mining model) found<sup>78</sup> that strategic decision making process is a deliberate and procedural process that mining firms engage in. The key factors (from the mining firm's perspective) that influence decision making were identified. Electricity price and taxation policy were found to be the most contentious cost components in the industry. However, when discussing electricity pricing, the respondents seemed to be more focused on the current price of electricity without considering the impact that future electricity price could have on the industry.

An analysis of the impact that increasing electricity price would have on the mining industry was carried out. The analysis found that not only would increasing electricity price reduce the industry's profitability and cathode output, but also that it would render some mining operations unprofitable. Further, under a scenario of constant energy prices and MRT, the analysis found that **ore grade**, available ore production capacity and a firm's profitability (of which copper price is a key component) are key

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<sup>78</sup>See sections 6.2 (of Chapter 6) and D.4 (in Appendix D) for the results.

determinants of how much copper cathodes could be produced. The impact of energy efficiency investment and expansion strategy on the evolution of the industry were also discussed.

# Chapter 8

## Conclusions

In this chapter, the main research findings and conclusions of the research are presented. It then highlights how these findings contribute to knowledge and finally concludes with suggestions for possible future research work.

### 8.1 Restatement of the research problem

This research hoped to address the policy challenges that Zambian government decision makers face. They are faced with the challenge of balancing between increasing access to [clean energy](#) and enhancing economic growth. On one hand, increase in access to [clean energy](#) lead to increase in electricity demand (as electricity is currently the only [clean energy](#) alternative). Increase in electricity demand further exacerbates the ready existing supply shortage; thus to curb it, more capital investments would be required in the energy sector. This translates to increase in electricity price.<sup>1</sup> On the other hand, the government hopes that growth in the economic sector (particularly the mining sector) would provide the needed finance to facilitate increase to [clean energy](#). However, because increase in [clean energy](#) leads to increase in electricity price, growth of the economic sectors would

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<sup>1</sup>This takes in consideration that the current generation stock in Zambia's electricity sector has almost been amortised. Therefore, any capital investment in the sector leads to increase in the electricity price.

be hindered.

These complex interactions between the social goals (increasing access to [clean energy](#)) and economic development (growth of the mining sector), which are under-researched for many African countries, were analysed in this study. This was important because the outcomes of these interactions are not straightforward, as there are several feedback loops that would act as barriers from realising these aspirations. Further, apart from the need to expand the supply infrastructure, there is lack of knowledge of how mining firms (the mining industry is central to these economic growth plans) in Zambia make strategic decisions. Therefore, to effectively address these challenges, three research questions were posed:

1. How would Zambia's energy sector evolve by 2050?
2. How do mining organisations make strategic investment decisions and what are the key decision variables in the mining sector?
3. What impact does increasing access to [clean energy](#) have on mining sector's profitability?

## 8.2 Main research findings

This section summarises the main findings of the research as a whole. Below are the main findings of the research, grouped by research question.

### 8.2.1 Evolution of Zambia's energy sector

Research question 1: "How would Zambia's energy sector evolve by 2050?" considered two parts. The demand part which focused on energy use and how future energy demand is modelled, and the supply part which considered the capital investment cost required to meet projected demand, how the generation costs would change and also the impact of inputs on the supply model.

The main findings are:

## Demand modelling

1. Total final energy demand in Zambia would increase by at least 120% (and as much as 190%) by 2050 relative to the 2010 demand (of 162 PJ). The projected demand is driven by population growth, fuel transition, electricity access, economic growth and copper production assumptions. In all the five scenarios considered, the residential sector will continue to dominate demand. This dominance by the residential sector is partly because of the continued use of traditional fuels in scenarios 1 to 3, and also because of increased electricity consumption due to fuel transition and increased household income in scenarios 4 to 5.
2. The residential sector is projected to be the main consumer of final electricity by 2050, in all the five scenarios. This dynamic is largely driven by population and electricity access (part of which is how electricity is used within the sector) assumptions. Consumption in the residential sector is projected to increase from 8.8 PJ to at least 84 PJ (in scenario 1) and to a maximum of 137 PJ (scenario 5) while demand in the mining sector is only projected to increase to a maximum of 63 PJ.
3. Of the total (all sectors) difference of 75 PJ (between scenarios) in electricity demand in 2050, the residential sector accounts for 70% of it. This shows that plans targeting increase in access to [clean energy](#) need to carefully consider how population, income and energy use patterns (both fuel transition and energy access) in the residential sector would change. These assumptions have significant impacts on the total demand. For instance, a scenario (scenario 4) that considers introduction of gas as a cooking and heating fuel in the residential sector leads to a saving of 30 PJ of electricity.

### Supply modelling

1. To meet electricity demand, the supply capacity would need to be increased from 1, 900 MW (2010) to at least 10, 100 MW and a maximum of 16, 100 MW. This would require a total investment cost of US\$ 35 billion and US\$ 60 billion for the minimum and maximum capacity development respectively.
2. As a result of increased capital investment, the average generation cost is expected to increase from US\$ 4/MWh (in 2010) to US\$ 29/MWh (minimum) and US\$ 48/MWh (maximum) by 2050. Further, it is projected that total electricity demand would increase by 600% in the scenario 5 (relative to 2010).
3. While hydro technology is projected to continue dominating electricity supply (by at least 40%, from 99% in 2010), participation of coal technology is projected to increase from 0% in 2010 to at least 27% in 2050 (under least cost assumptions). This would lead to an increase in carbon intensity of between 300  $gCO_{2eq}/kWh$  (minimum) and 421  $gCO_{2eq}/kWh$  (maximum), from 4.25  $gCO_{2eq}/kWh$  in 2010.
4. A trade-off analysis between electrification and deforestation found that to save a hectare of forest, it could cost a minimum of US\$ 6, 800 while the possible benefit from that hectare would be a maximum of US\$ 5, 100. Thus, it could not make financial sense if the main purpose of electrification is to reduce deforestation. This is an important finding because some African countries (such as Uganda and Zambia) have in the past entered into forest cover preservation agreements that are premised on increasing access to [clean energy](#).

### Supply model sensitivity analysis

1. Electricity demand has the most impact on the supply model. This re-emphasises the importance of using appropriate methods when estimating energy demand. Two other important factors are discount rate and the level of participation of coal technology.



2. While technology learning could enhance penetration of renewable energy, a reduction in investment capital cost of solar technology by 62% (between 2010 and 2050) only led to an additional penetration of 8%. Thus, considering the available resources, the model is not very sensitive to solar PV technology learning (i.e. the results of the model did not change significantly despite this reduction in capital cost as a result of technology learning).

### 8.2.2 Decision making in mining firms

Research question 2: “How do organisations make strategic investment decisions and what are the key decision variables in the mining sector?” also considered decision making in mining firms operating in Zambia. This was important because decision making is content dependent. The main findings included:

1. Decision making in mining firms is a deliberate and procedural process a firm engages in. The process is always aided by analytic tools and techniques. However, the technical evaluation notwithstanding, the final decision could also be driven by the experience of the main decision maker.
2. The main analytic method used in evaluating decision alternatives in the copper industry is the Discounted Cash Flow (DCF) method. This finding was confirmed literature, industry reports and also from the data collected during my fieldwork.
3. Apart from requiring a minimum of 15% return on investment (RoI), the decision maker also considers [ore grade](#), recoverable copper from the ore, copper price and local policy environment (i.e. taxation being one of them) before a resource development decision would be made. Copper price was found to be a key influencer in decision making process; partly because access to project financing is dependent on the long-term outlook of the price.

4. Because mining firms operate in uncertain environment (the industry is exposed to various kind of uncertainty such as price and policy) and also considering that decision situations are made up of ill-structured problems, it found that the bounded rationality model was best suited for analysing decision making in organisations. This was found true from empirical studies that showed that decision makers simplify their decision rules because of limited time dedicated to a process. These simple rules (heuristics) take a form of thresholds such as 15% RoI.
5. As from literature, it was found that labour, repair and maintenance, energy costs, consumables, transport and taxation were the most significant productions costs. In Zambian mining industry, there are divergent opinions of what is considered a fair electricity tariff and rate of taxation. This could be because the two costs are susceptible to lobbying.

### 8.2.3 Impact of access to clean energy

Research question 3: “What impact does increasing access to clean energy have on mining sector’s profitability?” considered the impact that increasing access to [clean energy](#) (via increase in electricity price) would have on the copper industry in Zambia. The main findings included:

1. Increasing access to [clean energy](#) (through electrification) has a significant impact on the mining firm’s profit margin. In the five energy demand scenarios, this impact ranges between 13% and 41% as shown in [Figure 7.33](#). The impact is greatest in North-Western open pit mine (a marginal mine), which is not even an electricity intensive operation (being an open pit).
2. Even though the firm’s profit margins are impacted by increase in electricity prices (due to increased access to [clean energy](#)), the impact of electricity price on cathode production patterns is not significant except for North-Western open pit (a marginal mine) because of its

low **ore grade**. Among North-Western mines, the impacted is estimated to be between 4% and 19%. However, if access to **clean energy** is increased by using gas cathode production would be increased by about 2.5% (i.e. comparing scenarios 4 and 5). Thus, adoption of other fuel of **clean energy** would help minimise the barriers to industrial growth in Zambia.

3. The three main factors that determine how much copper cathode will be produced are available ore production capacity, **ore grade** and profitability. While available ore production capacity is within the control of the mining firm, and **ore grade** being an endogenous factor, profitability, on the other hand, is driven by both endogenous and exogenous factor. The exogenous factors (such as copper, electricity and raw material input prices) are what influences a firm to modify its behaviour in the short-term. Such a behaviour would be a firm deciding whether to produce or not, how much to produce (if it produces) and also on whether to invest or not in capital equipment.

## 8.3 Limitations and future work

While this research has presented important findings, there are some areas that would need to be addressed to further improve the results.

### 8.3.1 Modelling of mineral royalty tax

In this study, mineral royalty tax was assumed to be independent of the obtaining copper price. However, it has been observed in Zambia that the government comes under pressure (from the general citizenry) to increase the tax rates when the copper price is high and to reduce the rates when the price is low (the latter pressure is from the mining firms and their lobbying associations). Thus, it could be important to capture this behaviour endogenously in the model since mineral royalty tax is one of the critical drivers of the industry; and has the potential of altering investment and

operational behaviour of a mining firm. Apart from that, this would enhance the analysis of other strategic interactions and engagements between the mining firms and the government.

### 8.3.2 Macroeconomic linkage

Much of this study focused on the impact that increasing access to [clean energy](#) and copper production output would have on the copper industry. However, to further strengthen the analysis, it is imperative to create a link between copper production output, GDP growth (or reduction) and funds required to increase access to [clean energy](#). This could be done through a macroeconomic analysis. Such an analysis would also help answer if at all it is possible to achieve (in a sustainable way) the [clean energy](#) access targets in Zambia.

### 8.3.3 Modelling of ore grade

Even though [ore grade](#) was endogenously modelled in the mining model, an assumption was made that a firm produces high [ore grade](#) before producing from low grade ore. However, this is not correct because mining firms produce from the ore that is available and not from the high [ore grade](#) then low grade ore. Further, by modelling [ore grade](#) the way it was done in this research, the model shows that firms would make considerable profits in early years which would make them capable of financing their capital investments internally (no incentive to get external loan for the projects). This implies that, on average, cost of capital had little impact on the unit cost of production. If the [ore grade](#) is captured as in the actual industry, the importance of cost of capital would be noticed and the firm's unit cost would be relatively higher than shown in this study. Capturing of [ore grade](#), as in the real industry, could, however, require more disaggregated statistics and also further disaggregation of the mining model. For these reasons, a stylised approach was used (in this study).

### 8.3.4 Impacts of climate change

Having shown that electricity price would have a significant impact on the profit margins of all the firms, it would be essential to consider the impact that projected climate change patterns (see [Arnell \(2004\)](#); [Harrison and Whittington \(2002\)](#); [Mukheibir \(2007\)](#); [Ragab and Prudhomme \(2002\)](#); [Tadross et al. \(2005\)](#)) in Southern Africa would have on Zambia's hydro-power dominated electricity system. The evolution of the mining industry could then be analysed under scenario settings that are also driven by changes in climate. This is important because [Spalding-Fecher et al. \(2016; 2017\)](#) found that electricity production from hydro plants in the Zambezi River basin would reduce due to climate change. In the light of this thesis, such an analysis could bring to the fore two important questions: how much additional effort would be required to increase access to [clean energy](#) in Zambia? and, what impact would climate change effects have on the growth of the mining industry in Zambia?

### 8.3.5 A comprehensive energy resource mapping

The research found that the timing (when a resource would be available) and the size of the resource have an impact on how the energy system would develop and also on the average generation cost. Thus, in order to reduce uncertainty when estimating the required investment capital and sudden spikes in the average generation cost, it would be essential to comprehensively map out the energy resources that are available in Zambia and around Zambia. This would help minimise building of expensive technologies that serve as emergency power supply when all other capacities have been exhausted in a time step. For instance, the building and operating of oil technology between 2012 and 2016.

## 8.4 Thesis conclusion

This thesis reviewed literature and used a systems approach to fill some gaps in existing body of knowledge on the socio-economic challenges (with respect to [clean energy](#) access and industrial growth) that small developing countries like Zambia<sup>2</sup> face. It contributed to the body of knowledge of how to model an energy system of a small developing country, whose access to [clean energy](#) is low. It showed the challenges that countries that have limited options for increasing access to [clean energy](#) (in this case, Zambia only has electricity as a clean energy form) have. It found that beyond the economics of a household (household's ability to pay for [clean energy](#)), increasing access to [clean energy](#) would require considerable capital investment into the energy system. Which if not properly planned, would impact on the growth of the industrial sector, this, in turn, would make access to clean energy unsustainable (because households would not afford to pay for [clean energy](#)).

Furthermore, whereas past strategic investment studies in the mining industry focused on either the financial part or the engineering part of a firm, this thesis considered both parts and combined them when analysing investment behaviour under uncertainty. The mining model that was developed is novel in that it implements a bounded rational simulation model and captures the investment and operational behaviours of mining firms in detail. This helped in isolating critical strategic decision making drivers in the mining industry. It also considered the sequential and feedback loops between decision environments that are usually not accounted when studying decision making in firms. This thesis, therefore, devised a framework that could be used to study a country that hopes to use its natural resources to enhance its socio-economic development (an interdependence trade-off analysis between sectors of an economy).

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<sup>2</sup>This thesis produced energy and mining models and frameworks for critical analytical thinking for Zambia that did not exist before.

# References

- Adler, R. W. (2000). Strategic Investment Decision Appraisal Techniques: The Old and the New. *Business Horizons*, (November/December):15–22.
- Agostini, C. A. (2006). Estimating Market Power in the US Copper Industry. *Review of Industrial Organization*, 28:17–39.
- Aguirregabiria, V. and Luengo, A. (2015). A Microeconomic Dynamic Structural Model of Copper Mining Decisions.
- Akbaba, M. (1999). Energy conservation by using energy efficient electric motors. *Applied Energy*, 64:149–158.
- Alkaraan, F. and Northcott, D. (2006). Strategic capital investment decision-making: A role for emergent analysis tools? *The British Accounting Review*, 38(2):149–173.
- Alkaraan, F. and Northcott, D. (2007). Strategic investment decision making: the influence of pre-decision control mechanisms. *Qualitative Research in Accounting & Management*, 4(2):133–150.
- Alvarado, S., Maldonado, P., Barrios, A., and Jaques, I. (2002). Long term energy-related environmental issues of copper production. *Energy*, 27(2):183–196.
- Alvarado, S., Maldonado, P., and Jaques, I. (1999). Energy and environmental implications of copper production. *Energy*, 24(4):307–316.
- Arnell, N. W. (2004). Climate change and global water resources: SRES emissions and socio-economic scenarios. *Global Environmental Change*, 14(1):31–52.
- Artinger, F., Petersen, M., and Gigerenzer, G. (2014). Heuristics as adaptive decision strategies in management. *Organizational Behavior*, (August).

- Ashford, R. W., Dyson, R. G., and Hodges, S. D. (1988). The Capital-Investment Appraisal of New Technology: Problems, Misconceptions and Research Directions. *The Journal of the Operational Research Society*, 39(7):637–642.
- Auger, F. and Ignacio Guzmán, J. (2010). How rational are investment decisions in the copper industry? *Resources Policy*, 35(4):292–300.
- Auping, W. (2011). *The uncertain future of copper*. Masters thesis, Delft University of Technology.
- Barlas, Y. and Carpenter, S. (1990). Philosophical roots of model validation: two paradigms. *System Dynamics Review*, 6(2):148–166.
- Barnes, D. F. and Floor, W. M. (1996). Rural energy in developing countries: A Challenge for Economic. *Annu. Rev. Energy Environ*, 21:497–530.
- Barrett, M., Lowe, R., Oreszczyn, T., and Steadman, P. (2008). How to support growth with less energy. *Energy Policy*, 36(12):4592 – 4599. Foresight Sustainable Energy Management and the Built Environment Project.
- Barrett, M. and Spataru, C. (2013). Storage in energy systems. *Energy Procedia*, 42(Supplement C):670 – 679. Mediterranean Green Energy Forum 2013: Proceedings of an International Conference MGEF-13.
- Bartrop, S. and White, A. (1995). Spade work: how miners value resources. *JASSA*, pages 7–13.
- Bearden, N. J., Murphy, R. O., and Rapoport, A. (2005). A multi-attribute extension of the secretary problem: Theory and experiments. *Mathematical Psychology*, 49:410–422.
- Bhappu, R. R. and Guzman, J. (1995). Mineral investment decision making: study of practices. *Engineering and Mining Journal*, (July).
- Bhattacharyya, S. C. (2006). Renewable energies and the poor: niche or nexus? *Energy Policy*, 34:659–663.
- Bhattacharyya, S. C. and Timilsina, G. R. (2009). Energy Demand Models for Policy Formulation: A Comparative Study of Energy Demand Models.



- Bhattacharyya, S. C. and Timilsina, G. R. (2010). Modelling energy demand of developing countries: Are the specific features adequately captured? *Energy Policy*, 38(4):1979–1990.
- Bisschop, J. (2008). *AIMMS: Optimization Modeling*. Paragon Decision Technology, ES Haarlem.
- BNEF (2016). Scaling solar for Africa: Zambia’s 6-cent PV. Technical report, Bloomberg Finance, New York.
- Bortoni, E. D. C. (2009). Are my motors oversized? *Energy Conversion and Management*, 50(9):2282–2287.
- Botín, J. A., Castillo, M. F. D., Guzmán, R. R., and Smith, M. L. (2012). Real options: a tool for managing technical risk in a mine plan. pages 1–7, Seattle. SME Annual Meeting.
- Boulamanti, A. and Moya, J. A. (2016). Production costs of the non-ferrous metals in the EU and other countries: Copper and zinc. *Resources Policy*, 49:112–118.
- BoZ (2011). Annual Report 2011. Technical report, Bank of Zambia, Lusaka.
- Brennan, M. J. and Schwartz, E. S. (1985). Evaluating Natural Resource Investments. *The Journal of Business*, 58(2):135–157.
- Butler, R., Davies, L., Pike, R., and Sharp, J. (1991). Strategic investment decision-making: complexities, politics and processes. *Journal of Management Studies*, 28(July):395–415.
- Byron, M. (1998). Satisficing and Optimality. *Ethics*, 109(1):67–93.
- Cabraal, R. A., Barnes, D. F., and Agarwal, S. G. (2005). Productive Uses of Energy for Rural Development. *Annual Review of Environment and Resources*, 30(1):117–144.
- Cacho, O. J., Milne, S., Gonzalez, R., and Tacconi, L. (2014). Benefits and costs of deforestation by smallholders: Implications for forest conservation and climate policy. *Ecological Economics*, 107:321–332.
- Carpinelli, G. and Russo, A. (2014). Behavioral perspective of power systems’ decision makers. *Electrical Power and Energy Systems*, 58:111–119.
- Cauwenbergh, A. V., Durinck, E., Martens, R., Laveren, E., and Bogaert,

- I. (1996). On the role and function of formal analysis in strategic investment decision processes: results from an empirical study in Belgium. *Management Accounting Research*, 7:169–184.
- CEC (2013). CEC Electricity Statistics.
- Chidumayo, E. (1987). A Survey of Wood Stocks for Charcoal Production in the Miombo Woodlands of Zambia. *Forest Ecology and Management*, 20:105–115.
- Chidumayo, E. N. (1991). Woody Biomass Structure and Utilisation for Charcoal Production in a Zambian Miombo Woodland. *Bioresource Technology*, 37:43–52.
- Chidumayo, E. N. (2013). Forest degradation and recovery in a miombo woodland landscape in Zambia: 22 years of observations on permanent sample plots. *Forest Ecology and Management*, 291:154–161.
- CIMVAL (2003). Standards and guidelines for valuation of mineral properties. Technical Report February.
- Cochilco (2012). Mining Production Yearly Statistics Publications: 1997–2010.
- Cohen, M. D., March, J. G., and Olsen, J. P. (1972). A garbage can model of organizational choice. *Administrative Science Quarterly*, 17(1):1–25.
- CoM (2014). Presentation on the impacts of Vat Rule 18(b): Press Briefing.
- Cooremans, C. (2012). Investment in energy efficiency: do the characteristics of investments matter? *Energy Efficiency*, 5(4):497–518.
- Cortazar, G. and Casassus, J. (1998). Optimal Timing of a Mine Expansion: Implementing a Real Options Model. *The Quarterly Review of Economics and Finance*, 38:755–769.
- Covin, J. G., Slevin, D. P., and Heeley, M. B. (2001). Strategic decision making in an intuitive vs. technocratic mode: structural and environmental considerations. *Journal of Business Research*, 52(1):51–67.
- Coyle, R. G. (1983). The technical elements of the system dynamics approach. *European Journal of Operational Research*, 14.
- Craig, P. P., Gadgil, A., and Koomey, J. G. (2002). What can history teach us? A Retrospective Examination of Long-Term Energy Forecasts

- for the United States. *Annu. Rev. Energy Environ*, 27(1):83–118.
- Crowson, P. C. F. (2011). Mineral reserves and future minerals availability. *Mineral Economics*, 24(1):1–6.
- CSO (1994). Social dimensions of adjustment: priority survey II 1993. Technical report, Central Statistics Office, Lusaka.
- CSO (1996). Living Conditions Monitoring Survey-I 1996. Technical report, Central Statistic Office, Lusaka.
- CSO (2003). 2000 Census of population and housing. Technical report, Central Statistics Office of Zambia, Lusaka.
- CSO (2005). Living Conditions Monitoring Survey Report 2004. Technical report, Central Statistics Office, Lusaka.
- CSO (2007). Environment statistics in Zambia: Energy Statistics. Technical report, Central Statistics Office.
- CSO (2012). National Descriptive Tables. Technical report, Central Statistics Office.
- CSO (2013). CSO Copper and Cobalt Production Statistics.
- CSO (2016). Living Conditions Monitoring Survey Report 2015. Technical report, Central Statistics Office, Lusaka.
- Daioglou, V., Ruijven, B. J. V., and Vuuren, D. P. V. (2012). Model projections for household energy use in developing countries. *Energy*, 37:601–615.
- Daly, H. E., Scott, K., Strachan, N., and Barrett, J. (2015). Indirect CO<sub>2</sub> Emission Implications of Energy System Pathways: Linking IO and TIMES Models for the UK. *Environmental Science & Technology*, 49(17):10701–10709.
- Damnyag, L., Tyynelä, T., Appiah, M., Saastamoinen, O., and Pappinen, A. (2011). Economic cost of deforestation in semi-deciduous forests - A case of two forest districts in Ghana. *Ecological Economics*, 70(12):2503–2510.
- Davenport, W. G., King, M., Schlesinger, M., and Biswas, A. K. (2002). *Extractive Metallurgy of Copper*. Pergamon Press, fourth edi edition.
- de Almeida, A. T., Fonseca, P., and Bertoldi, P. (2003). Energy-efficient

- motor systems in the industrial and in the services sectors in the European Union: characterisation, potentials, barriers and policies. *Energy*, 28(7):673–690.
- de Groot, H. L., Verhoef, E. T., and Nijkamp, P. (2001). Energy saving by firms: decision-making, barriers and policies. *Energy Economics*, 23(6):717–740.
- Dean, J. W. and Sharfman, M. P. (1996). Does decision process matter? A study of strategic decision-making effectiveness. *The Academy of Management Journal*, 39(2):368–396.
- Decanio, S. J. and Watkins, W. E. (1998). Investment in energy efficiency: Do the characteristics of firms matter? *The Review of Economics and Statistics*, 80(1):95–107.
- DeCarolis, J., Daly, H., Dodds, P., Keppo, I., Li, F., McDowall, W., Pye, S., Strachan, N., Trutnevyte, E., Usher, W., Winning, M., Yeh, S., and Zeyringer, M. (2017). Formalizing best practice for energy system optimization modelling. *Applied Energy*, 194(Supplement C):184–198.
- DHEC (2011). Proposed Kabompo Gorge Hydro Electric Scheme: Environmental Impact Statement. Technical report, DH Engineering Consultants, Lusaka.
- Dimitrakopoulos, R., Farrelly, C. T., and Godoy, M. (2002). Moving forward from traditional optimization: grade uncertainty and risk effects in open-pit design. *Trans. Instn Min. Metall*, 111(April).
- Dimitrakopoulos, R. G. and Sabour, S. A. A. (2007). Evaluating mine plans under uncertainty: Can the real options make a difference? *Resources Policy*, 32:116–125.
- DiNuzzo, P., Bertinshaw, R., and Daley, A. (2005). Technical report: Lumwana Copper Project. Technical Report May, Aker Kvaerner Australia Pty Ltd, Melbourne.
- Dixit, A. and Pindyck, R. (1994). *Investment Under Uncertainty*. Princeton University Press, Princeton, New Jersey.
- Dutton, E., Walton, J., and Abrahamson, E. (1989). Important dimensions of strategic issues: Separating the wheat from the chaff. *Journal of*

- Management Studies*, 26(4):379–396.
- Eisenhardt, K. M. and Zbaracki, M. J. (1992). Strategic Decision Making. *Strategic Management Journal*, 13:17–37.
- Ekhholm, T., Krey, V., Pachauri, S., and Riahi, K. (2010). Determinants of household energy consumption in India. *Energy Policy*, 38(10):5696–5707.
- ERB (2008). Energy Sector Report 2008. Technical report, Energy Regulation Board, Lusaka.
- ERB (2013). ERB Energy Prices and Consumption Statistics.
- ERB (2015). Press Statement: Electricity tariff adjustments 2015.
- ERB (2017). Press statement: Electricity tariff adjustment 2017.
- ERC (2013). South African Times Model.
- Fais, B., Sabio, N., and Strachan, N. (2016). The critical role of the industrial sector in reaching long-term emission reduction, energy efficiency and renewable targets. *Applied Energy*, 162(Supplement C):699–712.
- Farrow, S. and Krautkraemer, J. A. (1989). Extraction at the intensive margin: metal supply and grade selection in response to anticipated and unanticipated price changes. *Resources and Energy*, 11:1–21.
- Ferguson, T. S. (1989). Who Solved the Secretary Problem? *Statistical Science*, 4(3):282–289.
- Fleiter, T., Hirzel, S., and Worrell, E. (2012). The characteristics of energy-efficiency measures - a neglected dimension. *Energy Policy*, 51:502–513.
- Fleiter, T., Worrell, E., and Eichhammer, W. (2011). Barriers to energy efficiency in industrial bottom-up energy demand models - A review. *Renewable and Sustainable Energy Reviews*, 15(6):3099–3111.
- Foley, P. T. and Clark, J. P. (1982). The Effects of State Taxation on United States Copper Supply. *Land Economics*, 58(2):153–180.
- Ford, A. and Flynn, H. (2005). Statistical screening of system dynamics models. *System Dynamics Review*, 21(4):273–303.
- Ford, D. N. (1999). A behavioral approach to feedback loop dominance analysis. *System Dynamics Review*, 15(1):3–36.
- Forrester, J. W. (1991). System Dynamics and the Lessons of 35 Years by.

- In Greene, K. B. D., editor, *The Systemic Basis of Policy Making in the 1990s*, pages 1–35.
- Forrester, J. W. and Senge, P. M. (1980). Tests for building confidence in system dynamics models. *Management Science*, 14:209–228.
- Fraunhofer ISE (2015). Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems. Study on behalf of Agora Energiewende. Technical report, Fraunhofer-Institute for Solar Energy Systems, Freiburg.
- Fredrickson, J. W. and Mitchell, T. R. (1984). Strategic Decision Processes: Comprehensiveness and Performance in an Industry with an Unstable Environment. *The Academy of Management Journal*, 27(2):399–423.
- Freeman, P. R. (1983). The Secretary Problem and Its Extensions: A review. *International Statistical Review*, 51(2):169–206.
- Fu, R., Feldman, D., Margolis, R., Woodhouse, M., , and Ardani, K. (2017). U.S. Solar Photovoltaic System Cost Benchmark: Q1 2017. Technical report, National Renewable Energy Laboratory, Denver.
- Gaudet, G. (2007). Natural resource economics under the rule of Hotelling. *Canadian Journal of Economics*, 40(4):1033–1059.
- Giacone, E. and Mancò, S. (2012). Energy efficiency measurement in industrial processes. *Energy*, 38(1):331–345.
- Giatrakos, G. P., Tsoutsos, T. D., and Zografakis, N. (2009). Sustainable power planning for the island of Crete. *Energy Policy*, 37(4):1222–1238.
- Gielen, D. and Taylor, M. (2007). Modelling industrial energy use: The IEAs Energy Technology Perspectives. *Energy Economics*, 29(4):889–912.
- Godfrey-Smith, P. (2006). The strategy of model-based science. *Biol Philos*, 21:725–740.
- GRZ (2006). Vision 2030. Technical Report December, Government of the Republic of Zambia, Lusaka.
- GRZ (2011). Sixth National Development Plan 2011-2015.
- Gupta, C. K. (2003). *Chemical Metallurgy: Principles and Practice*. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.

- Haglund, D. (2010). *Policy evolution and organisational learning in Zambia's*. Phd thesis, University of Bath.
- Harrison, G. P. and Whittington, H. W. (2002). Susceptibility of the Batoka Gorge hydroelectric scheme to climate change. *Journal of Hydrology*, 264(1):230–241.
- Haw, M. H. (2007). *National Energy Modelling for Sustainable Development Planning: 'Road Maps' for South Africa's Energy Future*. Masters thesis, KTH Royal Institute of Technology.
- Heaps, C. G. (2016). Long-range Energy Alternatives Planning (LEAP) system.
- Hearne, J., Dodd, D., Evans, M., Broome, M., Hearne, J., and Kirk, L. (2006). Kalukundi project: Technical Report. Technical report, RSG Global.
- Hibajene, S. H. and Kalumiana, O. S. (2003). Manual for charcoal production in earth kilns in Zambia. Technical report, Ministry of Energy and Water Development, Lusaka.
- Hosier, R. H. and Dowd, J. (1987). Household fuel choice in Zimbabwe. *Resources and Energy*, 9(4):347–361.
- Howells, M. (2009). Contribution to the OSMOSYS forum Open Source energy MOdeling SYStem Working paper : Documentation for OSMOSYS Model.
- Howells, M., Rogner, H., Strachan, N., Heaps, C., Huntington, H., Kypreos, S., Hughes, A., Silveira, S., DeCarolis, J., Bazillian, M., and Roehrl, A. (2011). OSeMOSYS: The Open Source Energy Modeling System. *Energy Policy*, 39(10):5850–5870.
- IEA (2012). Energy Statistics of Non-OECD Countries: 2012 Edition.
- IEA (2015). IEA Headline Global Energy Data.
- IEA/NEA (2010). Projected Costs of Generating Electricity. Technical report, OECD/IEA, Paris.
- IMF (2008). Zambia: Selected Issues. Report No. 08/29. Technical Report 08, International Monetary Fund, Washington.
- IPA (2007). Revised ZESCO's Cost of Service Report to ERB. Technical

- Report March, ERB, Lusaka.
- Jaffe, A. B. and Stavins, R. N. (1994). The Energy Efficiency Gap: What does it mean? *Energy Policy*, 22(10):804–810.
- Javadi, F. S., Rismanchi, B., Sarraf, M., Afshar, O., Saidur, R., Ping, H. W., and Rahim, N. A. (2013). Global policy of rural electrification. *Renewable and Sustainable Energy Reviews*, 19:402–416.
- Jebaraj, S. and Iniyar, S. (2006). A review of energy models. *Renewable and Sustainable Energy Reviews*, 10:281–311.
- JICA/MEWD (2009). Rural electrification master plan for Zambia 2008 - 2030. Technical report, MEWD, Lusaka.
- Jindal, R., Swallow, B., and Kerr, J. (2008). Forestry-based carbon sequestration projects in Africa: Potential benefits and challenges. *Natural Resources Forum*, 32:116–130.
- JORC (2012). Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (The JORC Code).
- Kahneman, D. and Tversky, A. (1979). Prospect Theory: An Analysis of Decision under Risk. *Econometrica*, 47(2):263–292.
- Kalaba, F. K., Helen, C., John, A., and Vinya, R. (2013). Floristic composition, species diversity and carbon storage in charcoal and agriculture fallows and management implications in Miombo woodlands of Zambia. *Forest Ecology and Management*, 304:99–109.
- Kerstholt, H. (1994). The effect of time pressure on decision-making in a dynamic task environment. *Acta Psychologica*, 86:89–104.
- Kesicki, F. (2012). *Decomposing long-run carbon abatement cost curves - robustness and uncertainty*. Phd thesis, University College London.
- Komatsu, S., Kaneko, S., Shrestha, R. M., and Ghosh, P. P. (2011). Non-income factors behind the purchase decisions of solar home systems in rural Bangladesh. *Energy for Sustainable Development*, 15(3):284–292.
- Koppelaar, R. H., Keirstead, J., Shah, N., and Woods, J. (2016). A review of policy analysis purpose and capabilities of electricity system models. *Renewable and Sustainable Energy Reviews*, 59(Supplement C):1531 – 1544.



- Krautkraemer, J. A. (1988). The Cut-Off Grade and the Theory of Extraction. *The Canadian Journal of Economics*, 21(1):146–160.
- Krautkraemer, J. A. (1989). Price Expectations, Ore Quality Selection, and the Supply of a Nonrenewable Resource. *Environmental Economics and Management*, 16:253–267.
- Lambert, R. J. and Stone, B. G. (2008). Feasibility Technical Report: El Morro Copper-Gold Project. Technical report, Pincock, Allen & Holt, Lakewood.
- Levy, H. and Wiener, Z. (2013). Prospect theory and utility theory: Temporary versus permanent attitude toward risk. *Journal of Economics and Business*, 68:1–23.
- Li, F. (2013). *Spatially explicit techno-economic optimisation modelling of UK heating futures*. Phd thesis, University College London.
- Lupala, Z. J., Lusambo, L. P., and Ngaga, Y. M. (2014). Management, Growth, and Carbon Storage in Miombo Woodlands of Tanzania. *International Journal of Forestry Research*, 2014.
- Marsden, J. O. (2008). Energy Efficiency & Copper Hydrometallurgy.
- Masera, O. R., Saatkamp, B. D., and Kammen, D. M. (2000). From Linear Fuel Switching to Multiple Cooking Strategies: A Critique and Alternative to the Energy Ladder Model. *World Development*, 28(12):2083–2103.
- Mayer, Z. and Kazakidis, V. (2007). Decision Making in Flexible Mine Production System Design Using Real Options. *Journal of Construction Engineering and Management*, 133(February):169–181.
- Mckay, M. D., Beckman, R. J., and Conover, W. J. (1979). A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code. *Technometrics*, 21:239–245.
- Mintzberg, H., Raisinghani, D., and Théorêt, A. (1976). The Structure of "Un-structured" Decision Processes. *Administrative Science Quarterly*, 21(2):246–275.
- MOF (2016). 2017 Budget Address by Honourable Felix C. Mutati, MP Minister of Finance. Technical report, Ministry of Finance, Lusaka.
- Montaldo, D. H. (1977). A system dynamics model of an underground

- metal mine. In *System Dynamics Conference*.
- MOP (2016). Gas Master Plan of Ghana. Technical Report June, Ministry of Petroleum of The Rep. of Ghana.
- Moyen, N. and Slade, M. (1996). Valuing risk and flexibility A comparison of methods. *Resources Policy*, 22(96):63–74.
- Mudd, G. M., Weng, Z., and Jowitt, S. M. (2013). A Detailed Assessment of Global Cu Resource Trends and Endowments. *Economic Geology*, 108:1163–1183.
- Mukheibir, P. (2007). Possible climate change impacts on large hydroelectricity schemes in Southern Africa. *Journal of Energy in Southern Africa*, 18(1):4–9.
- Naill, R. F. (1992). A system dynamics model for national energy policy planning. *System Dynamics Review*, 8(1):1–19.
- Nexant (2007). SAPP Regional Generation and Transmission Expansion Plan Study: Main Report. Technical Report October, Southern Africa Power Pool (SAPP), Harare.
- Norgate, T. and Haque, N. (2010). Energy and greenhouse gas impacts of mining and mineral processing operations. *Journal of Cleaner Production*, 18(3):266–274.
- Norgate, T. and Jahanshahi, S. (2010). Low grade ores - Smelt, leach or concentrate? *Minerals Engineering*, 23(2):65–73.
- Northey, S., Mohr, S., Mudd, G. M., Weng, Z., and Giurco, D. (2014). Modelling future copper ore grade decline based on a detailed assessment of copper resources and mining. *Resources, Conservation & Recycling*, 83:190–201.
- OECD/IEA (2010). Energy Poverty: How to make modern energy access universal? Special Early Excerpt of the World Energy Outlook 2010 for the UN General Assembly on the Millennium Development Goals. Technical Report September, Paris, France.
- Osemosys (2013). Osemosys. <http://osemosysmain.yolasite.com/>.
- Ouedraogo, B. I., Kouame, S., Azoumah, Y., and Yamegueu, D. (2015). Incentives for rural off grid electrification in Burkina Faso using LCOE.

- Renewable Energy*, 78:573–582.
- Pandey, R. (2002). Energy policy modelling : agenda for developing countries. *Energy Policy*, 30:97–106.
- Parker, C., Mitchell, A., Trivedi, M., and Mardas, N. (2009). The Little REDD+ Book.
- Patterson, M. G. (1996). What is energy efficiency? Concepts, indicators and methodological issues. *Energy Policy*, 24(5):377–390.
- Payne, J. W., Bettman, J. R., and Johnson, E. J. (1988). Adaptive Strategy Selection in Decision Making. *Experimental Psychology*, 14(3):534–552.
- Peck, M. and Chipman, R. (2007). Industrial energy and material efficiency: What role for policies? In *Industrial development for the 21st century: sustainable development perspectives*, pages 333–385. United Nations: Department of Economic and Social Affairs.
- Peters, B., Parker, H., Seibel, G., Jakubec, J., Lawson, M., Weissenberger, A., and Marais, F. (2013). Preliminary economic assessment: Kamoia copper project. Technical report, AMC Consultants Pty Ltd, ADELAIDE.
- Phelan, S. E. (1997). Exposing the illusion of confidence in financial analysis. *Management Decision*, 35(2):163–168.
- Phylipsen, D., Blok, K., Worrell, E., and Beer, J. D. (2002). Benchmarking the energy efficiency of Dutch industry: an assessment of the expected effect on energy consumption and CO2 emissions. *Energy Policy*, 30(8):663–679.
- Prain, R. (1975). *Copper: The anatomy of an industry*. Mining Journal Books Limited, 1st edition.
- R Core Team (2017). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria.
- Radetzki, M. (2009). Seven thousand years in the service of humanity - the history of copper, the red metal. *Resources Policy*, 34(4):176–184.
- Ragab, R. and Prudhomme, C. (2002). Soil and Water: Climate Change and Water Resources Management in Arid and Semi-arid Regions: Prospective and Challenges for the 21st Century. *Biosystems Engineer-*

- ing*, 81(1):3–34.
- Ramana, M. and Kumar, A. (2009). Least cost principles and electricity planning for Karnataka. *Energy for Sustainable Development*, 13(4):225–234.
- RECP (2017). Renewable Energy Potential.
- Riekkola-Vanhanen, M. (1999). Finnish expert report on best available techniques in copper production and by-production of precious metals. Technical report, Finnish Environment Institute, Helsinki.
- RMI (2015). Technology capital cost projections, 2010-2050.
- Rohdin, P., Thollander, P., and Solding, P. (2007). Barriers to and drivers for energy efficiency in the Swedish foundry industry. *Energy Policy*, 35(1):672–677.
- Rosnes, O. and Vennemo, H. (2012). The cost of providing electricity to Africa. *Energy Economics*, 34(5):1318–1328.
- Ross, J. G. (2004). Risk and uncertainty in portfolio characterisation. *Petroleum Science and Engineering*, 44:41–53.
- Rothschild (2008). KCM Valuation Report: Prepared for ZCI Holdings SA and Vedanta Resources Plc. Technical Report January, N M Rothschild & Sons Limited, London.
- Ruijven, B. V., Urban, F., Benders, R. M., Moll, H. C., Sluijs, J. P. V. D., Vries, B. D., and Vuuren, D. P. V. (2008). Modeling Energy and Development: An Evaluation of Models and Concepts. *World Development*, 36(12):2801–2821.
- Ruijven, B. V., Vries, B. D., Vuuren, D. P. V., and Sluijs, J. P. V. D. (2010). A global model for residential energy use: Uncertainty in calibration to regional data. *Energy*, 35(1):269–282.
- Sabour, S. A. A. (2001). Dynamics of threshold prices for optimal switches : the case of mining. *Resources Policy*, 27:209–214.
- Saidur, R., Rahim, N., Masjuki, H., Mekhilef, S., Ping, H., and Jamaluddin, M. (2009). End-use energy analysis in the Malaysian industrial sector. *Energy*, 34(2):153–158.
- Sarkar, A. and Singh, J. (2010). Financing energy efficiency in developing

- countries - lessons learned and remaining challenges. *Energy Policy*, 38(10):5560–5571.
- Savolainen, J. (2016). Real options in metal mining project valuation: Review of literature. *Resources Policy*, 50:49–65.
- Saygin, D., Worrell, E., Patel, M., and Gielen, D. (2011). Benchmarking the energy use of energy-intensive industries in industrialized and in developing countries. *Energy*, 36(11):6661–6673.
- Schleich, J. (2009). Barriers to energy efficiency: A comparison across the German commercial and services sector. *Ecological Economics*, 68(7):2150–2159.
- Sick, G. and Cassano, M. (2012). Forward Copper Price Models A Kalman Filter Analysis.
- Simon, H. A. (1955). A behavioral model of rational choice. *Quarterly Journal of Economics*, 59:99–118.
- Simon, H. A. and Newell, A. (1958). Heuristic Problem Solving: The Next Advance in Operations Research. *Operations Research*, 6(1):1–10.
- Slade, M. E. (1984). Tax Policy and the Supply of Exhaustible Resources: Theory and Practice. *Land Economics*, 60(2):133–147.
- Slade, M. E. (2001). Valuing Managerial Flexibility : An Application of Real-Option Theory to Mining Investments. *Environmental Economics and Management*, 41:193–233.
- SNL (2015). SNL Metal and Mineral Database.
- Sola, A. V. H. and Mota, C. M. D. M. (2012). A multi-attribute decision model for portfolio selection aiming to replace technologies in industrial motor systems. *Energy Conversion and Management*, 57:97–106.
- Sola, A. V. H., Mota, C. M. D. M., and Kovalski, J. L. (2011). A model for improving energy efficiency in industrial motor system using multicriteria analysis. *Energy Policy*, 39(6):3645–3654.
- Spalding-Fecher, R., Chapman, A., Yamba, F., Walimwipi, H., Kling, H., Tembo, B., Nyambe, I., and Cuamba, B. (2016). The vulnerability of hydropower production in the Zambezi River Basin to the impacts of climate change and irrigation development. *Mitigation and Adaptation*

- Strategies for Global Change*, 21(5):721–742.
- Spalding-Fecher, R., Senatla, M., Yamba, F., Lukwesa, B., Himunzowa, G., Heaps, C., Chapman, A., Mahumane, G., Tembo, B., and Nyambe, I. (2017). Electricity supply and demand scenarios for the Southern African power pool. *Energy Policy*, 101(Supplement C):403–414.
- Spataru, C., Kok, Y. C., Barrett, M., and Sweetnam, T. (2015). Techno-economic assessment for optimal energy storage mix. *Energy Procedia*, 83(Supplement C):515 – 524. Sustainability in Energy and Buildings: Proceedings of the 7th International Conference SEB-15.
- Sterman, J. D. (2000). *Systems Thinking and Modeling for a Complex World*. The McGraw-Hill Companies, Boston.
- Stevens, H. J. (1903). *The Copper Handbook*. Horace J. Stevens, Houghton, Michigan, vol. iii edition.
- Strachan, N., Fais, B., and Daly, H. (2016). Reinventing the energy modelling-policy interface. *Nature Energy*, 1:16012.
- Suarez, M. M. and Fernandez, P. L. (2009). Commodities prices modeling using gaussian poisson - exponential stochastic processes, a practical. In Otamendi, J., Bargiela, A., Montes, J. L., and Pedrera, L. M. D., editors, *European Conference on Modelling and Simulation*, number January. European Conference on Modelling and Simulation.
- Suganthi, L. and Samuel, A. a. (2012). Energy models for demand forecasting - A review. *Renewable and Sustainable Energy Reviews*, 16(2):1223–1240.
- Summers, D. M., Bryan, B. A., Nolan, M., and Hobbs, T. J. (2015). Land Use Policy The costs of reforestation: A spatial model of the costs of establishing environmental and carbon plantings. *Land Use Policy*, 44:110–121.
- Sverdrup, H. U., Vala, K., and Koca, D. (2014). On modelling the global copper mining rates, market supply, copper price and the end of copper reserves. *Resources, Conservation & Recycling*, 87:158–174.
- Tadross, M., Jack, C., and Hewitson, B. (2005). On RCM-based projections of change in southern African summer climate. *Geophysical Research*

- Letters*, 32(23):L23713.
- Tanaka, K. (2011). Review of policies and measures for energy efficiency in industry sector. *Energy Policy*, 39(10):6532–6550.
- Taylor, T. R. B., Ford, N., and Ford, A. (2010). Improving model understanding using statistical screening. *System Dynamics Review*, 26(1):73–87.
- Tembo, B. (2012). *Policy Options for the Sustainable Development of the Power Sector in Zambia*. Masters thesis, University of Cape Town.
- Thirugnanasambandam, M., Hasanuzzaman, M., Saidur, R., Ali, M. B., and Rajakarunakaran, S. (2011). Analysis of electrical motors load factors and energy savings in an Indian cement industry. *Energy*, 36:4307–4314.
- Todd, P. M. and Gigerenzer, G. (2000). Précis of Simple heuristics that make us smart. *The Behavioral and Brain Sciences*, 23(5):727–780.
- Tole, L. and Koop, G. (2013). Strathprints Institutional Repository. *Productivity Analysis*, 39(1):35–45.
- Trianni, A. and Cagno, E. (2012). Dealing with barriers to energy efficiency and SMEs: Some empirical evidences. *Energy*, 37(1):494–504.
- Trianni, A., Cagno, E., Thollander, P., and Backlund, S. (2013). Barriers to industrial energy efficiency in foundries: a European comparison. *Journal of Cleaner Production*, 40:161–176.
- UNIDO (2012). Energy efficiency in electric motor systems: Technology, saving potentials and policy options developing countries. Technical report, United Nations Industrial Development Organization, Vienna.
- Urban, F., Benders, R. M. J., and Moll, H. C. (2007). Modelling energy systems for developing countries. *Energy Policy*, 35:3473–3482.
- USGS (2013). Commodity Statistics and Information.
- Usher, W. (2016). *The Value of Learning about Critical Energy System Uncertainties*. Phd thesis, University College London.
- van Ruijven, B. J., Schers, J., and van Vuuren, D. P. (2012). Model-based scenarios for rural electrification in developing countries. *Energy*, 38(1):386–397.

- Vedanta (2015). Vedanta Annual Report. Technical report, Vedanta Resources, London.
- Ventana (2015). Vensim Professional Version. [www.vensim.com/](http://www.vensim.com/).
- Wang, K., Wang, C., Lu, X., and Chen, J. (2007). Scenario analysis on CO<sub>2</sub> emissions reduction potential in China's iron and steel industry. *Energy Policy*, 35:2320–2335.
- Wang, X., van Dam, K. H., Triantafyllidis, C., Koppelaar, R. H., and Shah, N. (2017). Water and energy systems in sustainable city development: A case of sub-saharan africa. *Procedia Engineering*, 198(Supplement C):948 – 957. Urban Transitions Conference, Shanghai, September 2016.
- Weber, L. (1997). Viewpoint: Some reflections on barriers to the efficient use of energy. *Energy Policy*, 25(10):833–835.
- Weisberg, M. (2007). Who is a Modeler? *The British Journal for the Philosophy of Science*, 58(2):207–233.
- Welch, W. J., Buck, R. J., Sacks, J., Wynn, H. P., Toby, J., Morris, M. D., Welch, W. J., Buck, R. J., Wynn, H. P., Mitchell, T. J., and Morris, M. D. (1992). Screening, Predicting, and Computer Experiments. *Technometrics*, 34(1):15–25.
- Welsch, M., Howells, M., Bazilian, M., DeCarolis, J. F., Hermann, S., and Rogner, H. H. (2012). Modelling elements of Smart Grids - Enhancing the OSeMOSYS (Open Source Energy Modelling System) code. *Energy*, 46(1):337–350.
- William, G., Soltan, M. O., and Johnson, P. V. (2012). Mineral reserves under price uncertainty. *Resources Policy*, 37(3):340–345.
- Wilson, C. and Dowlatabadi, H. (2007). Models of Decision Making and Residential Energy Use. *Annual Review of Environment and Resources*, 32(1):169–203.
- Wolstenholme, E. F. (1982). System Dynamics in Perspective. *The Journal of the Operational Research Society*, 33(6):547–556.
- World Bank (2013). World Bank databases. <http://databank.worldbank.org/data/databases.aspx>.
- World Bank (2015). GEM Commodities. <http://data.worldbank.org/data->



- catalog/commodity-price-data.
- World Bank (2018). Renewable Energy Resource Mapping in Zambia. <https://www.esmap.org/node/3300>.
- Worrell, E. and Price, L. (2001). Policy scenarios for energy efficiency improvement in industry. *Energy Policy*, 29(April 2001):1223–1241.
- Worrell, E., Ramesohl, S., and Boyd, G. (2004). Advances in Energy Forecasting Models Based on Engineering Economics. *Annual Review of Environment and Resources*, 29(1):345–381.
- Young, D. (1992). Cost Specification and Firm Behaviour in a Hotelling Model of Resource Extraction. *The Canadian Journal of Economics*, 25(1):41–59.
- ZESCO (2008). Environmental Impact Assessment - Addendum of the Itezhi Tezhi Hydroelectric Project. Technical report, ZESCO, Lusaka.
- ZESCO (2009). General Description of the Electricity System.
- ZESCO (2013). Zesco Electricity Statistics.
- Zeyringer, M., Pachauri, S., Schmid, E., Schmidt, J., Worrell, E., and Morawetz, U. B. (2015). Analyzing grid extension and stand-alone photovoltaic systems for the cost-effective electrification of Kenya. *Energy for Sustainable Development*, 25:75–86.
- ZRA (2013). Economic and Taxation Statistics.



# Appendix A

## Appendix to Chapter 1

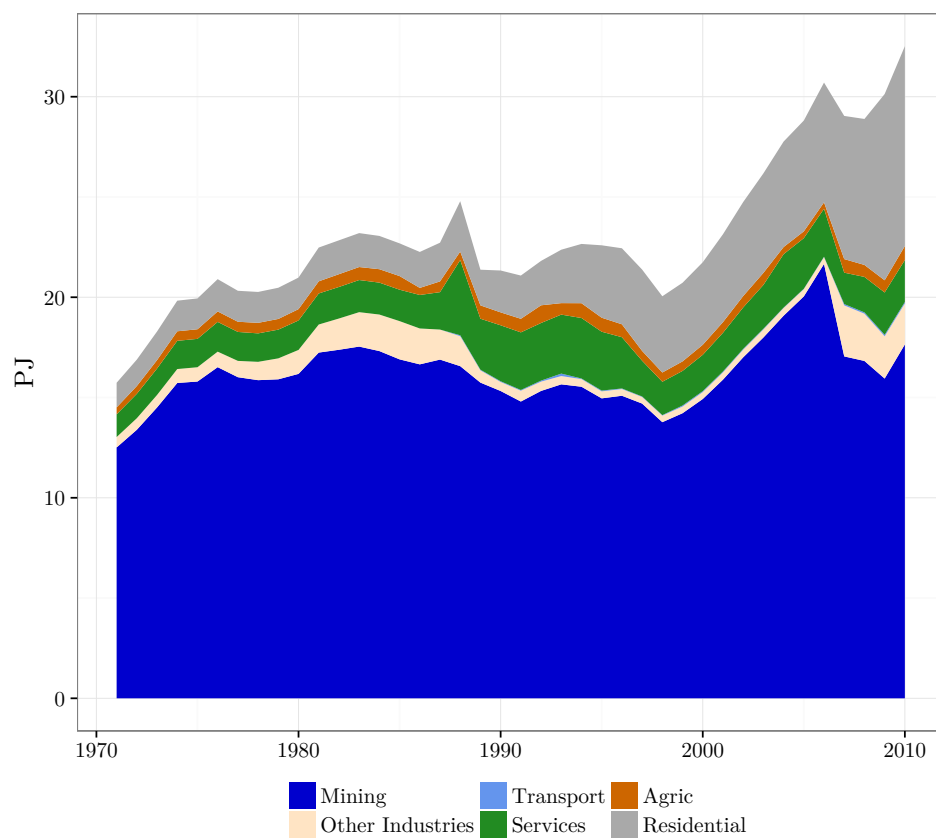


Figure A.1: Zambia's historical total final electricity consumption ([ERB, 2013](#); [IEA, 2012](#); [ZESCO, 2013](#))

## A.1 State of the electricity sector in Zambia

Zambia's electricity sector is dominated by hydro-power technologies. As of 31st March 2013, 99% of all electricity supply came from hydro technologies, most of which were built in the 1960s and 1970s. Even though Zambia's generation sub-sector has been privatised, the participation of Independent Private Producer (IPP) is still low. The most notable IPP are [CEC](#) and [Lunsemfwa Hydro Power Limited \(LHPL\)](#). This is largely due to the low electricity tariffs that have not encouraged investment into the sector ([ERB, 2015](#)).

Furthermore, the role of hydro technologies is projected to continue playing a critical role in the energy sector as most of its available resource (of 4, 500 MW) requires low capital investment cost. Apart from hydro, a number of coal and solar projects have been identified. However, there have been no sites for wind, natural gas and nuclear technologies that have been earmarked for development.

### A.1.1 Energy markets

Zambia's electricity supply is sourced from within the country and it is also one of the major electricity exporters in the SAPP region. Local electricity tariff is regulated by [ERB](#) while the export price is determined by supply and demand on the SAPP market. The local electricity tariffs have for a long time not been cost reflective as was acknowledged by [ERB \(2015; 2017\)](#). These low tariffs were as a result of the desire to stimulate economic growth (through the Mining sector) after the country had experienced economic down turn for about three decades, prior to privatisation of the mines (which happened in the late 1990s and early 2000s). Apart from that, electricity tariff is a sensitive political issue (which could come with significant electoral consequences) in Zambia, thus successive government has been forced to continue subsidising the sector.

The electricity tariffs within Zambia between 2004 and 2011, ranged between USc 1.91 and USc 5.44 per kWh. Local tariffs are quoted in

Kwacha. The tariffs shown in Figure A.1 below take into account the fluctuations in the exchange rate between the Kwacha and US Dollar. At these tariff levels, ZESCO made an estimate gross profit margin of between 10% and 30%. This is because the largest plants for ZESCO are almost fully amortised. However, this tariff is not profitable for development of new generation capacity. As ERB (2015) observed, a cost reflective tariff in Zambia could be about USc 10.40 per kWh.

Table A.1: Electricity tariffs in Zambia

Year	Units	Average Residential	Average Commercial	Average Large Users	Average Tariff
2004	USc/kWh	1.70	3.27	2.14	1.91
2005	USc/kWh	2.62	3.41	2.25	2.13
2006	USc/kWh	3.02	3.93	2.67	2.54
2007	USc/kWh	3.54	4.84	2.51	2.41
2008	USc/kWh	2.31	2.18	3.33	2.67
2009	USc/kWh	2.24	3.47	4.16	3.54
2010	USc/kWh	4.09	3.41	4.52	4.16
2011	USc/kWh	6.14	4.54	5.85	5.44

Source: ERB (2013)

## A.1.2 Electricity generation stock

Table A.2: Electricity generation capacity as of 31st March 2013

Type of Plant	Capacity (MW)	Owner of Plant
Hydro	1, 842.8	ZESCO
Diesel (off-grid)	10.8	ZESCO
OGT (Diesel/Gas)	80.0	CEC
Hydro	54.0	LHPL

Source: [ZESCO \(2013\)](#)

# Appendix B

## Appendix to Chapter 2

### B.1 Global consumption of copper

Table B.1: Copper consumption by country for 2011 ([Cochilco, 2012](#))

Country	Share (%)	Country	Share (%)
China	40.6	Spain	1.6
USA	9.0	Poland	1.3
Germany	6.4	Belgium	1.2
Japan	5.2	Mexico	1.2
South Korea	3.8	Thailand	1.2
Russia	3.5	Indonesia	1.1
Italy	3.1	Malaysia	1.1
Taiwan	2.3	Iran	1.0
Brazil	2.2	France	0.9
India	2.1	Other	9.2
Turkey	2.0		

## B.2 List of mine operators

Table B.2: Operating firms in Zambia as of 2011 (USGS, 2013)

Company	Major equity owners (%)	Facility
Kansanshi	Kansanshi H. Ltd, 79.4	Kansanshi Mine
	ZCCM-IH, 20.6	SX/EW Plant
FQM	FQM, 100	Ndola SX/EW Plant
Lumwana	Barrick Gold Corp., 100	Lumwana Mine
KCM PLC	Vedanta Res. PLC, 79.4 ZCCM-IH, 20.6	Nchanga Mine
		Chingola Mine
		Konkola Mine
		Nchanga Smelter
		Kitwe Refinery
		Chingola Tailings
		SX/EW Plant
MCM	Carlisa Inv. Corp., 90 ZCCM-IH, 10	Nkana Mine
		Mufulira Mine
		Nkana Cobalt Plant
		Mufulira Smelter
		Mufulira Refinery
		Nkana SX/EW Plant
NFCA	CNMM, 85	Chambishi Mine
	ZCCM-IH, 15	

*Continued on next page*



Table B.2: Operating firms in Zambia as of 2011 *Continued*

Company	Major equity owners (%)	Facility
Luanshya	NFCA, 100	Baluba Mine
Sino-Metals	CNMM & NFCA & China Hainan & Sino-Africa, 100	SX/EW Plant
Chambishi S.	CNMM, 60 YCI, 40	Chambishi Smelter
Chibuluma	Metorex Ltd, 85 ZCCM-IH, 15	Chibuluma Mine
Chambishi M.	ENRC PLC, 85 ZCCM-IH, 15	Cobalt Plant
Albidon Ltd		Munali Mine
Sable	Metorex Ltd, 100	Sable SX/EW Plant

Table B.3: Companies' full name

Name abbr.	Full Name
Kansanshi	Kansanshi Mining PLC
Kansanshi H. Ltd	Kansanshi Holdings Ltd
FQM	First Quantum Minerals Ltd
ZCCM-IH	ZCCM Investments Holding PLC
KCM PLC	Konkola Copper Mines PLC
Lumwana	Lumwana Mining Copper Ltd
MCM	Mopani Copper Mines PLC
Luanshya	Luanshya Copper Mines Ltd
NFCA	NFC Africa Mining PLC
CNMM	China Nonferrous Metal Mining Group
Sino-Metals	Sino-Metals Leach Zambia Ltd
YCI	Yunnan Copper Industry Group
Chibuluma	Chibuluma Mines PLC
Chambishi M.	Chambishi Metals PLC
Chambishi S.	Chambishi Copper Smelting Company Ltd
Sable	Sable Zinc Kabwe Ltd

## B.3 Mineral resources in Zambia

These resources are categorised by mining grouping level.

Table B.4: Mineral Resources in Zambia (SNL, 2015)

Mining grouping	Ore type	Share (%)	Copper	By-product
C-OP	Sulphide (tonnes)	50	322,238,000	
	Oxide (tonnes)	50	322,238,000	
	Cobalt (tonnes)	100		153,102
	Gold (oz)	100		0
	Nickel (tonnes)	100		0
	Uranium (tonnes)	100		0
C-UG	Sulphide (tonnes)	80	1,145,400,000	
	Oxide (tonnes)	20	286,350,000	
	Cobalt (tonnes)	100		331,536
	Gold (oz)	100		0
	Nickel (tonnes)	100		0
	Uranium (tonnes)	100		0
NW-OP	Sulphide (tonnes)	99	3,066,678,000	
	Oxide (tonnes)	1	1,867,000	
	Cobalt (tonnes)	100		435,000
	Gold (oz)	100		4,929,000
	Nickel (tonnes)	100		580,000
	Uranium (tonnes)	100		8,470

C-OP – Copperbelt Open Pit;

C-UG – Copperbelt Underground;

NW-OP – North-Western Open Pit



# Appendix C

## Appendix to Chapter 5

### C.1 CSO summary statistics

These statistics were extracted from [CSO Living Conditions Monitoring Survey 2004 report \(CSO, 2005\)](#).

Table C.1: Classification by lighting fuels in 2004

Fuel	Region	
	Urban (%)	Rural (%)
Electricity	47.6	3.1
Kerosene	19.5	62.3
Candles	31.5	9.7
Other	1.4	24.9

Table C.2: Classification by cooking fuels in 2004

Fuel	Region	
	Urban (%)	Rural (%)
Electricity	39.3	1.7
Charcoal	52.6	11.3
Wood	7.8	86.6
Other	0.3	0.4

## C.2 Input data for demand model

Table C.3: Residential total final energy intensities

Region	Unit	Energy Service		
		Cooking & Heating	Lighting	Other Uses
Urban				
Electricity	GJ/HH	11.72	0.114	See Eq. 5.9
Charcoal	GJ/HH	31.75		
Wood	GJ/HH	54.43		
Gas	GJ/HH	20.6		
Kerosene	GJ/HH		0.58	
Rural				
Electricity	GJ/HH	11.99	0.068	See Eq. 5.9
Charcoal	GJ/HH	32.46		
Wood	GJ/HH	54.67		
Gas	GJ/HH	21.06		
Kerosene	GJ/HH		0.60	

These intensities were estimated based on data from CSO (1994; 1996; 2003; 2005; 2012) and IEA (2012).

Table C.4: Economic sectors' total final energy intensities

Factor	Unit	Sector			
		Agric	Transport	Services	Other Ind.
Electricity	MJ/US\$	0.580	0.163	0.484	1.052
Diesel	MJ/US\$	0.841	25.100		1.111
Petrol	MJ/US\$	0.026	14.290		0.132
Kerosene	MJ/US\$	0.034			0.105
Coal	MJ/US\$				0.012
Gas	MJ/US\$				0.041
HFO	MJ/US\$				0.105
Jet Fuel	MJ/US\$		3.402		

All monetary units are in US\$ 2005 constant price.

These intensities were estimated based on data from [CSO \(2013\)](#), [World Bank \(2013\)](#) and [IEA \(2012\)](#).

### C.3 Regression results details

Table C.5: Regression Results

	<i>Dependent variable:</i>
	Energy Int. (GJ/HH)
Income variable	6.504*** (1.084)
Constant	-45.045*** (8.711)
Observations	10
R <sup>2</sup>	0.818
Adjusted R <sup>2</sup>	0.795
Residual Std. Error	0.322 (df = 8)
F Statistic	36.006*** (df = 1; 8)
<i>Note:</i>	*p<0.1; **p<0.05; ***p<0.01



## C.4 Projections of energy demand drivers

This section gives the projections for key energy drivers in all sectors apart from the mining sector; projections for the mining sector are given in section D.5 of Appendix D below.

All the data in the ‘2010’ column in all the Tables of this section are actual statistics, the rest are my own projections based on the assumptions that were used in this study. The source of data for 2010 statistics are [CSO \(2012\)](#) and [ZRA \(2013\)](#).

Table C.6: Population projections

Variable	Unit	2010	2020	2030	2040	2050
Population	Million	13.090	18.300	23.500	29.200	34.900
Households	Million	2.510	3.520	4.530	5.640	6.750
Rural	Percent	59.530	55.750	51.990	47.990	44
Urban	Percent	40.470	44.250	48.010	52.010	56

Table C.7: Sectorial GDP projections

Variable	Unit	2010	2020	2030	2040	2050
Agric	Scenario 1	1.267	1.928	2.934	4.557	7.076
Other Ind.	Scenario 1	2.363	3.595	5.471	8.496	13.194
Services	Scenario 1	4.668	7.102	10.807	16.783	26.064
Transport	Scenario 1	0.496	0.619	0.888	1.322	1.993
Agric	Scenario 2	1.267	1.928	2.934	4.557	7.076
Other Ind.	Scenario 2	2.363	3.595	5.471	8.496	13.194
Services	Scenario 2	4.668	7.102	10.807	16.783	26.064
Transport	Scenario 2	0.496	0.647	0.941	1.402	2.100
Agric	Scenario 3	1.267	1.928	2.934	4.557	7.076
Other Ind.	Scenario 3	2.363	3.595	5.471	8.496	13.194
Services	Scenario 3	4.668	7.102	10.807	16.783	26.064
Transport	Scenario 3	0.496	0.647	0.941	1.402	2.100
Agric	Scenario 4	1.267	2.223	3.902	6.988	12.514
Other Ind.	Scenario 4	2.363	4.145	7.275	13.028	23.332
Services	Scenario 4	4.668	8.189	14.372	25.738	46.092
Transport	Scenario 4	0.496	0.725	1.197	2.045	3.539
Agric	Scenario 5	1.267	2.223	3.902	6.988	12.514
Other Ind.	Scenario 5	2.363	4.145	7.275	13.028	23.332
Services	Scenario 5	4.668	8.189	14.372	25.738	46.092
Transport	Scenario 5	0.496	0.725	1.197	2.045	3.539

Table C.8: Rural cooking &amp; heating fuel shares

Scenario	Variable	Unit	2010	2020	2030	2040	2050
Scenario 1	Gas	Percent	0	0	0	0	0
Scenario 1	Charcoal	Percent	12.2	23.6	35	41	47
Scenario 1	Electricity	Percent	2	8.7	15	26.3	37.5
Scenario 1	Wood	Percent	85.8	67.7	50	32.8	15.5
Scenario 2	Gas	Percent	0	0	0	0	0
Scenario 2	Charcoal	Percent	12.2	23.6	35	41	47
Scenario 2	Electricity	Percent	2	8.7	15	26.3	37.5
Scenario 2	Wood	Percent	85.8	67.7	50	32.8	15.5
Scenario 3	Gas	Percent	0	0	0	0	0
Scenario 3	Charcoal	Percent	12.2	23.6	35	41	47
Scenario 3	Electricity	Percent	2	9.4	17.5	32.8	50
Scenario 3	Wood	Percent	85.8	67	47.5	26.2	3
Scenario 4	Gas	Percent	0	0	0	25	50
Scenario 4	Charcoal	Percent	12.2	23.6	35	25	15
Scenario 4	Electricity	Percent	2	21.6	43.8	39.4	35
Scenario 4	Wood	Percent	85.8	54.8	21.2	10.6	0
Scenario 5	Gas	Percent	0	0	0	0	0
Scenario 5	Charcoal	Percent	12.2	23.6	35	32.5	30
Scenario 5	Electricity	Percent	2	21.6	43.8	56.3	70
Scenario 5	Wood	Percent	85.8	54.8	21.3	11.3	0

Table C.9: Urban cooking &amp; heating fuel shares

Scenario	Variable	Unit	2010	2020	2030	2040	2050
Scenario 1	Gas	Percent	0	0	0	0	0
Scenario 1	Charcoal	Percent	53.9	53.7	53.5	44.5	35.5
Scenario 1	Electricity	Percent	38.6	40.4	43.5	54	64.5
Scenario 1	Wood	Percent	7.5	5.9	3	1.5	0
Scenario 2	Gas	Percent	0	0	0	0	0
Scenario 2	Charcoal	Percent	53.9	53.7	53.5	44.5	35.5
Scenario 2	Electricity	Percent	38.6	40.4	43.5	54	64.5
Scenario 2	Wood	Percent	7.5	5.9	3	1.5	0
Scenario 3	Gas	Percent	0	0	0	0	0
Scenario 3	Charcoal	Percent	53.9	50.1	46.3	30.2	14
Scenario 3	Electricity	Percent	38.6	43.8	50.8	67.5	86
Scenario 3	Wood	Percent	7.5	6.1	3	2.4	0
Scenario 4	Gas	Percent	0	0	0	25	50
Scenario 4	Charcoal	Percent	53.9	37.9	21.8	10.9	0
Scenario 4	Electricity	Percent	38.6	55.2	75.3	62.7	50
Scenario 4	Wood	Percent	7.5	6.9	2.9	1.5	0
Scenario 5	Gas	Percent	0	0	0	0	0
Scenario 5	Charcoal	Percent	53.9	37.9	21.8	10.9	0
Scenario 5	Electricity	Percent	38.6	55.2	75.3	87.2	100
Scenario 5	Wood	Percent	7.5	7	3	1.9	0

Table C.10: Lighting fuel shares

Region	Scenario	Variable	Unit	2010	2020	2030	2040	2050
Rural	Scenario 1	Kerosene	Percent	32.8	23.9	15	9	3
Rural	Scenario 1	Electricity	Percent	0	0	0	0	0
Urban	Scenario 1	Kerosene	Percent	7.5	5.2	3	1.5	0
Urban	Scenario 1	Electricity	Percent	0	0	0	0	0
Rural	Scenario 2	Kerosene	Percent	32.8	23.9	15	9	3
Rural	Scenario 2	Electricity	Percent	0	0	0	0	0
Urban	Scenario 2	Kerosene	Percent	7.5	5.2	3	1.5	0
Urban	Scenario 2	Electricity	Percent	0	0	0	0	0
Rural	Scenario 3	Kerosene	Percent	32.8	23.9	15	9	3
Rural	Scenario 3	Electricity	Percent	0	0	0	0	0

*Continued on next page*

Table C.10: Lighting fuel shares *Continued*

Region	Scenario	Variable	Unit	2010	2020	2030	2040	2050
Urban	Scenario 3	Kerosene	Percent	7.5	5.2	3	1.5	0
Urban	Scenario 3	Electricity	Percent	0	0	0	0	0
Rural	Scenario 4	Kerosene	Percent	32.8	23.9	15	9	3
Rural	Scenario 4	Electricity	Percent	0	0	0	0	0
Urban	Scenario 4	Kerosene	Percent	7.5	5.2	3	1.5	0
Urban	Scenario 4	Electricity	Percent	0	0	0	0	0
Rural	Scenario 5	Kerosene	Percent	32.8	23.9	15	9	3
Rural	Scenario 5	Electricity	Percent	0	0	0	0	0
Urban	Scenario 5	Kerosene	Percent	7.5	5.2	3	1.5	0
Urban	Scenario 5	Electricity	Percent	0	0	0	0	0

Table C.11: Other Uses fuel shares

Region	Scenario	Variable	Unit	2010	2020	2030	2040	2050
Rural	Scenario 1	Electricity	Percent	2.2	8.1	14	24.5	35
Urban	Scenario 1	Electricity	Percent	36.2	37.7	40.6	50.4	60.2
Rural	Scenario 2	Electricity	Percent	2.2	8.1	14	24.5	35
Urban	Scenario 2	Electricity	Percent	36.2	37.7	40.6	50.4	60.2
Rural	Scenario 3	Electricity	Percent	2.2	8.1	14	24.5	35
Urban	Scenario 3	Electricity	Percent	36.2	37.7	40.6	50.4	60.2
Rural	Scenario 4	Electricity	Percent	2.2	18.6	35	42	49
Urban	Scenario 4	Electricity	Percent	36.2	47.5	60.2	65.1	70
Rural	Scenario 5	Electricity	Percent	2.2	18.6	35	42	49
Urban	Scenario 5	Electricity	Percent	36.2	47.5	60.2	65.1	70

## C.5 Input data for supply model

Note that wind technology was not included on the list of possible technologies because there is no recorded wind resource suitable for electricity production in Zambia ([RECP, 2017](#)).

- The transmission and distribution losses were estimated to average 15%.
- Input to biomass technology was assumed to come from the sugar industry, not from the forestry sector (This is based on the characteristic of the bio-technology as described in [Nexant \(2007\)](#)).



Table C.12: LCoE input data

Variable	Unit	Big Hydro	Small Hydro	Gas	Coal*	Oil	Bio	Solar CSP	Solar PV**	Imports
PV Capital Cost	\$/kW	2,564.65	4,480.86	1,307	3,386.37	709	4,029	6,244	3,333	0
Fixed O&M	\$/MWh	2.48	3.97	2.33	2.87	0.93	15.14	9.55	7.92	0
Variable O&M	\$/MWh	1.01	0.88	1.02	5.76	1.02	4.08	0	0	40.75
Efficiency	Percent	100	100	48.21	36.82	30.19	37.50	100	100	100
Fuel Cost	\$/MWh	0	0	27.40	6.65	21.51	0	0	0	0
Availability	Percent	57	40	90	85	90	85	41	27	80
Life Time	Years	50	40	30	30	30	30	30	25	50
LCoE	\$/MWh	47.06	122.11	75.17	67.40	81.29	69.95	177.72	162.54	40.75

Discount Rate of 8% was used.

All costs and plant characteristics are based on [Nexant \(2007\)](#) and the monetary values were adjusted to US\$ 2010 constant price.

\* This is supercritical coal technology.

\*\* This is Solar PV (W-DC) that is connected directly to the end-user.

The Variable O&M costs for Oil, Gas and Coal technologies also include fuel costs (in the model).

Reserve margin of 15% was used.

Discount Rate of 8% was used.

Table C.13: Minimum electricity generating capacity to develop (MW)

Year	GenCooMaa	GenHydIT	GenHydKNE	GenHydKGL	GenHydNM	GenHydKL	GenHydKKB
2010	0	0	0	0	0	0	0
2015	0	120	360	0	30	0	0
2020	300	120	360	0	30	210	40
2025	300	120	360	750	30	210	40
2030	300	120	360	750	30	210	40
2035	300	120	360	750	30	210	40
2040	300	120	360	750	30	210	40
2045	300	120	360	750	30	210	40
2050	300	120	360	750	30	210	40

This table shows the capacity that is expected to be developed because investment capital has already been secured and committed to their development.

Table C.14: Techno-economic data electricity generating technologies

Technology	Input	Output	Eff. Percent	Var. Costs US\$/GJ	Cap. Factor Percent	Life Yr	Inv. Cost US\$/kW	Fix. Costs US\$/kW	First Yr	Max. Cap. MW
GenOilEx	Oil	Elec/Sec	29.6	24.24	85	30	0	8.40	Already	10
GenHydKN	Hydro	Elec/Sec	100.0	0.42	65	50	0	9.16	Already	720
GenHydKG	Hydro	Elec/Sec	100.0	0.42	77	50	0	9.16	Already	990
GenHydVF	Hydro	Elec/Sec	100.0	0.42	71	50	0	9.16	Already	108
GenHydLF	Hydro	Elec/Sec	100.0	0.42	61	50	0	9.16	Already	48
GenHydEM	Hydro	Elec/Fin	100.0	0.42	29	30	0	9.16	Already	23
GenCoaMaa	Coal	Elec/Sec	37.0	8.81	93	35	2,898	20.98	2016	300
GenHydIT	Hydro	Elec/Sec	100.0	0.42	66	50	3,012	9.16	2013	120
GenHydKNE	Hydro	Elec/Sec	100.0	0.42	38	50	1,054	9.16	2013	360
GenHydKGL	Hydro	Elec/Sec	100.0	0.42	47	50	2,753	9.16	2021	750

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Table C.14: Techno-economic data electricity generating technologies *Continued*

Technology	Input	Output	Eff. Percent	Var. Costs US\$/GJ	Cap. Factor Percent	Life Yr	Inv. Cost US\$/kW	Fix. Costs US\$/kW	First Yr	Max. Cap. MW
GenHydKL	Hydro	Elec/Sec	100.0	0.42	49	50	3,755	9.16	2020	210
GenHydKB	Hydro	Elec/Sec	100.0	0.42	48	50	4,717	9.16	2018	40
GenHydBG	Hydro	Elec/Sec	100.0	0.42	68	50	2,420	9.16	2017	800
GenHydDG	Hydro	Elec/Sec	100.0	0.42	68	50	2,439	9.16	2020	600
GenGasNew	Gas	Elec/Sec	48.2	21.04	95	30	1,307	21.01	2020	1000
GenOilNew	Oil	Elec/Sec	30.2	34.59	93	30	709	8.40	2013	1000
GenCoaNew	Coal	Elec/Sec	36.9	12.29	91	30	3,423	25.72	2016	4000
GenBioNew	Biomass	Elec/Sec	37.5	1.11	89	30	4,029	136.58	2020	500
GenCSPNew	Solar	Elec/Sec	100.0	0.00	43	30	6,244	86.15	2017	500
GenSPVNew	Solar	Elec/Fin	100.0	0.00	27	25	3,333	71.44	2012	3000

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Table C.14: Techno-economic data electricity generating technologies *Continued*

Technology	Input	Output	Eff. Percent	Var. Costs US\$/GJ	Cap. Factor Percent	Life Yr	Inv. Cost US\$/kW	Fix. Costs US\$/kW	First Yr	Max. Cap. MW
GenHydNM	Hydro	Elec/Fin	100.0	0.00	30	25	4,166	71.44	2012	30
GenHydNL	Hydro	Elec/Sec	100.0	0.00	60	50	2,758	47.76	2015	1490

Source: [Nexant \(2007\)](#), [ERB \(2008\)](#), [ZESCO \(2008; 2009\)](#), [JICA/MEWD \(2009\)](#) and [DHEC \(2011\)](#).

Table C.15: Variable costs for other technologies (US\$/GJ)

Year	GenImp	TramEle	DistEleMin	DistEleRes	DistEleOth
2010	13.28	0.15	0.15	0.92	0.92
2015	29.25	0.17	0.17	1.04	1.04
2020	36.41	0.19	0.20	1.17	1.17
2025	36.41	0.22	0.22	1.33	1.33
2030	36.41	0.24	0.25	1.50	1.50
2035	36.41	0.24	0.25	1.50	1.50
2040	36.41	0.24	0.25	1.50	1.50
2045	36.41	0.24	0.25	1.50	1.50
2050	36.41	0.24	0.25	1.50	1.50

This table shows imported electricity prices and transmission costs. They were captured as variable costs in the model.

GenImp: This represents the cost of electricity imports from the SAPP market.

TramEle: This represents the cost of operating the transmission lines.

DistEleMin: This represents the cost of operating the distribution lines into the Mining sector.

DistEleRes: This represents the cost of operating the distribution lines into the Residential sector.

DistEleOth: This represents the cost of operating the distribution lines into the other sectors (ex. the Mining and Residential sectors).

Table C.16: Technology production limits

Variable	Unit	2010	2015	2020	2025	2030	2035	2040	2045	2050
<u>Min. Production</u>										
GenImp	PJ/Year	0.05	2.90	0	0	0	0	0	0	0
ImpCOOldRef	PJ/Year	26.17	42.46	42.46	42.46	42.46	42.46	42.46	42.46	42.46
LocOldRef	PJ/Year	33	38	38	38	38	38	38	38	38
LocNewRef	PJ/Year	0	0	6,000	6,000	6,000	6,000	6,000	6,000	6,000
<u>Max Production</u>										
GenImp	PJ/Year	0.05	2.83	0	0	0	0	0	0	0
GenOilEx	PJ/Year	0.27	0.27	0.27	0.27	0	0	0	0	0
GenHydVF	PJ/Year	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40
GenHydLF	PJ/Year	0.53	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
GenHydEM	PJ/Year	0.21	0.21	0.21	0.21	0	0	0	0	0
GenHydNM	PJ/Year	0	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
ImpCOOldRef	PJ/Year	22.50	42.40	42.40	42.40	42.40	42.40	42.40	42.40	42.40
ImpDSL	PJ/Year	0.89	0	0	0	0	0	0	0	0
ImpGSL	PJ/Year	0.91	0	0	0	0	0	0	0	0

GenImp, ImpCOOldRef, ImpDSL and ImpGSL are import technologies for electricity, crude oil to old refinery, diesel and petrol respectively.

Table C.17: Electricity load profiles data

Season	Year Split	Demand Profiles		
		Residential	Mining	Other
SA1	0.103	0.086	0.098	0.115
SA2	0.207	0.206	0.205	0.245
SA3	0.069	0.069	0.072	0.083
SA4	0.034	0.030	0.033	0.039
SB1	0.042	0.036	0.041	0.055
SB2	0.084	0.087	0.085	0.120
SB3	0.028	0.030	0.030	0.041
SB4	0.014	0.013	0.014	0.019
SC1	0.105	0.097	0.101	0.144
SC2	0.210	0.233	0.212	0.316
SC3	0.070	0.079	0.074	0.107
SC4	0.035	0.034	0.034	0.049

The electricity demand profiles were estimated using data from [CEC \(2013\)](#) and [ZESCO \(2013\)](#)



## C.6 Sensitivity analysis data

Table C.18: Supply sensitivity scenarios inputs

Scenario	Variable to change	Description of scenario
High other elec. demand	Elec. demand	Increase demand by 10%
Low other elec. demand	Elec. demand	Reduce demand by 10%
High Disc. Rate	Discount Rate	Increase discount rate by 50%
Low Disc. Rate	Discount Rate	Reduce discount rate by 50%
High resid. elec. demand	Elec. demand	Increase demand by 10%
Low resid. elec. demand	Elec. demand	Reduce demand by 10%
High mining elec. demand	Elec. demand	Increase demand by 10%
Low mining elec. demand	Elec. demand	Reduce demand by 10%
High elec. demand	Elec. demand	Increase demand by 10%

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Table C.18: Supply sensitivity scenarios inputs *Continued*

Scenario	Variable to change	Description of scenario
Low elec. demand	Elec. Demand	Reduce demand by 10%
High Cap. Inv. Cost	Inv. Cost	Increase demand by 10%
Low Cap. Inv. Cost	Inv. Cost	Reduce demand by 10%
Tech. Learning RE Cost	Inv. Cost for RE technologies	Inv. Cost reduces to US\$2,500 (Solar PV) and US\$1,200 (Solar CSP) by 2050 ***
High fixed Costs	Fix. Cost	Reduce fixed costs by 10%
Low fixed Costs	Fix. Cost	Increase fixed costs by 10%
High variable Costs	Var. Cost	Reduce variable costs by 10%
Low variable Costs	Var. Cost	Increase variable costs by 10%
Low coal and no imports	Coal use and quant. of imports	Reduce coal tech. production with no imports
Low coal and low import price	Coal use and import price	Reduce coal tech. production with low imports price

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Table C.18: Supply sensitivity scenarios inputs *Continued*

Scenario	Variable to change	Description of scenario
Low coal and high import price	Coal use and import price	Reduce coal tech. production with high imports price
Zero mining demand by 2050	Mining demand	Reduce all demand to zero by 2050
Zero mining demand by 2040	Mining demand	Reduce all demand to zero by 2040
Zero mining demand by 2030	Mining demand	Reduce all demand to zero by 2030
High coal and low import price	Coal use and import price	Increase coal tech. production with low imports price
High coal and high import price	Coal use and import price	Increase coal tech. production with high imports price

\*\*\* Data for solar technology learning (inv. cost) was from [RMI \(2015\)](#).



# Appendix D

## Appendix to Chapter 6

### D.1 Interview questions

#### D.1.1 Interviews with industry consultants

##### Industry financiers

###### Part 1: “Details of the Informant”

- What is your job title?
- What is your core responsibility within the organisation?

###### Part 2: “Funding Process”

1. How do the current fiscal policies and regulations (in Zambia) affect long-term investments in the copper industry?
2. What industry performance indicators are critical in approving loans to the mining companies?
3. How are risk and profitability of a proposed investment option evaluated during the approval process?
4. Are mining firms required to submit analytic reports of proposed projects?

###### Part 3: “Any other Comments”

- Any other issues that we have not discussed that you would like to mention?

Thank you very much for your time.

### **Local experts**

#### **Part 1: “Details of the Informant”**

- What is your job title?
- What is your core responsibility within the organisation?

#### **Part 2: “Mining Investments”**

1. Generally, in the copper industry, relative to the copper prices, what is the maximum share of unit production cost that would be considered profitable?
2. What are the major cost centres in the Mining Industry?
3. How does the current policy environment (in Zambia) affect long-term investments in the copper industry?
4. What mechanisms or aspects if in place would further encourage the mining companies to invest more in long term projects?

#### **Part 3: “Hypothetical Situations”**

The section deals with hypothetical situations and assumes that ore grade, copper prices, labour costs, energy costs and mineral taxes are the key determinants of company’s profitability and survival.

What do you think a mining investment decision-maker in Zambia’s copper industry would do?

- **Ops 1 Scenario:** If the ore grade continues to reduce while, mineral taxes remain constant, but copper prices, energy prices and labour costs increase?
- **Ops 2 Scenario:** If the ore grade continues to reduce while, the copper prices, mineral taxes, energy prices and labour costs increase?

- **Ops 3 Scenario:** If the ore grade continues to reduce and copper prices fall, while the mineral taxes, energy prices and labour costs increase?

**Part 4:** “Any other Comments”

- Any other issues that we have not discussed that you would like to mention?

Thank you very much for your time.

## **D.1.2 Interviews with government agencies**

### **Taxation agency**

**Part 1:** “Details of the Informant”

- What is your job title?
- What is your core responsibility within the organisation?

**Part 2:** “Mining Taxation”

1. How do the current fiscal policies and regulations (in Zambia) affect long-term investments in the copper industry?
2. Is Zambia getting the maximum possible tax revenue from the mining industry? If no, what can be done to maximise tax revenue?
3. How adaptive are the mineral taxes to fluctuating copper prices?

**Part 3:** “Any other Comments”

- Any other issues that we have not discussed that you would like to mention?

Thank you very much for your time.

**Energy agency****Part 1: “Details of the Informant”**

- What is your job title?
- What is your core responsibility within the organisation?

**Part 2: “Energy Management”**

1. How is energy system expansion planning done in Zambia? How is this impacted by regulation by ERB?
2. When designing or approving energy prices, what aspects of the economy are explicitly considered? What other aspects should be considered?
3. According to the National Energy Policy, there is very little work that is being done to promote efficient use of energy in industry and residential sectors. What are the challenges or barriers that hinder such work?
4. In the National Energy Strategy, it was proposed that poor load factor should be penalised. What legislation or regulation has been put in place to ensure that mining company improve their load factor?

**Part 3: “Any other Comments”**

- Any other issues that we have not discussed that you would like to mention?

Thank you very much for your time.

**Mining agency****Part 1: “Details of the Informant”**

- What is your job title?
- What is your core responsibility within the organisation?



**Part 2: “Mining Investments”**

1. What are the main interests of this organisation in the copper industry?
2. Generally, in the copper industry, relative to the copper prices, what is the maximum share of unit production cost that would be considered profitable?
3. How does the current policy environment (in Zambia) affect long-term investments in the copper industry?
4. How adaptive are the Zambia’s policies and regulations towards movements in international copper prices and copper production?

**Part 3: “Any other Comments”**

- Any other issues that we have not discussed that you would like to mention?

Thank you very much for your time.

**D.1.3 Interviews with mining firms****Part 1: “Details of the Informant”**

- What is your job title?
- What is your core responsibility within the company?
- How many years have you worked in the copper industry?

**Part 2: “Investment Process”**

1. What motivates your organisation to invest in capital equipment?
2. How does your company assess and evaluate investment options?
3. How does the current policy environment (in Zambia) affect long-term investments in your company?

4. What mechanisms or aspects if in place would further encourage the company to invest more in long-term projects?

**Part 3: “Energy Use”**

1. How important is energy to your organisation and how has this changed over the past 5, 10 years?
2. Which activities consume the most energy in your organisation?
3. How are these activities projected to change in the future (say 10 years or more from now)?
4. Does your company have any energy consumption reduction targets?
  - i. If yes, how were these targets set and how do you hope to achieve them

**Part 4: “Hypothetical Situations”**

The section deals with hypothetical situations and assumes that ore grade, copper prices, labour costs, energy costs and mineral taxes are the key determinants of company’s profitability and survival.

As an investment decision-maker, what would you do:

- **Ops 1 Scenario:** If the ore grade continues to reduce while, mineral taxes remain constant, but copper prices, energy prices and labour costs increase?
- **Ops 2 Scenario:** If the ore grade continues to reduce while, the copper prices, mineral taxes, energy prices and labour costs increase?
- **Ops 3 Scenario:** If the ore grade continues to reduce and copper prices fall, while the mineral taxes, energy prices and labour costs increase?

**Part 5: “Any other Comments”**

- Any other issues that we have not discussed that you would like to mention?

Thank you very much for your time.

## D.2 Information and consent form

Information Sheet for		<i>MPhil/PhD</i>	in Research Studies
Title of Project: <b>ENERGY EFFICIENCY IN ZAMBIA'S COPPER INDUSTRY</b>			
This study has been approved by the UCL Research Ethics Committee (Project ID Number): <b>6116/001</b>			
Name	Bernard Tembo		
Work Address	UCL Energy Institute, 14 Upper Woburn Place, London, WC1H 0NN, UK		
Contact Details	Bernard.tembo.12@ucl.ac.uk		
	( +44 ) 203 108 5938		
<p>We would like to invite you to participate in this research project.</p> <p>This research investigates how changing energy drivers will impact on energy demand and profitability of Zambia's copper industry, and how the effects of the changes can be mitigated by investing in energy efficient technologies. This research is funded by UCL Institute of Sustainable Resources (<a href="http://www.bartlett.ucl.ac.uk/sustainable">http://www.bartlett.ucl.ac.uk/sustainable</a>), and is supervised by Prof. Neil Strachan and Dr. Ilkka Keppo both from University College London (UCL).</p> <p>The copper industry is critical Zambia's economy. In 2010, the industry contributed 10% to the GDP and accounted for over 80% of the country's foreign exchange earnings. Furthermore, the industry consumes over 50% of the country's commercial energy. Therefore, not only is the industry important to the economy, it is also important to the energy sector. With the projected growth in national energy demand, the energy prices are expected to rise. Also, the reduction in ore grade and changes in mining methods in the industry would lead to an increase in energy demand and also change in types of energy used. Thus, apart from increase in industry's production costs, the development of the energy system will also be affected.</p> <p>This research will therefore focus on identifying the main drivers of energy demand in the industry and the key decision variables that the mine operators consider when making investment decision in energy consuming technologies. These two aspects will help develop a model that can be used to propose mechanisms, policies or regulations that would protect both the industry and the national economy.</p> <p>The interview process will take approximately 40 minutes.</p> <p>Any information you provide will be treated as confidential and handled in accordance with the UK Data Protection Act 1998. Unless stated otherwise, participants will not be identified by name nor by their organisation in any outputs from this research. If for any reason you want to withdraw from this study, you may do so at any time. More details of UK's data protection policy can be found on the following link: <a href="http://www.ucl.ac.uk/informationsecurity/policy/public-policy/Data_protection_policy_ISC_20110215">http://www.ucl.ac.uk/informationsecurity/policy/public-policy/Data_protection_policy_ISC_20110215</a></p> <p>If you have any questions or comments about this study, please feel free to ask me. My contact details can also be found at the top of this information sheet. Thank you</p> <p>Kind regards,</p> <p>Bernard Tembo</p>			

Informed Consent Form for *MPhil/PhD* in Research Studies

**Please complete this form after you have read the Information Sheet and/or listened to an explanation about the research.**

Title of Project: **ENERGY EFFICIENCY IN ZAMBIA'S COPPER INDUSTRY**

This study has been approved by the UCL Research Ethics Committee (Project ID Number): **6116/001**

Thank you for your interest in taking part in this research. Before you agree to take part, the person organising the research must explain the project to you.

If you have any questions arising from the Information Sheet or explanation already given to you, please ask the researcher before you to decide whether to join in. You will be given a copy of this Consent Form to keep and refer to at any time.

**Participant's Statement**

I

- have read the notes written above and the Information Sheet, and understand what the study involves.
- understand that if I decide at any time that I no longer wish to take part in this project, I can notify the researchers involved and withdraw immediately.
- consent to the processing of my personal information for the purposes of this research study.
- understand that such information will be treated as strictly confidential and handled in accordance with the provisions of the UK Data Protection Act 1998.
- agree that the research project named above has been explained to me to my satisfaction and I agree to take part in this study.

Signed:

Date:

## D.3 Description of the respondents

**Miner#1** The respondent was male, has worked in the mining industry for over 12 years and Zambia's copper industry for about 8 years for Miner#1. He is finance and supply person. Responsible for financial control of a mining organisation.

**Miner#2** The representatives of Miner#2 was a panel of five senior managers at Miner#2. They were from the finance, underground, metallurgical, electrical and production departments.

**ME#1** The respondent was male, a mining economist. He has held senior positions in government and has also worked in the industry for more than 20 years.

**ME#2** The respondent was male. He is a Lecturer and mining economist at one of Zambia's leading universities. He worked for a mining companies as a mining production manager for more than 30 years before joining the academia.

**EE#1** The respondent was male. He a Lecturer and economic advisor, who has worked Zambia's mining sector and has also been involved auditing the operations of mining firms in Zambia.

**EE#2** The respondent was male. He worked as an economist for an association that represented the interests of the mining firms in Zambia. He had less than 5 years in the industry.

**GA#1** The respondents were two senior managers (male and female). They worked for a government agency that focuses on developing and enforcing tax and related policies.

**GA#2** The respondent was male, an employee of the [Department of Energy \(DoE\)](#). He has worked in Zambia's energy sector for over 12 years, and his work mainly focuses on energy management and power system development.

**GA#3** The respondent was male, an employee of the [Department of Mines \(DoM\)](#). He has worked in Zambia’s mining sector for over 15 years, and his work focuses on at mine licensing, mine development and general operation of the mine throughout its life span.

**EE#3** The respondent was male. He is an energy expert and a University Professor at one of Zambia’s leading universities. He is advisor and seats on different boards.

**EE#4** The respondent was male. He is an energy management expert and a metallurgist, who has done industrial energy-related research for over 10 years.

**BE#1** The respondent was female. She has worked in the banking and financial sector for over 8 years. Her employer at the time of the interview was one of the major banks that finance projects in the mining sector.

## **D.4 Summary findings of the interviews**

This section presents and discusses the findings of the semi-structured interviews (The description of the referenced respondents can be found in section [D.3](#) above). The interviews<sup>1</sup> sought to understand how mining firms make strategic investment decisions in Zambia. They also sought to get the perspective of the mining industry stakeholders on what variables are key drivers in their decision making. The central research question of this section is, “How do organisations make strategic investment decisions and what are the key decision variables in the mining sector?” By answering this question and its related sub-questions, decision rules (that are key inputs in the mining model in section [7.2](#) below) will be identified.

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<sup>1</sup>See section [D.1](#) above for the interview questions that were used.

### D.4.1 Investment process

The decision making process in the mining industry was explained by Miner#2. When an investment opportunity is identified, it is evaluated and costed by the local team. If the opportunity has a positive NPV value, it is forwarded to the headquarters of the firm (in this case, outside Zambia)<sup>2</sup>; where it is again evaluated and considered along with opportunities from other operations before it is submitted to the shareholders for approval. If it is approved, it is sent back to the local team for implementation. In the case of a resource development investment opportunity, the implementation process would be in four stages: exploration, ore evaluation, ore development and production. Strategic investments are, however, not limited to resource development but also include replacement of equipment, expansion of company business (such as investing in a smelter), sustaining business operations and improving efficiency.

It was emphasised that the basis of all strategic capital investments made by mining firms is increasing shareholders' wealth. As Miner#2 explained “. . . the bottom-line [of our capital investments] is to increase shareholders' wealth, but along the process, both [sic] the employees, society and the business itself benefits . . .” These sentiments were also expressed by Miner#1 who observed that there has been a boom in capital investments post-2004 in Zambia. Miner#1 explained that during this period, they had invested about US\$ 2 billion in capital infrastructure. These post-2004 investments coincides with the period of sustained high copper prices (from US\$ 2, 235 per tonne in 2003 to US\$ 8, 104 per tonne in 2011<sup>3</sup> for instance), confirming the view that shareholders anticipated to receive a better dividend for their investment.

Miner#1, ME#1 and EE#1 identified **ore grade**, recoverable copper from the ore, copper price and local policy environment (such as stability of the policies and level of taxation) as key factors that determine whether an investment would be made or not. While **ore grade** and quantity of

<sup>2</sup>See section B.2 of Appendix B for the list of mining companies that operate in Zambia.

<sup>3</sup>The prices are in real 2010 US Dollars.

recoverable ore are geological characteristics, local policy environment is determined by the host country. Thus, to attract more investment, the host country would need to set-up attractive policies.

This was also noted by Miner#2 and EE#2 who argued that despite being exposed to the same low copper prices, Anglo-America pulled out of Zambia (in the early 2000s) to invest in the Democratic Republic of Congo (DR Congo). They observed that during this period, even though the DR Congo was not politically stable it still managed to attract investment because of its good policies. However, there are alternative explanations as to why Anglo-America decided to exit Zambia and invest in DR Congo during this period.

As GA#1 explained that DR Congo has a weak fiscal regime that favoured them (as investors) more than the host country and its general citizenry. As GA#1 observes, Zambia has a stringent tax regime such as restrictions on the length of time a firm is allowed to carry forward its losses. This, they argue, is not the case in DR Congo hence investors in DR Congo can carry forward their losses for a much longer period at the expense of the host country which loses out on tax based revenue. Apart from this, it can also be argued that because DR Congo has higher [ore grade](#) (see Mudd et. al., 2013), production costs there would be lower than in Zambia. Thus, minimising the losses an investor could incur if the copper price is depressed for much longer. According to EE#1, this was the line of argument that Anglo-America gave when exiting the Zambian industry. The financial and economic reasoning notwithstanding, ME#1 argued that companies (such as Anglo-America) can choose to invest or disinvest based on their lobbying position. As he (ME#1) explained “. . . he [the then President] gave Anglo-America the best package of mines after privatisation, but Anglo-America continuing to operate in Zambia was based on the arrangement that they had a captive national leadership [who they had bribed during privatisation process, according to ME#1] . . . but when there was change of national leadership, they exited the Zambian industry.”

On the whole, the firm exiting an industry is driven by one of two



factors: local and global. Under the local factors, the conditions (such as taxation and unit production cost) within a host country determines whether it would be profitable for a firm to continue operating in the country. Such a case is Anglo-America's decision to pull out of Zambia and invest in DR Congo. The global factors, on the other hand, focus on the impact that copper price (a global variable) has on the profitability of a firm. A firm that exits an industry due to global factors almost always struggles to find buyers for the mining site because the obtaining state of the industry is not attractive regardless of the location and local conditions of the mining site.

#### **D.4.2 Project evaluation and financing**

After the investment opportunity has been identified, it is evaluated using the NPV/Discounted Cash Flow (DCF), IRR and pay-back period methods. According to both Miner#1 and Miner#2, while IRR and pay-back analysis are optional, an NPV analysis has to be done on all big projects<sup>4</sup>. This is because it is an acceptable method of evaluating projects in the industry. To address some limitation of the NPV method, IRR and pay-back analysis could also be done.

It was found that a decision maker would be interested in developing a project that has a return on investment (RoI) ranging between 15%-30% (according to Miner#2 and ME#1), which according to ME#1 is slightly higher than the global average of 10%-15%. Both Miner#2 and ME#1 further argue that a positive RoI does not mean that the project will be implemented because the company has to consider the country risks. Risks such as political risks and consistency in fiscal policies. Miner#2 also discussed the role of experience in decision making, they observed that "gut-feeling" type of decisions can only be made by the top most persons in an organisation. For them (Miner#2's local team), they have to make decisions based on technical evaluation analysis of the project.

After the project has been approved, a firm can either use its internal

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<sup>4</sup>Any project above US\$ 5 million according to Miner#1.

resources or approach a financial institution to finance the development of the project. From a financier's perspective, funding of projects is largely determined by the long term outlook of the industry, not short-term policy inconsistencies. As BE#1 said “ . . . we tend to rely so much on the industry reports, that look at both the short and long-term industry outlook. Generally, the view taken is that as long as the long term outlook is positive, we will still continue to see investments into the copper industry. I think we have seen FQM [the largest mining operation in Zambia] despite the little hiccups we have had in regulation, they have still continued to invest in the sector.”

The three main factors that are considered when approving funding for a mining project in Zambia were identified: 1. who their off-taker [the buyer of their produce] is; 2. the role that the Zambian asset plays in the group (in terms of value); and 3. the parent organisation of the firm. According to BE#1, accessing finance for projects in Zambia's industry is more determined by global factors and organisation structure than local policies because firm's market is outside the country (so access to foreign exchange is guaranteed).

### **D.4.3 Production costs**

Similar to literature reviewed, it was found that the seven main production cost components were labour, repair and maintenance, energy costs, cost of capital<sup>5</sup>, consumables, transport and mining royalty tax (MRT) costs.<sup>6</sup> The view of what was the most important of these components and also how these factors could change in future varied from one respondent to another. For instance, Miner#2 thought that the best way to reduce the labour cost (the largest cost component according to Rothschild (2008)) was to mechanise the mining operation. However, this would increase the energy cost further, which according to Miner#1 was already high. Further,

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<sup>5</sup>This is more relevant to the new entrants of the industry according to EE#1 and GA#1

<sup>6</sup>The cost structure of KCM (Zambia's largest integrated mine operation) can be found in section E.3 of Appendix E.

Miner#1 said “. . . there is a lot that needs to be done in Zambia’s power sector because there is a shortage [in power supply]. . . . despite the stability agreement<sup>7</sup>, we have also seen an increase in electricity price by 300% to 400% . . .” Another way that would help to reduce the production cost according to Miner#1 and ME#1 would be to have a functioning rail system. As Miner#1 explained, “. . . if there is an efficient rail network, we [Miner#1] would save at least 40%-50% on transport cost.”

Of the seven cost components, energy cost and MRT were the most contentious. When discussing the energy cost (particularly the electricity price), EE#3, EE#4, GA#2 and ME#1 argued that the current electricity tariffs were low. GA#2 further argued that these low tariffs have acted as barriers to energy efficient practises in the industry, because even after using the energy inefficiently, the mining firms are still able to make a profit. Apart from acting as a barrier to energy efficiency, ME#1 further argued that these low tariffs have rendered development of new electricity capacity impossible as the current tariffs are not attractive enough. EE#3 and EE#4 also added that the tariffs have been kept low because the mining industry is a critical and powerful industry (both politically and economically) in Zambia. For example, EE#3 observes that “. . . attempts have been done to come up with recommendations that would make the electricity industry viable [financially viable, via cost reflective tariffs] . . . there is resistance from the industry, the copper industry especially . . . they always refer to the agreements [stability agreements] which they made a long time ago, which were not realistic in terms of the real price of electricity”. On the fuels energy cost, GA#3 observed that the Zambian firms pay more for each litre of fuel they use than those operating in neighbouring countries to Zambia. He (GA#3) gave an example for how Kalumbila mine (one of new North-Western open pits) plans to install a dual energy consuming trolley system so that it can be switching to electricity during the off-peak period in order to reduce its fuel expenditure. This, on the other hand, implies that electricity is considerably cheaper

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<sup>7</sup>These are agreements that the government and the mining firms entered into during privatisation that the government thought would make the industry more attractive.

than fuel.

Conversely, Miner#1, Miner#2 and EE#2 felt that the price of electricity has considerable impact on the profitability of the industry. While Miner#1 argued that government should honour the stability agreements, EE#2's argument focuses on economies of scale. He argues that “. . . the tariffs [to the mines] have to reflect the quantity of electricity consumed by the industry.” Further, Miner#2 was more concerned about how the future energy costs would impact its operations. They (Miner#2) however observed that if they increase their mechanising levels, they would be able to off-set the impact of increasing energy cost by reducing their labour cost (on the total production cost); provided government invests in more electricity supply infrastructure. However, when asked about the share of electricity cost towards the total production cost, Miner#2 said “. . . before the electricity [price] was increased, the share of electricity was 4% and now with the increment of 28% it just threw everything over board . . . now the share of electricity is about 6% . . .” This, however, suggests that electricity cost is not a significant cost and also not a very sensitive input in Miner#2's operations.

On taxation, there were two arguments: the way taxes are charged and the rates of taxation. Taxes can be collected based on the firm's gross revenue or based on its profit. Gross revenue taxes such as MRT and Wind Fall Tax (WFT) were favoured by ME#1 and EE#1. As EE#1 argues, revenue based tax is ideal “. . . given the sophistications of operations at Zambia Revenue Authority (ZRA), competencies ability or capacity to handle multi-national companies trying to avoid or evade tax.” Similar sentiments were expressed by ME#1, when he argued “. . . it is the easiest and most affordable way of taxing and I would encourage any mining country which has no expertise in follow-up and auditing mining operations to use WFT.”

The profit based taxes were favoured by Miner#1 and EE#2. As EE#2 argued “while the logic of WFT is fine, the trouble is where it is applied . . . it would be better to tax it at net revenue, because that way profitability

of the mine operation is protected.” However, ME#2 was indifferent to either taxation method and instead proposed a different tax regime that could enhance the level of local content in the mining industry such as passing regulations that require mining companies to buy certain inputs locally.

From an efficiency perspective, a revenue based tax is better because it forces the mining firm to minimise its process losses and also reduce wastage such as inefficient use of electricity. For instance, if a firm operating at 60% can still make its desired profit margin, there would be no incentives to increase its efficiency since it only pays for what it produces. As ME#2 observed “ . . . as the price [of copper] started increasing [post-2004 period], people [the firms] started doing things differently. They hired more expensive labour, more expensive drilling and blasting . . . People [the firms] started processing low grade ore that were previously unprofitable, . . . which increased the total production costs.” This behaviour did not cost the mining firms a lot of income because a significant portion of their taxes was based on profits and not on revenue. In other words, the firms were not incentivised to optimise their operations. This, I argue, is the other advantage of the revenue based taxes. Besides, this is the view that GA#1 missed when they said “ . . . we don’t tax losses [process losses].”

Apart from where the tax is applied, there are also opposing views on what tax rates are fair. There is a consensus that the WFT which were briefly introduced in 2008 had steep graduations and ill-timed. However, the current rates of taxation are also in contention. Both ME#1 and EE#1 argued that the mining industry is currently not paying its fair share of taxes while EE#2 argues that the industry is over taxed. Miner#2, on the other hand, argues that the current structure<sup>8</sup> of taxation is good for both the government and the mining firms; it guarantees government predictable tax revenue while providing a safe-net for a firm. However, Miner#1 was more concerned with the stability of tax policies. As GA#3 agreed with Miner#1, when he observed that “ . . . there has been frequent changes

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<sup>8</sup>The current structure is a combination of both revenue based and profit based taxes.

in the fiscal policy.”

#### **D.4.4 Investment policy environment**

There was a general consensus that the fiscal policy environment was less predictable. Miner#1, Miner#2, BE#1, ME#1, EE#2 and GA#3 all talked about how MRT rates have changed over the years and also the Statutory Instruments (SIs) that the Ministry of Finance had put in place only to reverse them. The respondents, however, had varying views of how they thought this instability affected the mining industry. Miner#1 and Miner#2 said it affected their evaluation of investment projects (since fiscal policies were key inputs into the evaluation process) and also had a short-term impact on their cash-flow. Further, the two miners felt that because Zambia depends on foreign capital to grow its industry, this instability would discourage investors from investing in the country. They hoped to have a stable fiscal space (whether too high or low was secondary to them).

While EE#2 thought that instability greatly affected investment into the industry, BE#1 argued that as financiers of industry project, investment into the industry was largely driven by the outlook of the global copper industry. In addition, GA#3 observed that while there was instability in the fiscal space, core policies in the sector were stable and predictable. ME#1’s argument was that this instability was inevitable as the government is still trying to find a fair rate at which to tax the mining firms as the previous rate of 0.6% (of MRT) was too low. GA#1 further adds that making the fiscal environment more responsive would in itself lead to instability in the fiscal space. Similar to the argument of ME#1, EE#1 argued that instability in the fiscal policy was because of lack of transparency. There is a perception (according to EE#1) that the mining firms are not paying a fair share of taxes.

### D.4.5 Industry drivers

This sub-section reviewed the responses to hypothetical scenarios<sup>9 10</sup> presented to mining firms and experts on what they thought were critical drivers of mining operations. Five drivers (ore grade, copper prices, labour costs, energy costs and mineral taxes) were presented to the respondents.

Under ops 1 scenario, all the four respondents said they would continue investing in the industry. Miner#2's response focused on the level to which the ore grade reduces while Miner#1 and ME#1 focused on the impact of the copper prices. ME#1 further observed that significant increase in price tends to change the behaviour of mining in the short-term. ME#2's response was largely driven by his argument that profitability of a firm is determined by the business strategy that a firm decides to adopt. Thus, his response was similar in all the three scenarios. Further, he (ME#2) observes that increase in copper price is always a desirable thing.

For ME#1, ops 2 and 3 scenarios have the same end result: the firm will exit the industry. He argued that at local level, the variable that has the largest impact on decision making is taxation. For Miner#1 and Miner#2, ops 2 scenario is still favourable for investments but the magnitude of change in each of the variables would be of great importance. Both miners observe that if the level of unit cost of production is high, then the movement in the copper price would play an important role in their decision making. Ops 3 scenario would lead to a bare minimum type of operation for Miner#1 while Miner#2 said they would defer all their planned investments.

Overall, from the analysis of the responses to the presented scenarios, copper price, ore grade and taxation were identified as the most impactful variables in decision making. The importance of the copper price was

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<sup>9</sup>See section D.1 for the interview questions that were used.

<sup>10</sup>Hypothetical scenarios (See section D.1 in Appendix D):

Ops 1 scenario: If the ore grade continues to reduce while, mineral taxes remain constant, but copper prices, energy prices and labour costs increase?

Ops 2 scenario: If the ore grade continues to reduce while, the copper prices, mineral taxes, energy prices and labour costs increase?

Ops 3 scenario: If the ore grade continues to reduce and copper prices fall, while the mineral taxes, energy prices and labour costs increase?

elevated when the discussion was about marginal mines (high cost mines that is).

In summary, the interviews revealed that strategic decision making in firms is a deliberate and procedural process that a firm engages in. As part of the decision process, various analytic techniques are applied when evaluating investment options, but the final decision does not solely depend on the results of the analytic analysis as the experience of decision makers also play a role in the process. The final decision is therefore determined by a combination of different criteria and decision rules. Similar to the findings in literature, NPV analysis is the most common and required technique for evaluating investments in the Zambian copper industry (stochastic techniques were not common).

While copper price<sup>11</sup> and ore grade were acknowledged as key inputs into the investment decision making process, the interviews found that the respondents were more concerned with the price of electricity and taxation policy. This could be because the respondents recognise that these two inputs are susceptible to lobbying. On electricity price, their concerns were immediate: the current electricity tariff and its past increments. However, all the respondents recommended increased capital investment into the energy sector for two primary reasons: to satisfy the current electricity demand and to facilitate mechanisation of the mining operations. Yet, not much consideration was given to how increased capital investment in the energy sector would impact the profitability of the mining industry.

On taxation, the main contentions were on the type of taxes, the rates of taxes and the stability in the taxation policy. While instability in taxation was widely thought to significantly impact investments, the respondents from the banking and financial sector argued that the long-term outlook of the industry (the outlook of the copper price that is) was the key determinant to accessing funds for an investment project. However, instability

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<sup>11</sup>The copper price used when analysing the profitability of an investment is usually based on a long-term forecast or historical average according to Miner#1 and EE#1.



can potentially reduce the profits that a firm realises from the investment. Thus, all recommendations on how to enhance long-term investments in the industry were focused on stabilisation of the fiscal policy.

## D.5 Input data for mining model

Table D.1: Unit costs and other general inputs and assumptions

Variable	Site	Unit	Average	Min	Max	Distribution
ElecRef Consumables	General	US\$/tonCuCathode	14.12	12.71	15.53	Random uniform
ElecRef Labour	General	US\$/tonCuCathode	24.61	22.15	27.07	Random uniform
ElecRef Other	General	US\$/tonCuCathode	4.65	4.18	5.12	Random uniform
ElecRef R&M	General	US\$/tonCuCathode	9.61	8.65	10.57	Random uniform
ElecWin Consumables	General	US\$/tonCuCathode	377.49	339.74	415.24	Random uniform
ElecWin Labour	General	US\$/tonCuCathode	72.38	65.14	79.62	Random uniform
ElecWin Other	General	US\$/tonCuCathode	22.95	20.66	25.25	Random uniform
ElecWin R&M	General	US\$/tonCuCathode	51.19	46.07	56.31	Random uniform
Admin. & General	General	US\$/tonOre	2.60	2.34	2.86	Random uniform

*Continued on next page*

Table D.1: Unit costs and other general inputs and assumptions *Continued*

Variable	Site	Unit	Average	Min	Max	Distribution
Smelter Consumables	General	US\$/tonConc	19.75	17.77	21.73	Random uniform
Smelter Labour	General	US\$/tonConc	20.24	18.22	22.26	Random uniform
Smelter Other	General	US\$/tonConc	9.12	8.21	10.03	Random uniform
Smelter R&M	General	US\$/tonConc	9.04	8.14	9.94	Random uniform
Transport	General	US\$/tonCuCathode	150	135	165	Random uniform
Consumables	Open Pit	US\$/tonOre	4.51	4.06	4.96	Random uniform
Labour	Open Pit	US\$/tonOre	2.41	2.17	2.65	Random uniform
Other	Open Pit	US\$/tonOre	1.10	0.99	1.21	Random uniform
Repair & Maint	Open Pit	US\$/tonOre	2.36	2.12	2.60	Random uniform
Consumables	Underground	US\$/tonOre	6.48	5.83	7.13	Random uniform
Labour	Underground	US\$/tonOre	8.31	7.48	9.14	Random uniform

*Continued on next page*

Table D.1: Unit costs and other general inputs and assumptions *Continued*

Variable	Site	Unit	Average	Min	Max	Distribution
Other	Underground	US\$/tonOre	2.06	1.85	2.27	Random uniform
Repair & Maint	Underground	US\$/tonOre	4.13	3.72	4.54	Random uniform
Copper Price	General	US\$/tonne	7,000	3,500	10,500	Random uniform
Disc. Rate	General	Percent	0.08	0.07	0.09	Random uniform
EE. Motor efficiency	General	Percent	92	92	96	Random uniform
EE. Motor Inv. Cost	General	US\$/motors	4,000	3,600	4,400	Random uniform
ElecRef Cap. Inv. Cost	General	US\$/tonCuCathode	436.31	392.68	479.94	Random uniform
Electricity Supply Scenario	General	Index	6	1	6	Vector
ElecWin Cap. Inv. Cost	General	US\$/tonCuCathode	1,308.92	1,178.03	1,439.81	Random uniform
Loss Tolerance Time	General	Months	6	3	9	Vector
Mineral Roy. Tax	General	Percent	6	3	9	Random uniform

*Continued on next page*

Table D.1: Unit costs and other general inputs and assumptions *Continued*

Variable	Site	Unit	Average	Min	Max	Distribution
Motor invest. Threshold	General	Index	1.25	1.12	1.38	Random uniform
Motor requirement	Open Pit	tonOre/motors	12,500	11,250	13,750	Random uniform
Motor requirement	Underground	tonOre/motors	12,500	11,250	13,750	Random uniform
Oil Price	General	US\$/bbl	85	20	120	Random uniform
OP Cap. Inv. Cost	General	US\$/tonOre	58.68	52.81	64.55	Random uniform
Ore production threshold	General	Index	1.25	1.12	1.38	Random uniform
Price Recovery Threshold	General	Index	0.80	0.72	0.88	Random uniform
Profit Margin Threshold	General	Index	0.20	0.10	0.30	Random uniform
Smelter Cap. Inv. Cost	General	\$/tonConc	654.46	589.01	719.91	Random uniform
Std. Motor efficiency	General	Percent	85	85	92	Random uniform
Std. Motor Inv. Cost	General	US\$/motors	3,500	4,000	5,000	Random uniform

*Continued on next page*

Table D.1: Unit costs and other general inputs and assumptions *Continued*

Variable	Site	Unit	Average	Min	Max	Distribution
UG Cap. Inv. Cost	General	US\$/tonOre	202.77	182.49	223.05	Random uniform

Table D.2: Ore characteristics inputs and assumptions

Variable	Unit	Average	Min	Max	Distribution
Share of Exports	Percent	0	0	5	Random uniform
Ore grade error	Percent	0	0	2	Random uniform
Expansion target	Percent	0	0	2	Random uniform
Avg. NW OP Ore grade	Percent	0.84	0.76	0.92	Random uniform
Avg. CB OP Ore grade	Percent	1.74	1.57	1.91	Random uniform
Avg. CB UG Ore grade	Percent	2.46	2.21	2.71	Random uniform
NW OP share of Oxide ore	Percent	10	5	15	Random uniform
CB UG share of Oxide ore	Percent	20	10	30	Random uniform
Inventory factor	Index	0.20	0.10	0.30	Random uniform
CB OP share of Oxide ore	Percent	50	25	75	Random uniform
CB OP ore resources	Tonnes	644,476,000	580,028,400	708,923,600	Random uniform
CB UG ore resources	Tonnes	1,431,750,000	1,288,575,000	1,574,925,000	Random uniform
NW OP ore resources	Tonnes	3,068,550,000	2,761,695,000	3,375,405,000	Random uniform
CB UG Share of ByProducts Credit	Percent	4.17	3.75	4.58	Random uniform
CB OP Share of ByProducts Credit	Percent	6.04	5.44	6.65	Random uniform
NW OP Share of ByProducts Credit	Percent	17.64	15.87	19.40	Random uniform

Strip ratios for NW OP and CB OP are 11 and 4.4 respectively.

Table D.3: Energy intensities inputs and assumptions

Variable	Site	Unit	Average	Min	Max	Distribution
Other uses	General	GJ/tonOre	0.0007	0.0006	0.0007	Random uniform
Smelter HFO	General	GJ/tonConc	0.9511	0.8560	1.0462	Random uniform
Other water pumping Elec.	General	kWh/tonOre	1.6060	1.4454	1.7666	Random uniform
Concentrator pumping Elec.	General	kWh/tonOre	8.4740	7.6266	9.3214	Random uniform
Concentrator FFR Elec.	General	kWh/tonOre	11.7140	10.5426	12.8854	Random uniform
Concentrator Milling Elec.	General	kWh/tonOre	32.1580	28.9422	35.3738	Random uniform
Leach Plant Elec.	General	kWh/tonOre	33.3677	30.0309	36.7045	Random uniform
Smelter Elec.	General	kWh/tonConc	310.4900	279.4410	341.5390	Random uniform
Electrorefinery Elec.	General	kWh/tonCuCont	835.52	751.97	919.07	Random uniform
Electrowinning Elec.	General	kWh/tonCuCont	1,933.06	1,739.75	2,126.37	Random uniform
Mining Diesel	Open Pit	GJ/tonOre	0.1798	0.1618	0.1978	Random uniform
Mining other uses Elec.	Open Pit	kWh/tonOre	4.2330	3.8097	4.6563	Random uniform
Mining Diesel	Underground	GJ/tonOre	0.0170	0.0153	0.0187	Random uniform
Mining other uses Elec.	Underground	kWh/tonOre	5.1640	4.6476	5.6804	Random uniform
Ventilation Elec.	Underground	kWh/tonOre	7.3040	6.5736	8.0344	Random uniform
Mining winders Elec.	Underground	kWh/tonOre	8.9320	8.0388	9.8252	Random uniform
Water pumping Elec.	Underground	kWh/tonOre	9.2650	8.3385	10.1915	Random uniform
Compressor Elec.	Underground	kWh/tonOre	9.3850	8.4465	10.3235	Random uniform



## D.6 Model Tests

These model test are adapted from [Sterman \(2000\)](#), Table 21-3 in particular.

### 1. **Boundary Adequacy test:**

- (a) Are the important concepts for addressing the problem endogenous to the model?
- (b) Does the behaviour of the model change significantly when boundary assumptions are relaxed?
- (c) Do the policy recommendations change when the model boundary is extended?

### 2. **Structure Assessment test:**

- (a) Is the model structure consistent with relevant descriptive knowledge of the system?
- (b) Is the level of aggregation appropriate?
- (c) Does the model conform to basic physical laws such as conservation laws?
- (d) Do the decision rules capture the behaviour of the actors in the system?

### 3. **Dimensional Consistency test:**

- (a) Is each equation dimensionally consistent without the use of parameters having no real world meaning?

### 4. **Parameter Assessment test:**

- (a) Are the parameter values consistent with relevant descriptive and numerical knowledge of the system?
- (b) Do all parameters have real world counterparts?

### 5. **Extreme Conditions test:**

- (a) Does each equation make sense even when its inputs take on extreme values?
- (b) Does the model respond plausibly when subjected to extreme policies, shocks, and parameters?

**6. Integration Error test:**

- (a) Are the results sensitive to the choice of time step or numerical integration method?

**7. Behaviour Reproduction test:**

- (a) Does the model reproduce the behaviour of interest in the system (qualitatively and quantitatively)?
- (b) Does it endogenously generate the symptoms of difficulty motivating the study?
- (c) Does the model generate the various modes of behaviour observed in the real system?
- (d) Do the frequencies and phase relationships among the variables match the data?

**8. Behaviour Anomaly test:**

- (a) Do anomalous behaviours result when assumptions of the model are changed or deleted?

**9. Family Member test:**

- (a) Can the model generate the behaviour observed in other instances of the same system?

**10. Surprise Behaviour test:**

- (a) Does the model generate previously unobserved or unrecognised behaviour?
- (b) Does the model successfully anticipate the response of the system to novel conditions?

**11. Sensitivity Analysis test:**

- (a) Numerical sensitivity: Do the numerical values change significantly . . .
- (b) Behavioural sensitivity: Do the modes of behaviour generated by the model change significantly . . .
- (c) Policy sensitivity: Do the policy implications change significantly . . .
- (d) . . . when assumptions about parameters, boundary, and aggregation are varied over the plausible range of uncertainty?

**12. System Improvement test:**

- (a) Did the modelling process help change the system for the better?

**D.6.1 Applied extreme test**

In order to check that model behaves as expected, it was exposed to extreme conditions<sup>12</sup>. Firstly, all the model mathematical equations and relationships were inspected to check if they were logical and represented as those in the real system. Then input variables of electricity price, oil price, mineral royalty tax and copper price were varied to check how the model would behave. Table D.4 below shows the values of the variable used in the test.

Test 1 considers a situation where all inputs and copper price favour continuous production, and from Figure D.1 it can be seen that all three sites continue to produce copper ore. Test 2 shows the significance of copper price in the model, production drops to zero once the copper price drop to \$1, 000/ton because this price is less that the unit production cost incurred by a mining firm. Similar to Test 2, Tests 3 to 5, show that the model behaves as expected (stopping production) once extreme values are introduced (after 2015).

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<sup>12</sup>An analysis of inputs that are key driver in the model are given in sub-section 7.2.2 above.

Table D.4: Extreme test key inputs

	Test 1	Test 2	Test 3	Test 4	Test 5
Copper*	High	Low	High	High	High
Tax (MRT)**	Low	Low	High	Low	Low
Electricity***	Low	Low	Low	High	Low
Oil****	Low	Low	Low	Low	High

\* Copper price: Low is \$1, 000/ton and High is \$10, 000/ton)

\*\* Mineral Royalty Tax: Low is 0% and High is 99%

\*\*\* Electricity price: Low is \$0/kWh and High is \$1, 000, 000/kWh

\*\*\*\* Crude oil price: Low is \$1/bbl and High is \$1, 000, 000/bbl

Figure D.2 shows how production capacity could change over time, based on the extreme tests the model was subjected to. On the whole, because ore production capacity was modelled to increase (in order to maintain copper cathode production level<sup>13</sup>), production capacity in Tests 2 to 5 continue to increase even when ore production stops in 2016. This is because project development lead time and service life of capacity was taken into consideration when developing the model. This is important because it accounts for the financing costs that a firm incurs when it is suspends production, say when the copper price is lower than production cost. Further, by considering project lead time, it also means that the model controls for sudden copper production shocks due to sudden copper price increases.

<sup>13</sup>To maintain the same level of cathode production, ore production capacity has to be increased to cover for the effects of reducing [ore grade](#).

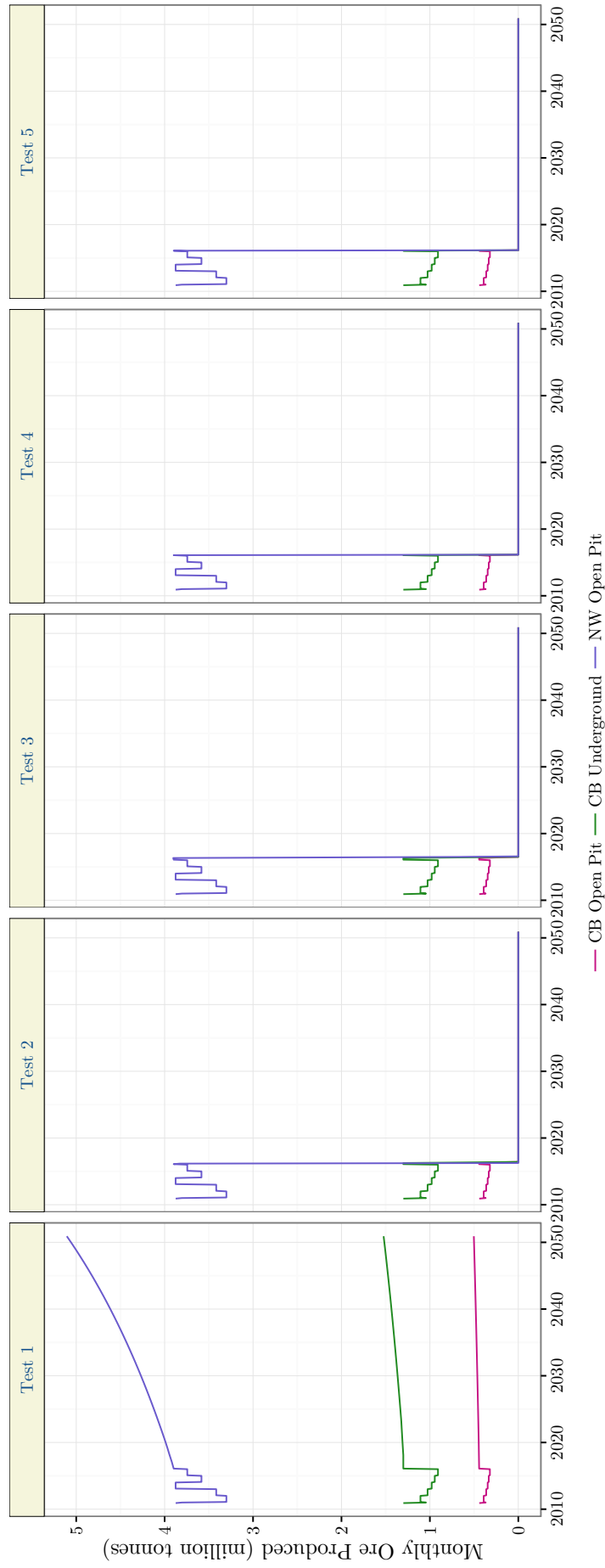


Figure D.1: Model extreme conditions testing: Ore production

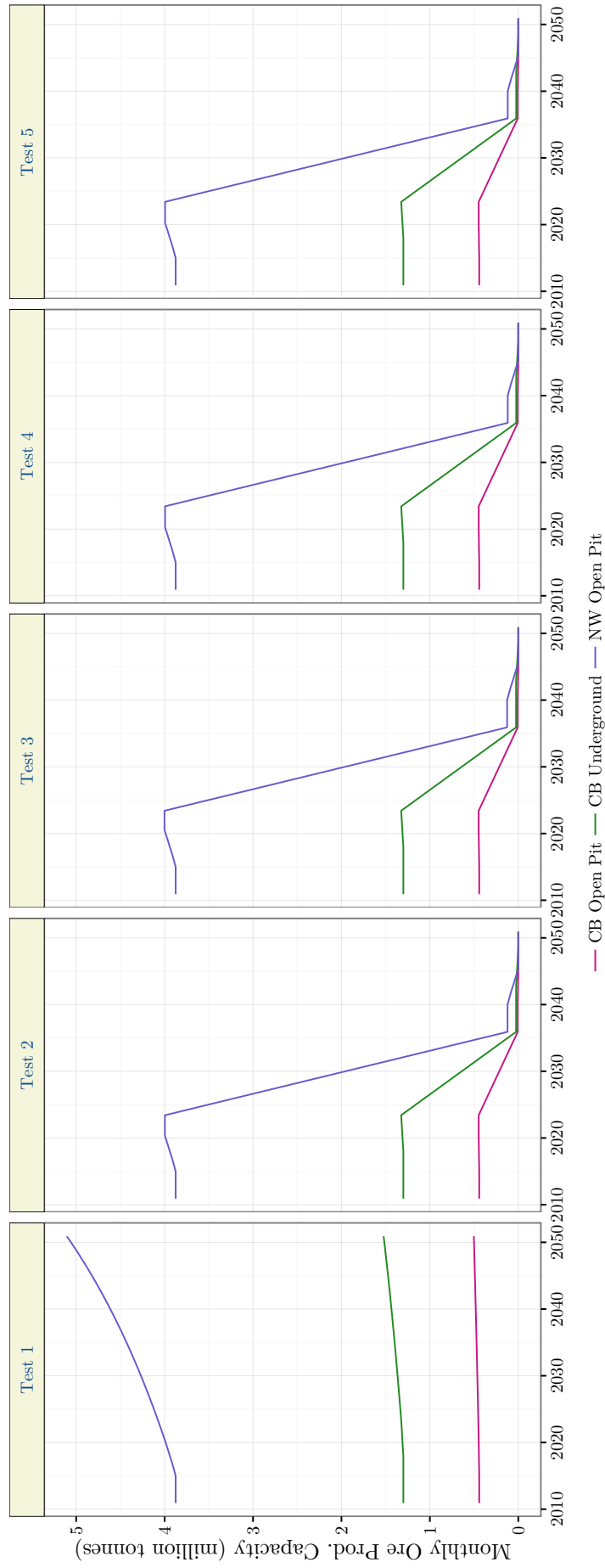


Figure D.2: Model extreme conditions testing: Ore capacity

# Appendix E

## Appendix to Chapter 7

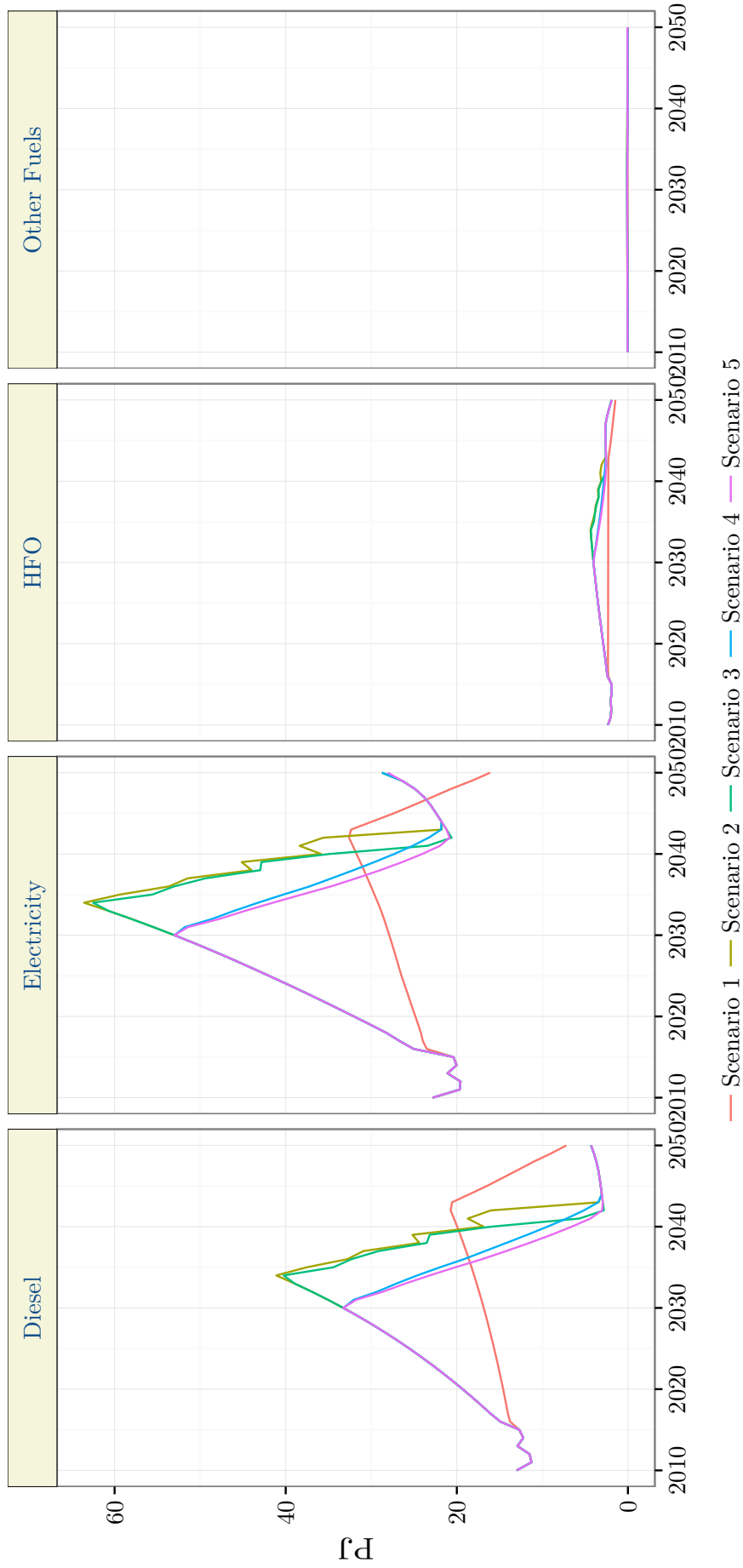


Figure E.1: Projected energy demand of the mining sector at scenario level of the final iteration



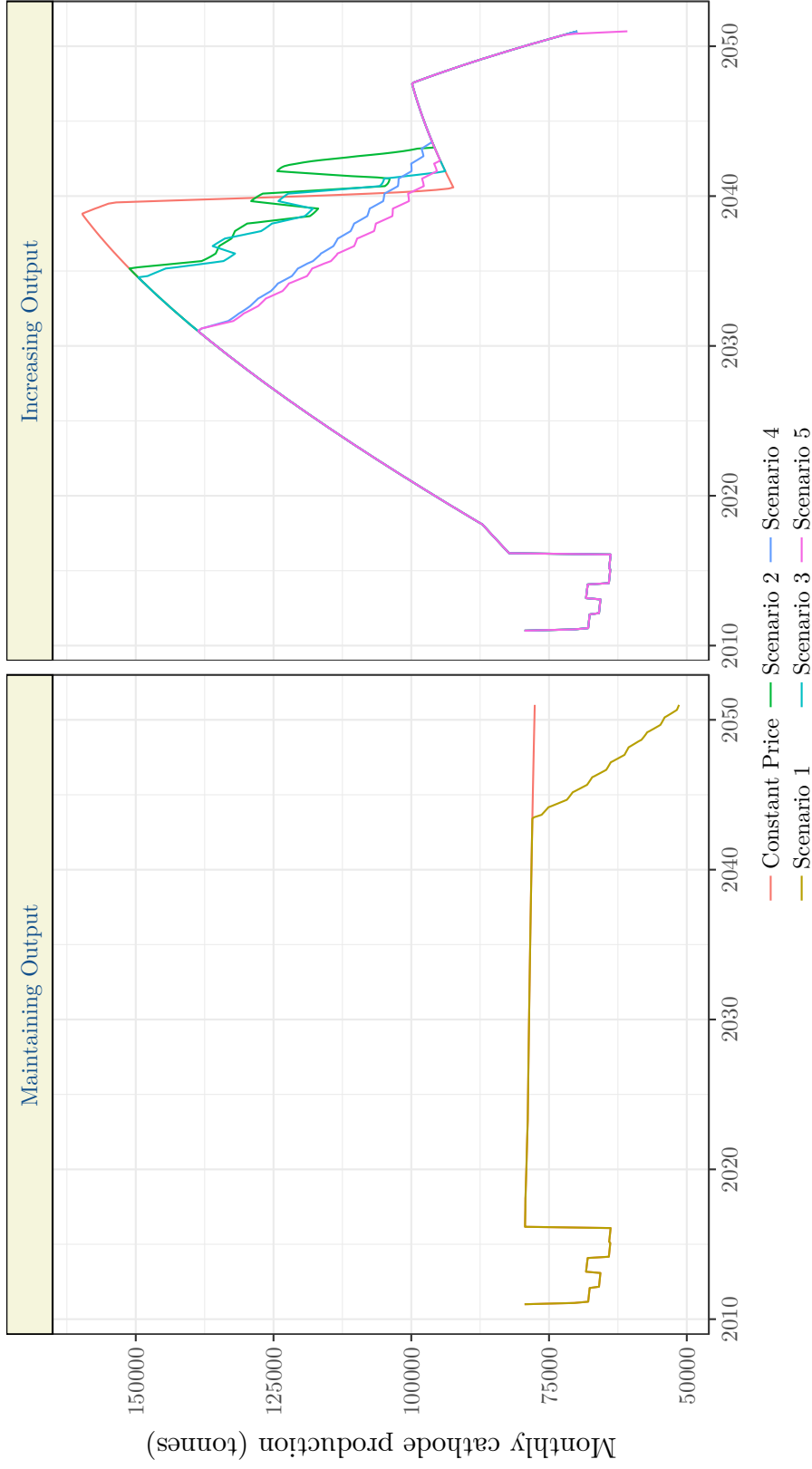


Figure E.2: Projected mining production outputs at industry level for initial and final iteration

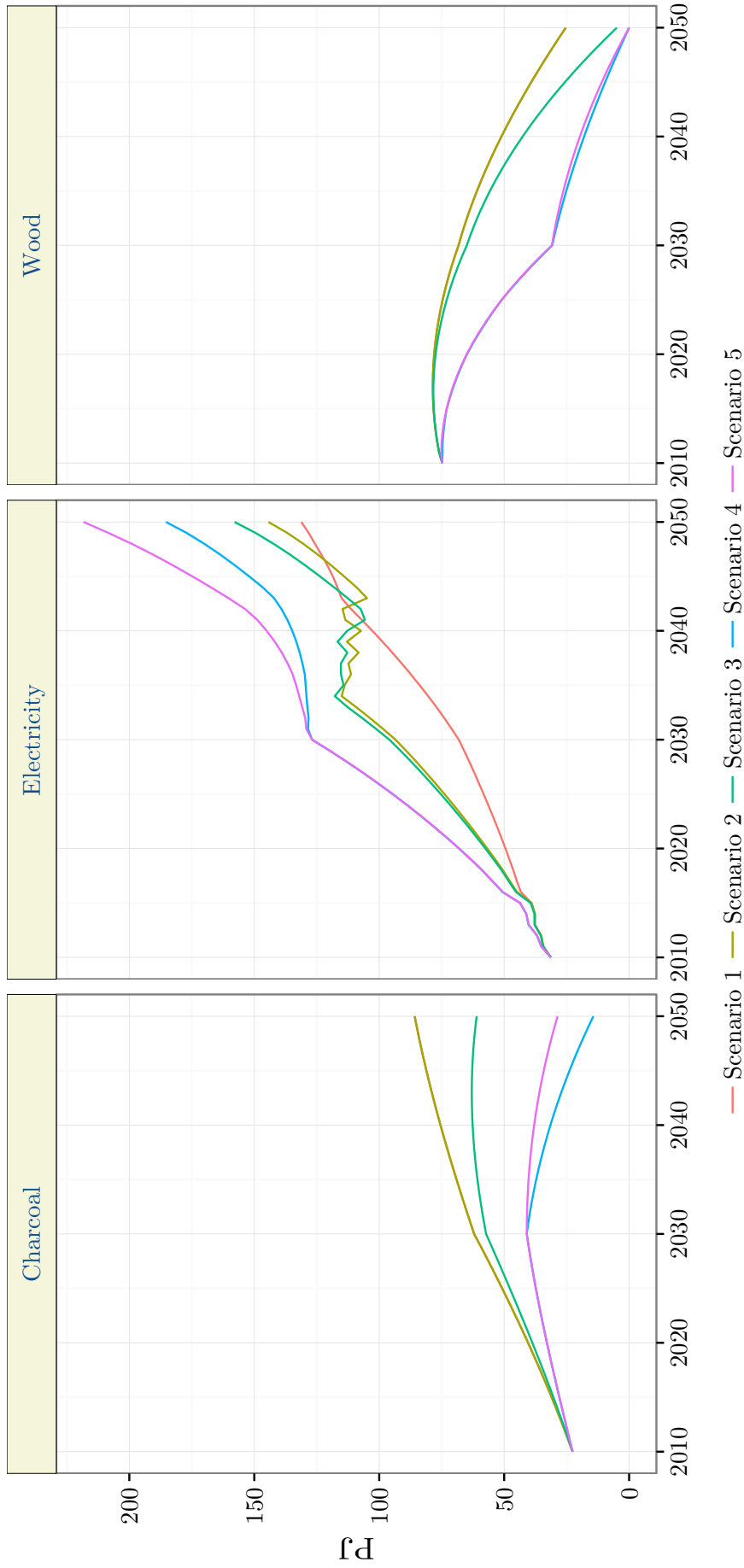


Figure E.3: Projected energy demand for electricity, charcoal and wood at scenario level

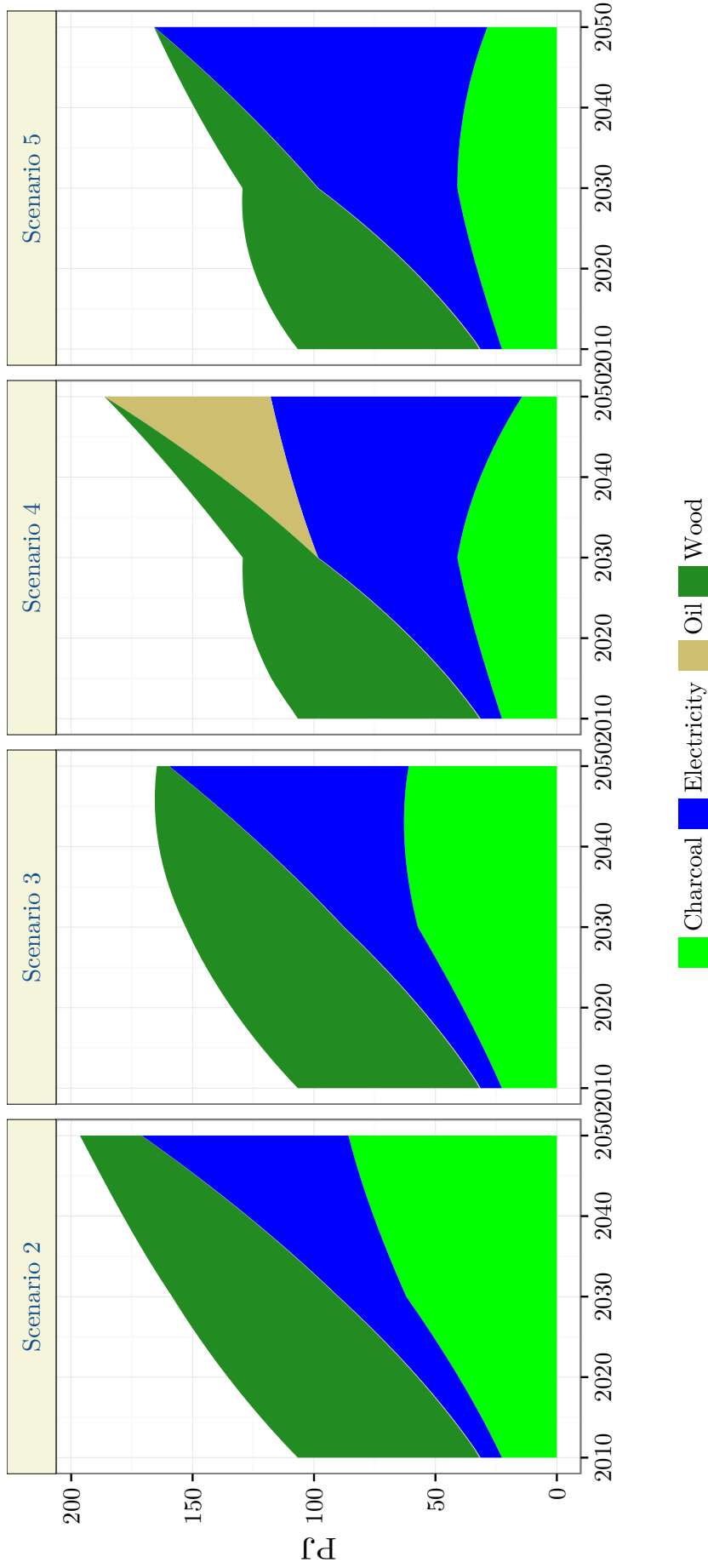


Figure E.4: Residential energy demand projection for scenarios 2-5

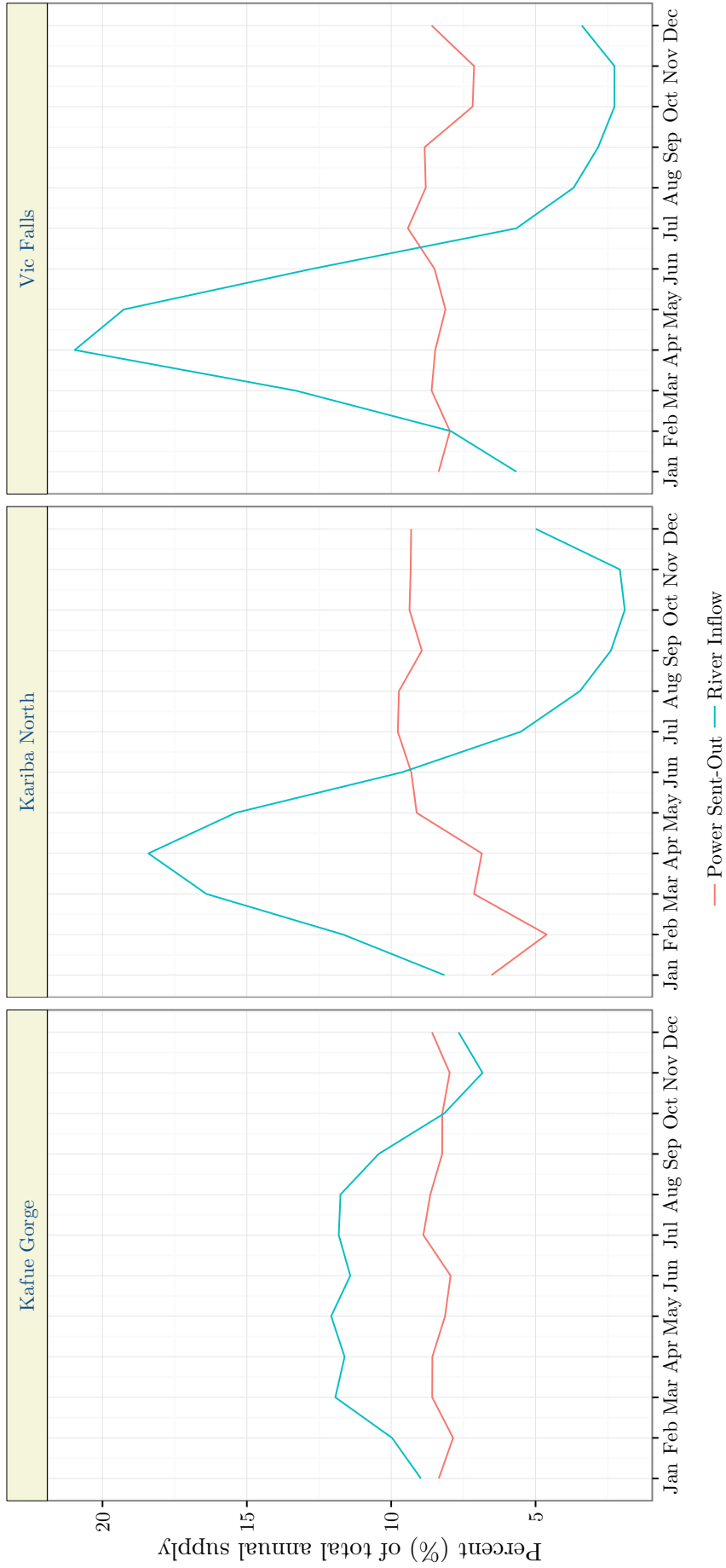


Figure E.5: Share of the total river inflows and power output of hydro-plants (adapted from Tembo (2012))

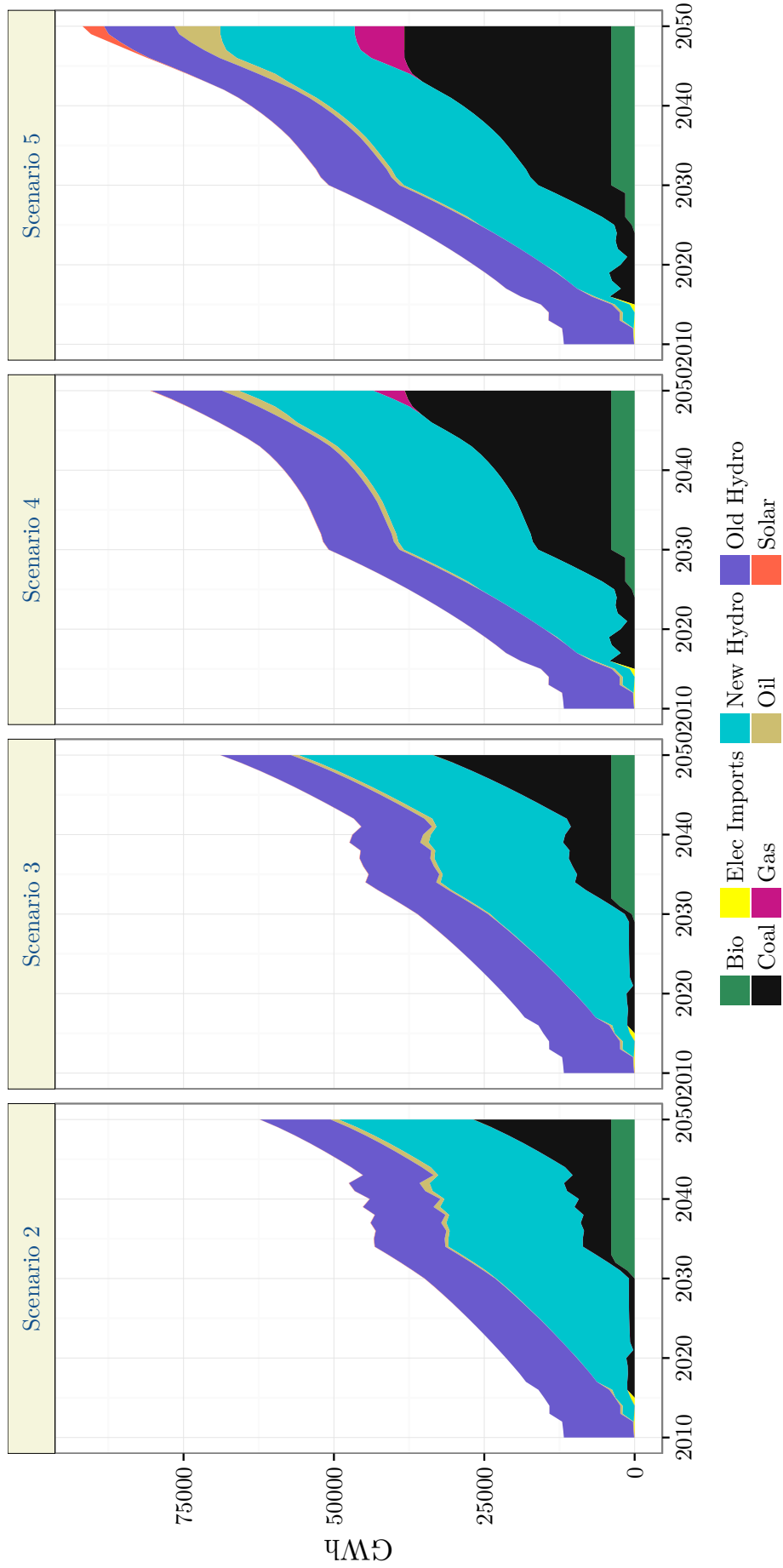


Figure E.6: Total electricity generation by technology in scenarios 2-5

## E.1 Trade-off analysis

Table E.1: Deforestation versus electrification trade-off analysis factor

Variable	Factor	Source
Carbon stored	15.5 to 36.6	<a href="#">Lupala et al. (2014)</a>
( $tC/ha$ )**	38.1 to 41.1	<a href="#">Kalaba et al. (2013)</a>
$tC/tCO_{2eq}$	3.70	<a href="#">Lupala et al. (2014)</a>
factor	3.67	<a href="#">Hibajene and Kalumiana (2003)</a>
Opport. costs	2.68 to 13.33	<a href="#">Damnyag et al. (2011)</a>
( $US\$/tCO_{2eq}$ )	1.08 to 33.44	<a href="#">Cacho et al. (2014)</a>

\*\* Miombo woodlands account for the majority of forest cover and charcoal production in Zambia [Chidumayo \(1987\)](#), [Chidumayo \(1991\)](#), [Hibajene and Kalumiana \(2003\)](#) and [Chidumayo \(2013\)](#)

## E.2 Coal vs Solar comparison analysis

This section focuses on the comparison of coal and grid-connected solar technologies. It pays particular attention to the projected changes in the capital investment cost of solar technology and the impact that this could have on Zambia's energy system. This analysis is an extension of the model and analysis results that are presented in sections [7.1.2](#) and [7.1.3](#) above.

Table [C.12](#) gives the LCoE of technologies that were used to develop the model described in Chapter [5](#). The LCoE of coal technology presented here is the same as that in Table [C.12](#), though the monetary value in this analysis was adjusted to the 2017 value. However, because no grid-connected solar PV technology was considered in Table [C.12](#), the techno-economic data for grid connected solar PV was based on [Fraunhofer ISE \(2015\)](#) and [Fu et al. \(2017\)](#).<sup>1</sup>

<sup>1</sup>Bloomberg's Analyst Reaction article ([BNEF, 2016](#)) was reviewed and considered. The data used in this article (which they use to estimate US\$60.26/MWh) is close to the data in [Fu et al. \(2017\)](#).

Table E.2: Coal-Solar PV-Pump Storage LCoE input data

Variable	Unit	Coal*	Utility-Scale Solar PV **													Pump Storage***
			2010	2011	2012	2013	2014	2015	2016	2017	2050					
PV Capital Cost	\$/kW	3,725	4,630	3,208	2,500	2358	2,295	1,852	1339	660	780					
Fixed O&M	\$/MWh	3.16	7.92	7.92	7.92	7.92	7.92	7.92	7.92	7.92	1.82					
Variable O&M	\$/MWh	6.34	0	0	0	0	0	0	0	0	0					
Efficiency	Percent	36.82	100	100	100	100	100	100	100	100	73					
Fuel Cost	\$/MWh	7.32	0	0	0	0	0	0	0	0	Varies***					
Availability	Percent	85	21	21	21	21	21	21	21	21	93					
Life Time	Years	30	25	25	25	25	25	25	25	25	50					
LCoE	\$/MWh	74.12	307.71	273.49	201.07	165.01	157.77	154.58	105.90	71.33	Varies					

Discount Rate of 8% was used.

All the monetary values were adjusted to US\$ 2017 constant price. The monetary values for Solar PV are for AC (Alternative Current), which are approximately 1.3 higher than those for DC (Direct Current).

\* This is supercritical coal technology. The techno-economic data is the same as that in Table C.12.

\*\* This is Solar PV that is connected to the grid through a solar park/farm. The Solar PV in Table C.12 is modelled as connected directly to the end-user.

Secondly, two scenarios and assumptions were made on the Fixed O&M (\$/MWh) of the Solar PV. In one scenario, it was assumed that it remains constant (as shown in this table) and in another it was assumed that is it a fraction (2.04%) of the capital investment costs. Thus, would reduce over time.

\*\*\* This techno-economic data for pump storage was based on ERC (2013). The fuel (electricity) used in pump storage is from Solar PV, thus the LCoE will vary depending on the LCoE of solar PV.

Figure E.7 below shows the changes in LCoE over time. It can be seen that in three out of four LCoE projections, the LCoE for solar and solar plus pump storage is expected to be cheaper than Coal's LCoE by 2046.<sup>2</sup>

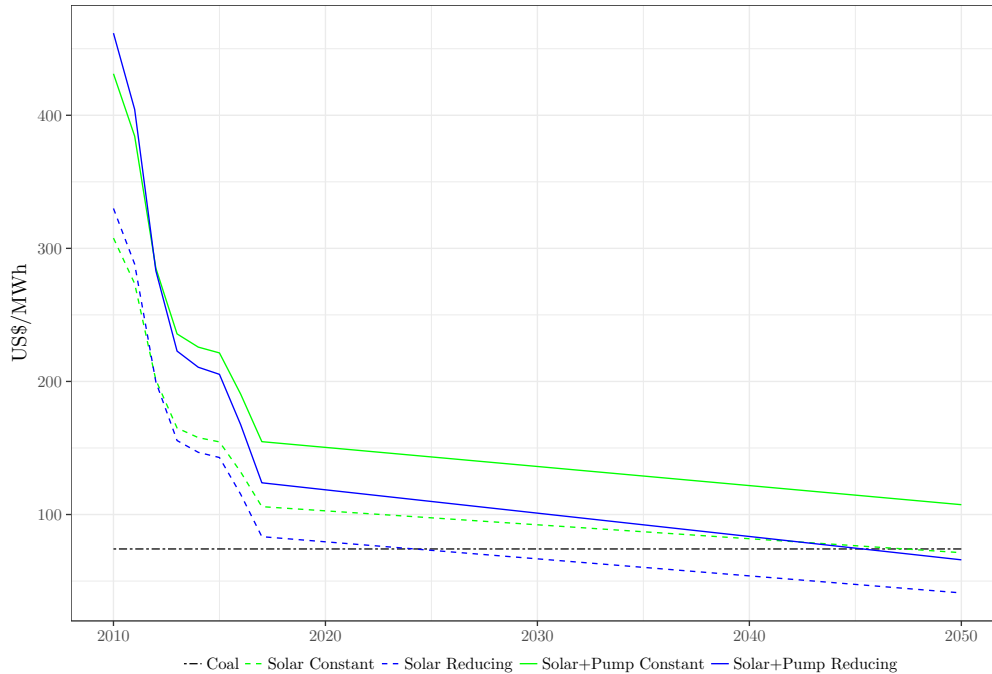


Figure E.7: LCoE analysis for coal, solar PV and pump storage

Having calculated the LCoE, this analysis now focuses on considering what this means for solar and solar plus storage diffusion in the energy system. Development of new coal capacity described in the five energy scenarios (see section 5.3 for the scenario description) was used to analyse how solar and solar plus storage could diffuse in Zambia's energy system. Basically, the analysis looks at how cost effective solar would be in replacing coal technology in the system. The quantity of electricity produced from coal (in these scenarios) was used as a basis for estimating the size of capacity (in MW) of the replacement technology. Figures E.8 to E.11 below show the estimated development of coal and the diffusion of solar and solar plus storage in the system (after considering the calculated LCoE).

<sup>2</sup>In Figure E.7, "Solar Constant" represents Solar PV with constant Fixed O&M costs, "Solar Reducing" represents Solar PV with reducing Fixed O&M costs (a fraction (2.04%) of the capital investment costs), "Solar+Pump Constant" represents Solar PV system with pump storage, which has constant Fixed O&M costs and finally "Solar+Pump Reducing" represents Solar PV system with pump storage, which has reducing Fixed O&M costs (a fraction (2.04%) of the capital investment costs of Solar PV).



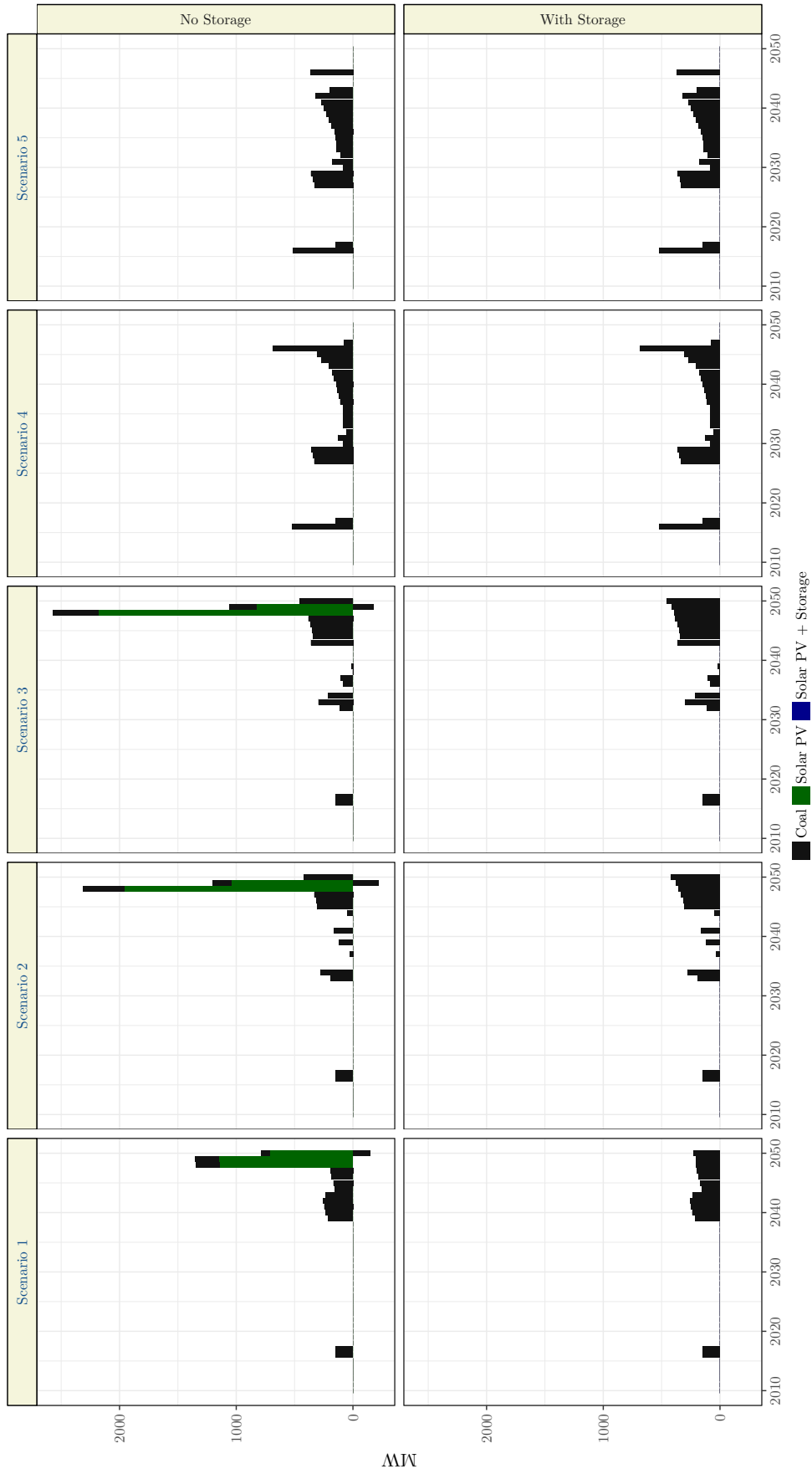


Figure E.8: Replacing coal capacity with solar or solar plus storage by considering constant Fixed O&M costs for solar PV.

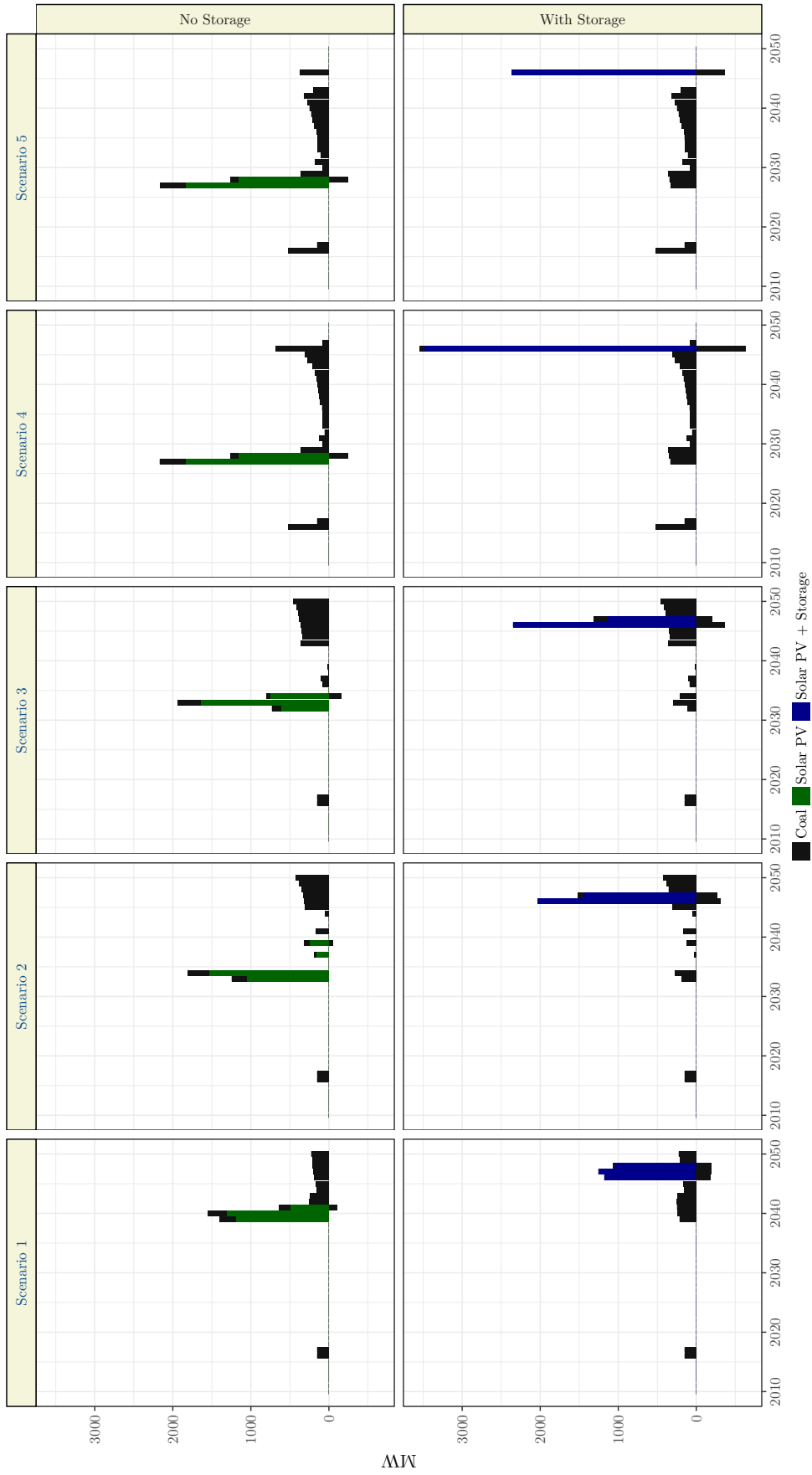


Figure E.9: Replacing coal capacity with solar or solar plus storage by considering reducing Fixed O&M costs for solar PV.

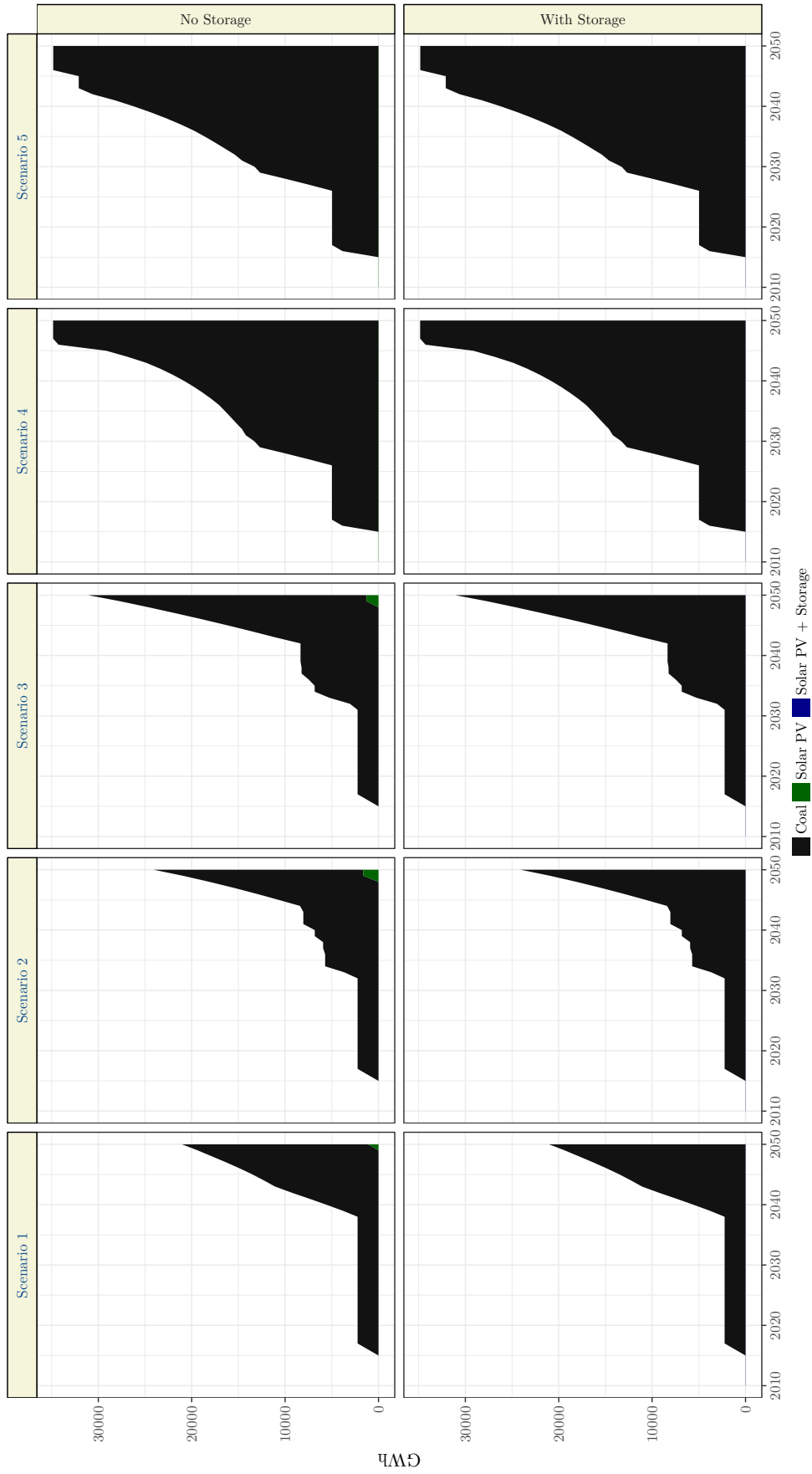


Figure E.10: Replacing coal production with solar or solar plus storage by considering constant Fixed O&M costs for solar PV.

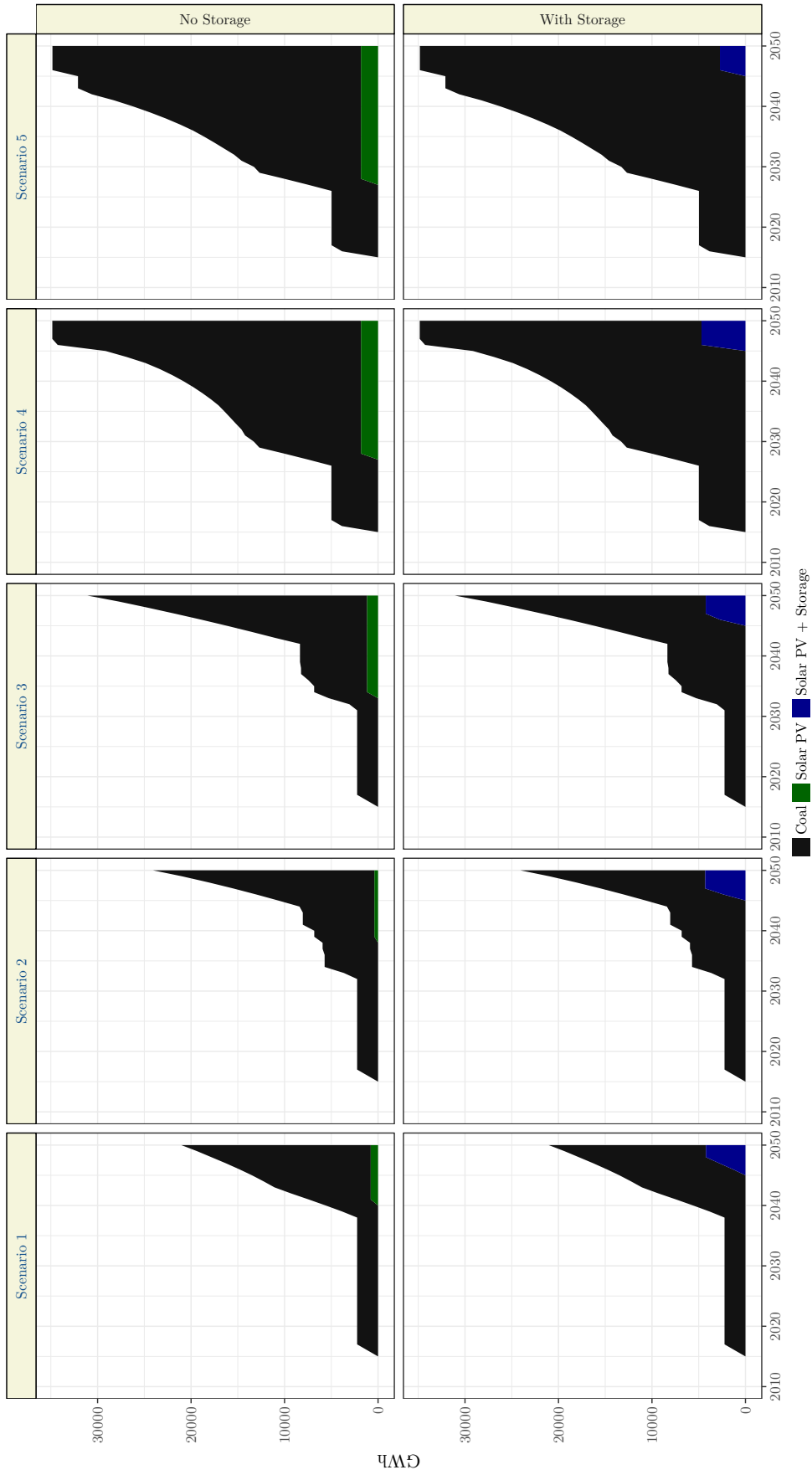


Figure E.11: Replacing coal production with solar or solar plus storage by considering reducing Fixed O&M costs for solar PV.

From the Figures, it can be seen that despite having lower LCoE (in three out of four LCoE projections), diffusion of both solar and solar with storage into the Zambia's energy system is still limited. This is mainly because:

1. In the model, available maximum solar capacity was set to 3,000 MW (and coal was set to 4,300 MW) – see Table C.14. Thus, the available solar capacity is not enough to replace all the coal capacity. This is even more true, when we take into account the quantity of electricity that each capacity (of solar and coal technologies) is able to produce based on their capacity factor.
2. By the time solar plus storage becomes cheaper, most of the coal capacity would have already been deployed. Therefore, only a small portion of coal gets replaced (i.e. solar plus storage is developed instead of coal.)

The second point takes into consideration that even though solar (without storage) would have a lower LCoE, it could not be possible to replace coal capacity using it. This is because of the variability that comes with solar technology. Thus, to effectively replace coal, solar would need to be coupled with a storage technology. In this case, pump storage was considered. Pump storage (like all other technologies) has a cost to it and this defers the decision to deploy solar technology to a later time.

In sub-section 8.3.5 (where I discussed possible future works), I recommended that a comprehensive energy resource mapping for Zambia should be done in order to improve the results of this thesis. Such an exercise would help quantify the size of available resources for solar and other similar technologies that could potentially be used to replace coal and other similar carbon emitting technologies. To address this gap, the [World Bank](#) is currently running a project called 'Renewable Energy Resource Mapping in Zambia' ([World Bank, 2018](#)).

Further, while it was assumed that pump storage was available for development in Zambia, there are no official records to that effect. But if it

is assumed that Zambia's hydro resources could be used to develop pump storage technology, this assumption would break-down when the nature of hydro resources in Zambia are taken into account. This is because the water resources in Zambia, and generally the SADC region, are trans-boundary resources. Therefore, development of any pump storage in Zambia would require changes in laws and regulations of how these resources are utilised. For instance, keeping water resources longer (through pump storage) in Zambia could significantly impact the operations of Mozambican hydro plants.

Thus, at the minimum, to effectively analyse how solar could replace coal in Zambia, there would be need to have a comprehensive energy resource profile and also to have an array of inexpensive storage technologies that could be deployed along side solar and other similar technologies.

### **E.3 KCM costs structure**

Table E.3: Production cost components for KCM between 2003 and 2005

Cost Component	Unit	Type of mining operation						
		Open Pit	Underground	Concentrator	Leaching/ SX/EW	Smelter	Refinery	Eng. & Admin.
Manpower	Percent	17.60	31.41	17.29	7.66	15.00	29.96	28.70
Fuel	Percent	24.60	1.60	0.71	0	29.91	0	4.63
Power	Percent	1.30	23.86	15.60	13.22	13.48	34.91	45.37
Stores and Spares	Percent	20.50	7.03	13.74	2.68	8.93	10.83	0.93
Acid	Percent	0	0	0	37.36	0	0	0
Freight Charges	Percent	0	0	5.28	3.64	0	0	0
Other Ops. Costs	Percent	11.60	15.65	19.76	27.39	18.39	6.78	0.93
Repair and Maint	Percent	16.90	12.21	19.33	5.56	6.79	11.80	6.48
Other	Percent	7.50	8.22	8.29	2.49	7.49	5.71	12.96
Share of Total Cost	Percent	15.35	29.06	11.54	20.88	17.45	2.98	2.74

Source: Rothschild (2008)

## E.4 Copper price model estimations

The data used in estimating the model is based on [World Bank Commodity Price Data \(World Bank, 2015\)](#). The commodity prices were adjusted to constant price of US\$ 2010 value. The R script used in estimating the model factors is given below – basically, the model is a discrete version of Eq. 3.4 which is represented by Eq. 3.8. Table E.4 shows the factor estimates of the model. It can be seen that the range of time series used significantly impacts the magnitude of factors.

Listing E.1: Discrete copper price estimation model

```

1 require(dplyr)
2
3 # Reading price data into R
4 comprices <- read.csv(choose.files(), header=T, sep=",")
5
6 # Extraction copper price data
7 modelfactorsest <- function(Input, prVar, yrVar){
8   prCu <- ts(select(Input, prVar))
9   prdiff <- as.numeric(diff(prCu))
10  prlag <- as.numeric(prCu[1:671])
11  Dates <- select(Input, Month, Year)[1:671,]
12  prdata <- cbind.data.frame(Dates, prlag, prdiff)
13  prdata <- filter(prdata, Year >= yrVar)
14  regmodel <- lm(prdiff ~ prlag, data = prdata)
15  regdata <- summary(regmodel)
16 }
17
18 mfact <- modelfactorsest(comprices, "LnCopper", 1960)
19
20 # Extraction of model factors
21 pricemean <- mfact$coeff[1] * -1/mfact$coeff[2]
22 pricemean2 <- exp(pricemean) # US$/tonne
23 modelmu <- log(1 + mfact$coeff[2]) * -1
24 halflife <- log(2)/modelmu # in months
25 msigma <- mfact$sigma * 2 * modelmu
26 msigma2 <- (1 - exp(-2 * modelmu))
27 modelsigma <- sqrt(msigma/msigma2)

```



Table E.4: Model estimates for Copper prices

---

Factor	Unit	1960-2015	1980-2015	2000-2015
Mean Price	Index	8.225796	8.148373	8.699925
Mean Price	US\$/ton	3736.10	3457.75	6002.46
Speed of reversion	Index	0.012043	0.008987	0.013787
Half life	Months	57.55	77.13	50.27
Std. Dev.	Index	0.266581	0.256761	0.266566

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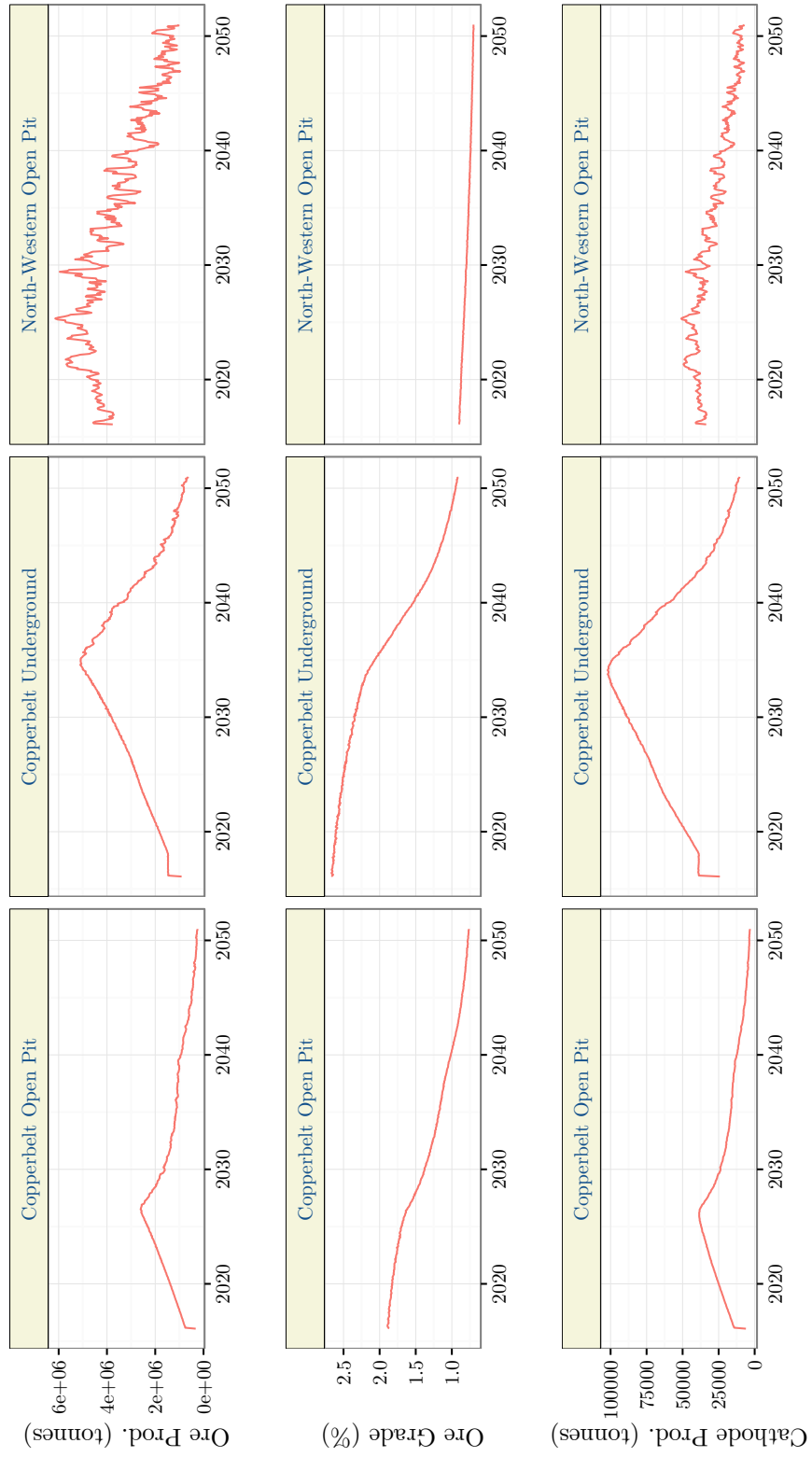


Figure E.12: Average ore grade, ore and cathode production

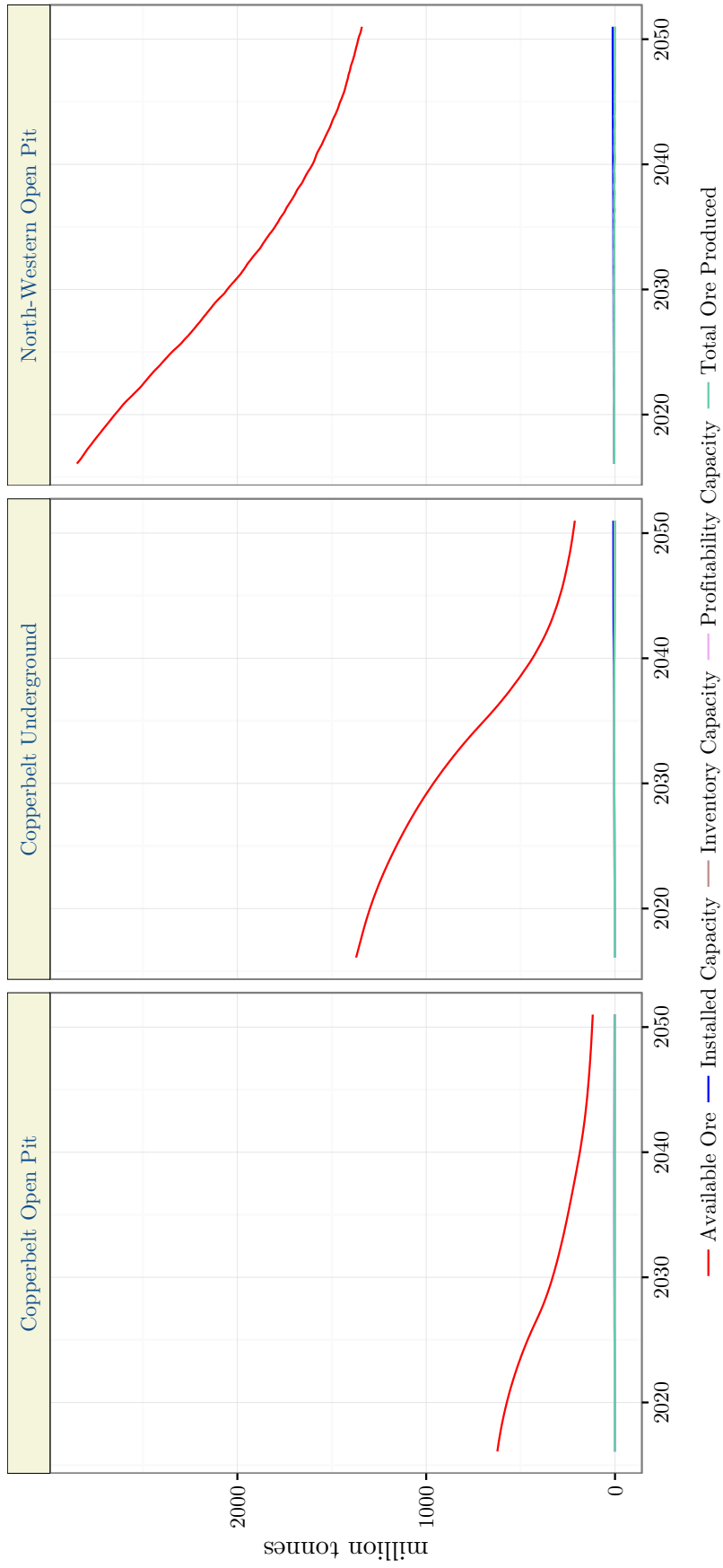


Figure E.13: Available ore versus produced ore and production capacities

## E.5 Impacts of price, ore share and grade

This section elaborates the impacts that copper price, [ore grade](#) and ore share have on cathode production at industry level. It builds on and is an extension of Section 7.2.2 in Chapter 7 above. This analysis focused on the impact that [ore grade](#), mix of reserve ore type and copper price have on production, holding all other variables constant.

- **Ore grade:** The estimated initial [ore grade](#) (current ore being mined) for each mining site was varied between  $\pm 10\%$ , and an internal [ore grade](#) variance range of between 0–2% was considered.
- **Mix of ore reserve:** The estimated available ore reserve share of oxide ore was varied between  $\pm 50\%$ . From the analysis in Chapter 7 and in Section D.5 of Appendix D, it can be seen that costs and energy consumption of oxide and sulphide ores are different.
- **Copper price:** Copper price in this analysis was randomly varied between US\$ 1, 710 and US\$ 9, 147 per tonne of cathode. These two prices represent the minimum and maximum historical observed real prices (between January 1960 and December 2015).

Figure E.14 below shows the results of this analysis, 200 simulation runs were done for each variable. From this figure, it can be seen that copper price has the largest impact on the production behaviour of a mining operation.

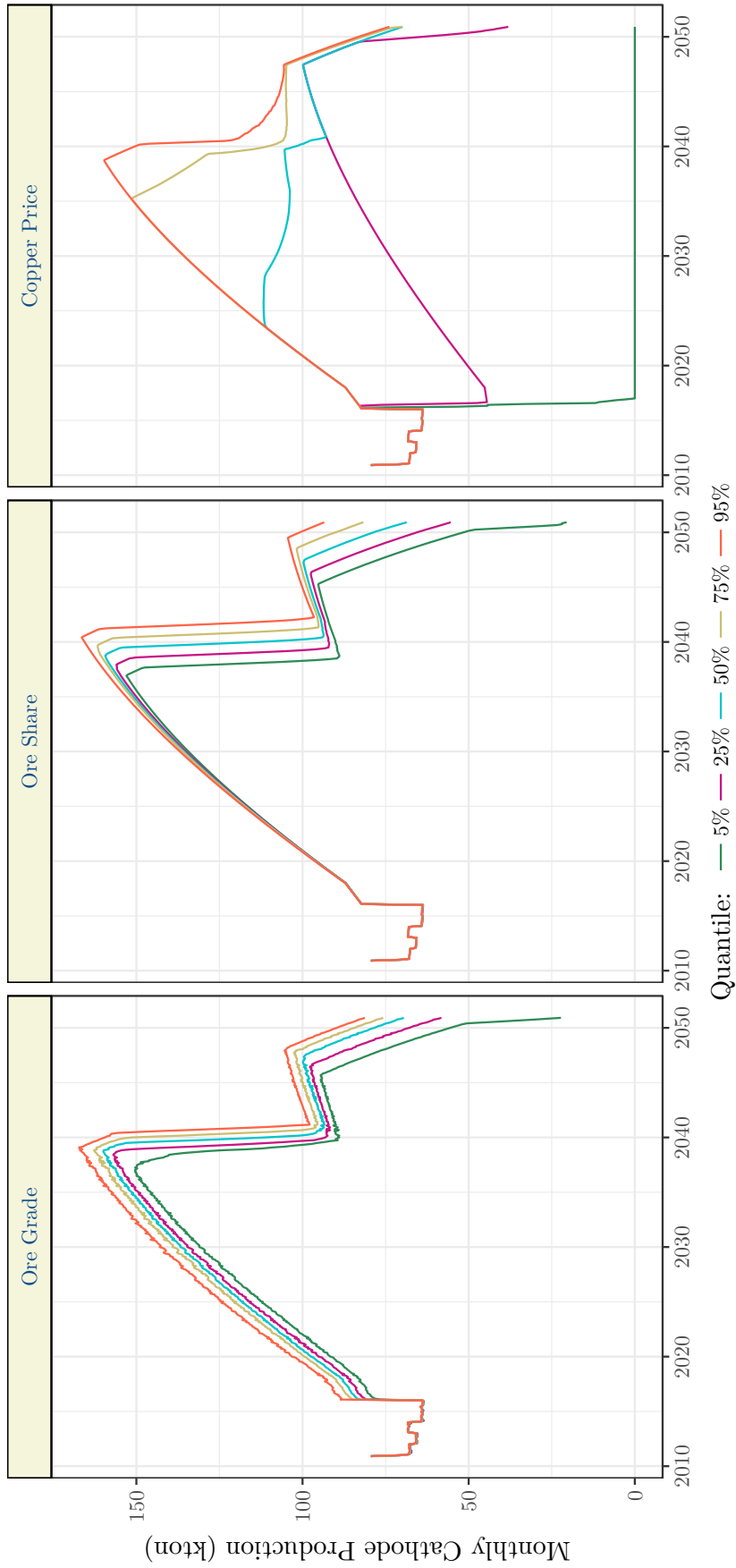


Figure E.14: Impact of varying ore grade, ore type share and copper price on cathode productions

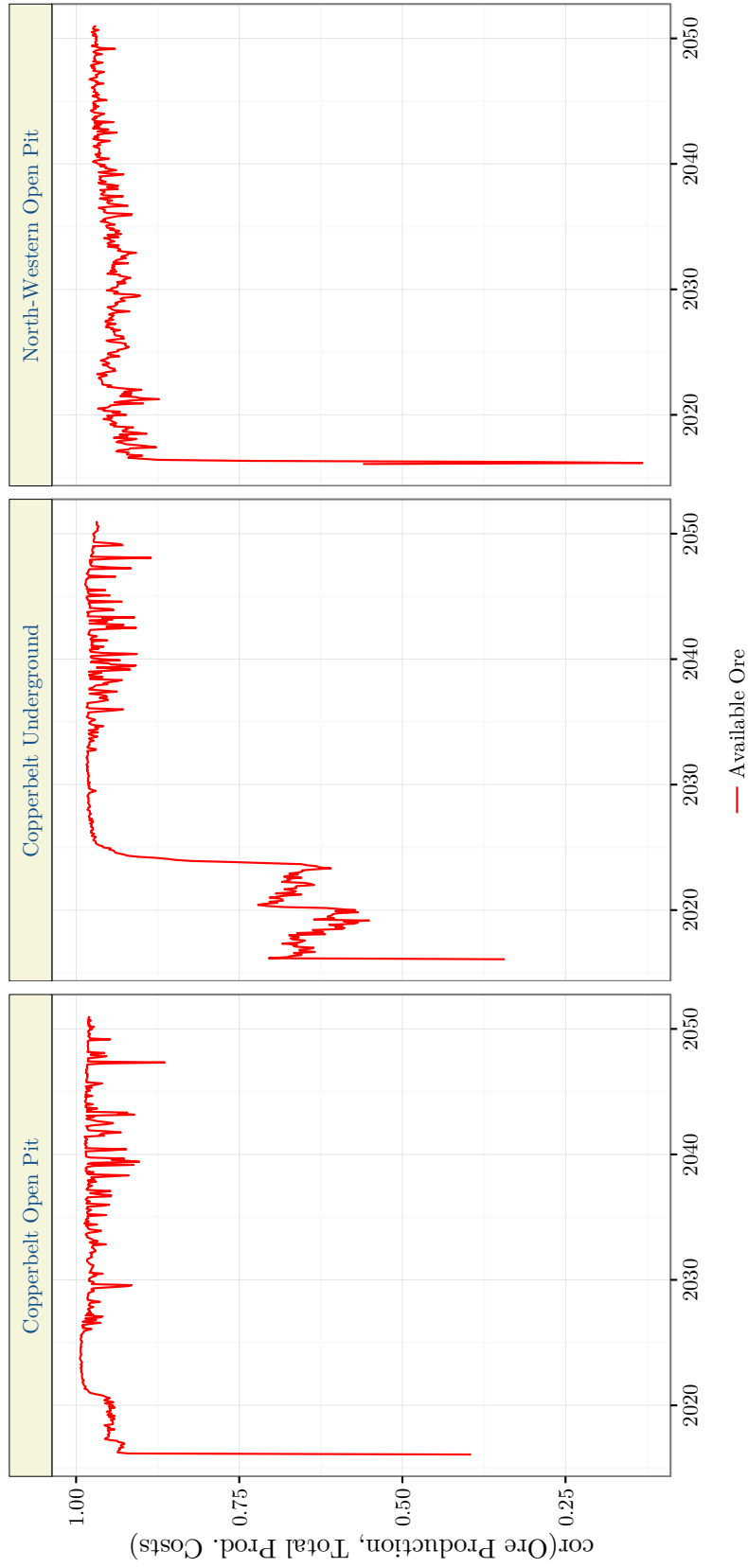


Figure E.15: Correlation of ore production and total production cost

