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# The Ring of Fire

Priority Setting for Nuclear Power in the North

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”In memory of my grandfathers, whose  
name I will always carry ”

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— Enzo Adrianus Johannes Diependaal

# Abstract

The objective of this work is the creation of a framework for future priority-setting regarding the deployment of small modular reactor in isolated Northern energy grids. For this purpose this study uses a model-based approach, making use of the TIMES modeling environment. With energy being an absolute necessity in these regions, energy security is of the utmost importance. Currently, the most secure way of generating electricity comes mainly from diesel fuel. However, diesel power comes at a high cost in the form of emissions, operational expenses and pollution. This puts an extreme financial burden on local communities and deters mining companies from investing in these inhospitable regions. The creation of the TIMES-Ring of Fire model makes it possible to analyze different scenario's at the proposed Eagle's Nest mine. Here, the proposed energy from diesel power is compared to multiple theoretical nuclear reactors. Small modular reactors prove to be competitive, however, they have a high level of uncertainty due to their limited data and experimental nature. With current assumptions, SMRs prove to be competitive between discount rates of 0-8%, and become increasingly competitive at longer energy-system lifetimes. The possible introduction of a carbon tax increases SMRs competitiveness even further. Discount rates turn out to be a major variable in the assessment of SMR technology, as all investments are placed in the first year, compared to diesel fuel which has most expenses in the future. Diesel fuel therefore is discounted more and has a relatively steady levelized cost of energy (LCOE). In contradiction, SMR LCOEs changes considerable with a varying discount rate. As a measure of competitiveness, the LCOE of nuclear power can drop to  $\sim 31\%$  of the comparable diesel system (20 year lifetime, linear carbon tax, 0% discount rate). This study, besides confirming past results, warrants future research and provides a flexible framework for this purpose.

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# Preface

The inspiration for this research came as an extension of the "Sustainable Energy in the Arctic" course at the University Center in Svalbard (UNIS). The course included the creation of a working paper regarding an energy project in the Arctic. As Longyearbyen is expected to run out of coal in 7 years, our project group, consisting of 4 students, set out to model different energy futures for Longyearbyen, based on continuation of their current system (using coal imports) and the introduction of renewable energy systems. Simultaneously, we attended a commercial meeting on the possible energy futures for Longyearbyen. After all proposals, one person in the audience asked why nobody thought about nuclear power, which was greeted with laughter.

While people laughed about the idea of a nuclear power station (given the normal stereotype of 1000+ MW reactors, complete with giant cooling towers), I found myself intrigued by the possibilities. As a proponent of nuclear power in the right conditions, and being acquainted with the new developments in the nuclear field in particular the field of small modular reactor (SMR) and very small modular reactor (vSMR) technology, I set out to model this option within our working paper. It turned out that in this specific case, nuclear would be the cheaper option, as compared to the renewable option. The continuation of coal was the most in-expensive, as it did not require new infrastructure. While the outcome regarding nuclear power as an option was received sceptically, it was also the basis for this thesis project. The results of the working paper showed that in the conditions as presented in Longyearbyen, nuclear power would be considerably less expensive than a renewable alternative.

With the idea that nuclear power could provide affordable and reliable energy to isolated locations, I proposed a research into the modeling of these SMR-systems in order to recommend improvements on their design and use based upon the models outcome. As a surprise, I was contacted by Dr. Akira Tokuhiko, inviting me to Canada to conduct my research at the University of Ontario, Institute of Technology.

Starting my research, I discovered that previous research was conducted and available. Most recent research was done by Gihm, for Hatch ltd. (2016) and Moore, for the Canadian nuclear laboratories (CNL) (2017). These studies were however limited in scope (through a limited economic calculation), or used non-verifiable techniques (through the use of "in-house" knowledge). The creation of a verifiable frame-work for future priority-setting therefore still made sense.

While I was unable to fulfill all my stated intentions, as I would have liked to do much more with regards to the technology development within this vastly interesting and developing field, the study did provide the means for future priority-setting and the creation of a framework in which one might continue further research.

I owe the University of Ontario, Institute of Technology (UOIT) much gratitude for showing interest in my idea, and inviting and hosting me at the Faculty of Energy Systems and Nuclear Sciences (FESNS).

I would sincerely like to thank Dr. Akira Tokuhiko, Dean & Professor of FESNS for having interest and faith in my ideas and work, and for his kind invitation to Canada. I further need to thank Dr. Tokuhiko for his warm welcome and answering my questions whenever I had them and his continuous support through my time being in Canada.

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Secondly, I would like to express my sincere gratitude to Dr. Jennifer McKellar, for her warm welcome and helping me find my way before and after my arrival. After settling in, Dr. McKellar was kindly willing to answer all my questions and reach out to industrial and academic partners for the resources I requested. I can honestly say that I felt very comfortable working with Dr. McKellar.

Additional warm feeling go out to all my colleagues at FESNS for all the fun outings and having me within their group, answering all my work and non-work related questions.

My gratitude is also expressed to Einar Jón Ásbjörnsson for his continuous support and faith in my work abroad and for the final assessment of my work.

Finally, I would like to thank Birte Uhlig, for her continued interest in my work and proofreading my report in the shortest amount of time. I'm sorry that I ruined your day off in the process of creating this thesis.

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# 1 | Executive summary

"The Ring of Fire - Priority Setting for Nuclear Power in the North" describes a techno-economical study to assess the feasibility of small modular reactor (SMR) deployment for mining purposes in the northern regions of Canada.

## Objective

The primary goal is a feasibility assessment of small modular reactor deployment in isolated power grids and the provision of a framework for priority-setting for future research, legislation and investment opportunities.

## Methodology

The research is performed as a single case approach study, based on an extensive literature study and a model-based approach. The model was created with the TIMES (The Integrated MARKAL-EFOM System) model generator. The resulting TIMES-Ring of Fire (ROF) model uses the demand profile and energy system characteristics of the proposed Eagle's Nest mine, as given by Noront Mining Ltd. (2012).

Previous research proved to be either limited in scope, or done by the use of non verifiable and reproducible means. This research tries to mitigate these problems by using operational and economic values from peer-reviewed studies, other trusted sources and the vendors themselves, for all utilized technologies. All values are retrievable in the public domain.

The results from TIMES-ROF were analyzed directly, and through the use of an levelized cost of energy (LCOE) calculation. The LCOE provides the reader with a cost per unit of energy, in \$/MWh, to compare the technologies over their intended lifetime.

The following assumptions and actions were applied to this research:

- All monetary values were recalculated using the United States Bureau of Labor Statistics CPI Inflation Calculator, and expressed in 2017-USD
- The price of fuel is fixed in time, at 64 ¢/liter
- The discount rate is set at 8%
- The used technologies have no salvage value
- For systems with a first of a kind (FOAK) cost estimate, the expected cost for a 8th of a kind reactor system, through an Nth of a kind (NOAK) estimate, was calculated
- For the possible carbon tax calculations, the medium expected price-path was used
- All values are given pre-tax

## The Eagle's Nest

The Eagle's nest will be a subsurface platinum group element mine, operating for 11 years. A lifetime extension by an additional 9 years is possible.

**Table 1.1:** *The assumed average power requirements during each phase of the mine for the period 2023-2033. The upper row represents an assumed demand of 21.3 MW, the second row is based on a demand of 22.05 MW. The values is given on a per-year basis*

	2020	2021	2022	2023-2033
MW	1.95	5.37	6.51	21.3
MW	1.95	5.96	7.3	22.05

The mine's energy system is designed to be operated at 21.3 MW. As past research focused on 22.05 MW, both numbers are used for the final analysis. The energy system is designed in an N+2 configuration, housing 10 generators of which 2 are on stand-by. Final assumed values for the power demand are provided in Table 1.1

For the generators, a capacity factor of 0.96 is assumed. To account for the extra capacity, an additional peak power reserve of 20% of total generating capacity is set. the capital expenditures for the gensets were estimated at \$1750 \$/MW and operational expenses were estimated at 15 \$/MWh.

### Carbon tax

The Carbon Tax has been estimated based upon the long-term carbon price forecast (LTCPF) as given in the Long-Term Carbon Price Forecast Report written by ICF Consulting Canada Inc. For this study, their medium growth price forecast was used, and extrapolated over the intended lifetime of the mine by means of a linear and exponential growth prediction.

For the linear growth prediction, the expectations are for the carbon tax to climb to a 80\$/ton CO<sub>2</sub> in 2034. For the exponential growth predictions, the carbon tax is expected to climb to 118\$/ton CO<sub>2</sub> in 2034.

### SMR selection

For this study, 57 Small Modular Reactor systems were analyzed for their applicability at the Eagle's Nest. SMR information was retrieved from the IAEA, Canadian Nuclear Safety Commission (CNSC) and the US Department of Defense. Out of the 57 initial SMRs, 17 proved to be applicable to the Eagle's Nest, based on power output (<25MW).

A further selection was made based on the availability of economic data. This led to a final short-list of 8 SMR systems applicable for this research. An overview of the SMRs and their economic assumptions can be found in Table 1.2

### TIMES - Ring of Fire

The TIMES-ROF model is created through the use of the TIMES model generator. TIMES is run with the use of scenario's, describing possible energy futures, calculating their optimal energy system and associated cost. A visual representation of the times model is given in Figure 1.1:

**Table 1.2:** *Summary of used SMRs and cost assumptions*

Nr.	Name	CAPEX \$/GW	Fixed OPEX \$/GW	Variable OPEX \$/MWh
1	MegaPower	77706	Included	Included
2	U-battery	12055	15.3	Included
3	HOLOS	5769	Included	Included
4	4S	10250	12.8	Included
5	SEALER	27778	Included	Included
6	UNITHERM	47027	Included	Included
7	ABV-6E	8713	Included	39.9
8	ABV-6E	5808	Included	26.6

The following scenarios were used within this research:

- Business as usual (BAU) scenario
  - Presenting the expected development of the mine as would be the case without the use of new technologies.
- Carbon tax scenario
  - Two separate scenarios. One of them assuming a linear carbon tax growth forecast, the other one assuming an exponential growth forecast. The absence of both of these scenarios implicitly creates a third scenario, the "no-tax" case.
- (v)SMR scenario
  - With this scenario, all SMR technologies are added to the model, providing The Integrated MARKAL-EFOM System (TIMES) with the 8 applicable SMR technologies, to choose from.
- Peak power
  - The Peak power scenario provides TIMES with the order to reserve 20% of total installed capacity for peak power purposes (in addition, this power can be used during maintenance, breakdowns or refueling of other generators or the SMRs alike).

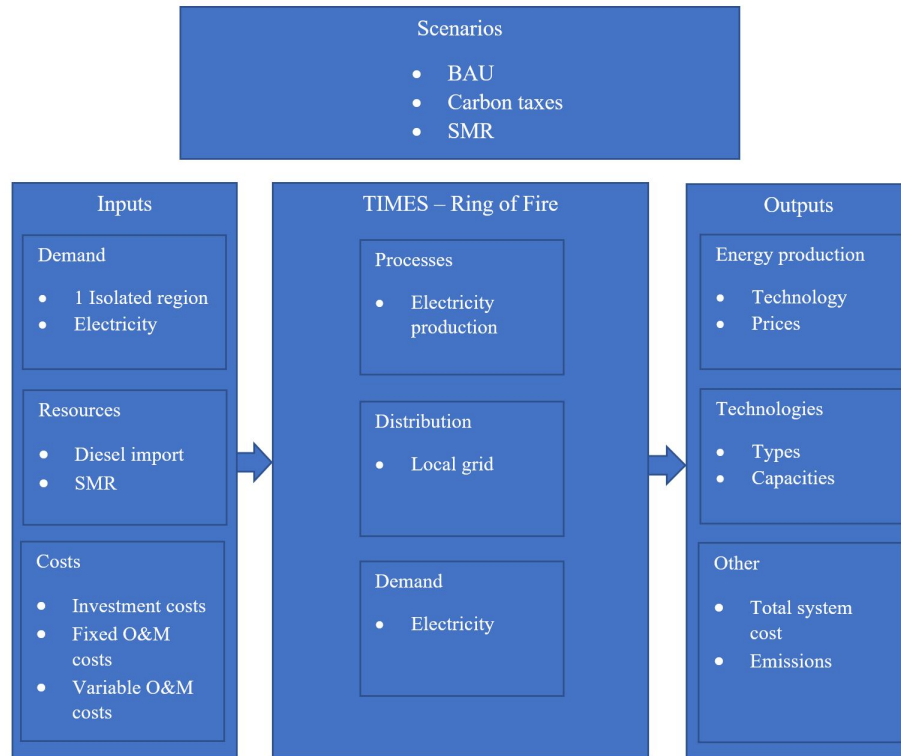
Next to the scenarios, TIMES uses the following parameters:

- Energy demand as defined by the user
- 0% Losses on the local electricity grid

Limited calibration of the model and assumptions were done through comparison of operation data from the data provided by the Qulliq Energy Corporation (QEC) and the Noront's feasibility study. Direct calibration of the model is not possible as there are no operational data from the mine.

## Final results

The final results verify past research and warrant prioritizing further research into the deployment of SMRs in isolated grids. Even with the gensets being modeled under favorable conditions (a low



**Figure 1.1:** Visual representation of the TIMES-ROF model structure, as adopted from the TIMES-Noway report by Lind et al. (2013) [1]

estimate for the future diesel prices), the SMRs have an economic advantage provided the current economic assumptions.

In absolute terms, the conventional system would come at a cost of 449 M\$, over the intended lifetime of the mine. Carbon taxes only increase this value, up to 526 M\$. Applying the 8% discount rate as utilized by Noront, the initial value is discounted to 272 M\$. In comparison, the cheapest SMR comes in at a total system cost of 156 M\$ at a 0% discount rate, and at 150 M\$ at an 8% discount rate. The well documented U-Battery comes in at respectively 282 M\$ for a 0% discount rate and 297 M\$. at an 8% discount rate.

A better comparison can be made using the LCOE-calculation. Gensets have an LCOE of between 206-248 \$/MWh. The most inexpensive SMR delivers power between 69 and 125 \$/MWh. The U-Battery delivers power between 225-228 \$/MWh at an 8% discount rate and at 137 \$/MWh for a 0% discount rate.

The calculations indicate that lengthening the lifetime of the system, or reducing the discount rate, results in favorable conditions for the SMR.

If the full 20 years of the mine is used, In absolute term the conventional system would cost 761 M\$ without taxes, and 951 M\$ with an linear carbon tax in absolute terms. In terms of an LCOE, this would be 197 \$/MWh, and 247 \$/MWh, respectively. As a comparison, the U-battery would cost 300 M\$ at an LCOE of 78 \$/MWh.

At current assumptions, the U-Battery, would be competitive at a discount rate of 0-8% for the intended lifetime of the mine. Increasing fuel prices will increase the range of competitiveness even further. Furthermore, the U-Battery could mitigate up to 2820 kt of CO<sub>2</sub> emissions.

## **Recommendations**

Recommendations for further research include an in-depth analysis for the SMR technology with regards to their investment and operational costs. One of the considerations is to perform a components-based analysis, if possible. Additionally, the user should take into account salvage values, which might allocate additional value to the SMRs.

The same recommendations apply to the input parameters for the gensets, for which values with a high degree of certainty should be obtained.

Another consideration is the use of discrete commitment within TIMES. The use of this module will deliver a result better representing the total needed available capacity under all circumstances. Another consideration within TIMES is to utilize a demand function, instead of the inelastic demands used at the moment. Furthermore, commodity demand curves (for example heat) should be considered. These additional demand profiles should ideally be defined per season and at an increased resolution an could provide additional incentives for SMR deployment.

Additional improvements towards this specific study can be obtained by the use of additionalal generation sources to offer a more extended energy mix.

Finally, is is recommended to look beyond the techno-economic assessment of this study and incorporate legislative bodies, utilities and communities.



## 2 | Introduction

This master’s thesis will provide the reader with a feasibility study for the deployment of SMRs at the proposed ”Eagle’s Nest” mine. The study will deliver a framework for priority setting for future SMR research and isolated grid based energy development, through a model-based approach.

While previous literature and studies exist on this matter, new developments within the energy and nuclear industry warrant a reassessment on the feasibility of SMR deployment. The most recent research proved to be either unverifiable, due to the use of ”in house knowledge” (Hatch 2016, [2]), or was limited with respect to the techno-economic assessment employed (Moore 2017 [3]). This study, tries to mitigate these problems by the use of a generally available model generator and an in-depth assessment of the techno-economic values of the used technologies. Its explicit aim is to do so in a verifiable manner.

### 2.1 Research questions

The primary goal of this study is to provide the tools to:

- Comprehensively assess the feasibility and implications of SMR and vSMR deployment in isolated power grids.
- Provide a framework for priority-setting for future research, legislation and investment opportunities.

The underlying research design commits to the the scientific method and provides an academically relevant research question:

”Does SMR technology indicates to provide a feasible way of powering mining sites in the remote North?”

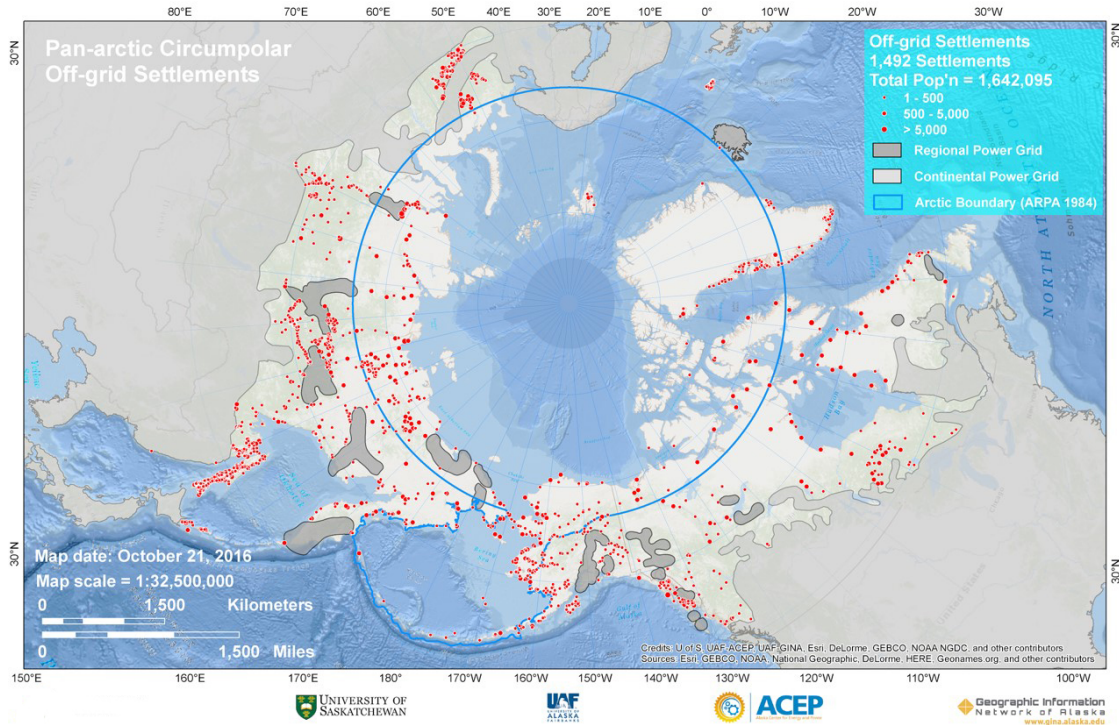
This main research question is answered by means of the following sub-questions:

- Which technologies are applicable?
- What is the total economic evaluation?

### 2.2 Background

In the northern regions of Canada, population is spread thin and nature all-embracing. The pristine wilderness however hosts vast riches, resources hidden from sight within the subsurface. With the need for resources rising all over the world, expansion of mining companies into these harsh lands is inevitable.

In these regions, power is a necessity for life. The (sub)-Arctic climate is harsh and power consumption is high. Both for local communities and mining companies alike, this creates a problem,



**Figure 2.1:** Map from the University of Saskatchewan and University of Alaska Fairbanks, depicting the extend of the circumpolar energy grid extend [4]

as the northern-American energy grid does not extend this far north, as can be seen in Figure 2.1. As extending the grid is often undesirable due to the high costs, generation of energy on a local level is the only method currently used.

With energy being an absolute necessity in these regions, energy security is of the utmost importance. Currently, the most secure way of generating electricity comes from fossil fuels, mainly diesel fuel. Diesel generators operate independently of the weather and have load following capabilities, providing the security and flexibility needed for these local isolated energy grids.

However, diesel power does not comply with the wish of pursuing long-term sustainable energy development. Diesel power is prone to rising concerns regarding greenhouse gas (GHG) emissions, high operational expenses, pollution and possible spills. These high costs put extreme financial burdens on local communities and deters mining companies from investing in these inhospitable regions, adding to the poverty of local communities. While one might question, if development of these regions on an industrial scale would be desirable, the lack thereof currently also means the development for the region as a whole is put on hold.

With renewable energy currently being used to create hybrid systems, lowering over-all energy costs, they can not fully replace diesel power as they are prone to weather-induced power fluctuations, negatively affecting the energy security.

SMR technology has promise to provide sustainable energy in these regions, being able to provide heat and power, load follow and operate at low costs. This study will look into that promise and compare it to the current diesel generators.

## 2.3 The modular reactor promise

Nuclear power has a history of consisting of large-scale, multi-billion dollar projects, which have a tendency to exceed their budget and to fall behind schedule. In the light of these growing industry problems, development of smaller systems became a priority, lowering up front needed capital and providing a more accessible form of nuclear power generation.

SMR technology describes small nuclear power units, usually below 300 MWe, which are built with modular technology. The smallest of the SMRs are categorized as vSMR's . These vSMR's provide power typically up to <15 MWe [5].

It is these new, modular, technologies that have promises in far-off places, where a power source must be reliable, load following (to cope with shifting demands) and preferably inexpensive. vSMR technology is expected to provide the same amount of energy as diesel generators, with less fuel transports and less local pollution.

In the light of these developments, new research into the feasibility of these technologies is on the rise. During this research, a 1 million memorandum for new SMR research for deployment in northern communities was signed between Bruce Power and Laurentian University, highlighting the interest in the field even more [6].



## 3 | Methodology

For this study, the preferred method is a quantitative, single case approach, by means of an energy system model. While single case assessment, by the very nature of its methodological design, should not allow for generalizations, the approach tries to create a framework for future in-depth research for energy development within the "Ring of Fire" (Northern Ontario, see chapter 4), other related isolated energy systems, and to provide a special focus on the assessment of SMR (and vSMR) technology.

The study's focus point is the planned "Eagle's Nest" mine in Ontario's "Ring of Fire". The Eagle's Nest is the first project going through permitting in the region [7]. As part of the permitting process, its environmental impact assessment (EIA) and feasibility study are available in the public domain, providing the necessary background information [8, 9, 10]. A further restriction within this study is the decision to solely focus on the possibility of replacing diesel power by SMR technology. The framework can however be used in the future to assess other generating options as well.

As a result, this study aims to provide the means for priority setting for future SMR and vSMR nuclear research, sustainable (Arctic) mining site development, and governmental legislative bodies, resulting in possible environmental impact mitigation through the use of new energy technologies.

The necessary information for this research is derived from literature research, as presented within section 3.1. The energy system modeling tool of choice is the TIMES model generator, as described within section 3.2.

### 3.1 Literature research

Most of the information used within this study is literature derived, using publicly available sources. Peer reviewed scholarly articles and publications from renowned institutions were used whenever possible. The use of publicly available sources ensures the repeatability of the study. The used resources provide information on the background situation regarding both the current situation and the development of SMR technology, and the Eagle's Nest. This information includes the expected performance and expenditures for the new nuclear technologies and the planned construction and electrical layout for the Eagle's Nest.

As the literature used was written during different periods in time, and the reviewed technologies are experimental, assumptions have to be made:

- All monetary values are recalculated using the United States Bureau of Labor Statistics CPI Inflation Calculator, and expressed in 2017-USD
- The price of fuel is fixed in time
- The discount rate is set to 8%
- The used technologies have no salvage value
- For systems with a FOAK cost estimate, the expected cost for a 8th of a kind reactor system, also called the NOAK estimate, was calculated
- For the possible carbon tax, the medium expected price-path was used
- All values are given pre-tax

### 3.2 The Integrated MARKAL-EFOM System

The single-case assessment will be carried out through the creation of an energy system model within the TIMES model generator environment. TIMES is an economic model generator for local, national or global energy systems. It provides a technology-rich basis for representing energy systems over a multi-period time horizon. While TIMES is commonly used for the description of an entire energy system, it is also useful for studies of single sectors, such as electricity or heat.[11]

For the reader not familiar with the TIMES model generator, it is possible to find a brief introduction to TIMES and its functions in Appendix A.

### 3.3 LCOE

The levelized cost of energy (LCOE) is a computational method which tries to compare energy sources over their lifetime, on an economic, cost driven, basis. It does this by taking into account all expenses accrued over the lifetime of the energy source, and dividing this by the total energy production, providing a final monetary value as costs per unit of power.

$$y = \frac{\sum_{n=0}^N \frac{C_n}{(1+d)^n}}{\sum_{n=1}^N \frac{Q_n}{(1+d)^n}}$$

Where:

- C<sub>n</sub>** = Total lifetime costs (CAPEX, OPEX and fuel expenditures)
- Q<sub>n</sub>** = Total lifetime energy production (MWh)
- n** = Total lifetime of the system
- d** = Discount rate

One should note that the energy production is also discounted. While this does not say anything about the technical capabilities of the generator, it is necessary to take into account the "future value" of energy.

The LCOE has advantages and disadvantages. While it provides a possibility to compare the price of electricity from different generators (as a comparison of cost), over the entire expected lifetime of the system, it is heavily influenced by assumptions such as the capacity factor. Furthermore, the LCOE does not take into account other aspects such as dispatchability and availability.

Levelized avoided cost of energy (LACE) provides an alternative way of comparison, through the value per unit of energy, by describing what it would cost the grid to generate the same amount of electricity through other generators. Renewable generators for example do not have dispatchability, as would be the case with thermal operators. If a renewable unit would mostly deliver during off-peak hours, revenue, and therefore the projects' value, would decline. The LACE provides a possibility to compare the value of generating against the cost of generating (the LCOE), to provide an indication for the projects' feasibility. Generally speaking, if LACE > LCOE, investing in this generating capacity would be economically attractive [12].

As for the Eagle's Nest, there is currently no added benefit in using the LACE. All production is in a base-load configuration, and both the diesel gensets and the SMR technology are load-following. Therefore, the total value of energy is equal within the LCOE and LACE and a comparison of the two technologies with the LCOE suffices.



## 4 | Intended deployment study area

It is below the shallow lakes and dense peat of the James Bay lowlands, in the remote wilderness 1000 kilometers north-west of Toronto, where in the early 2000s major ore deposits were discovered. Located here, within the area called the Ring of Fire (named after the famous Johnny Cash song) [13], is the "Eagle's nest" claim, the first mining claim to file for approval within the region. The Eagle's Nest claim and proposed mining operations encompass a planned project covering a high-grade nickel-copper-platinum group element (PGE) deposit.

A more in-depth description of the ROF, for better understanding of its location and associated challenges, will be provided within section 4.1. Following upon this area description, the proposed mine will be presented within section 4.2. The intended energy infrastructure, which will be the focal-point of this study, is given separately and in-depth in section 4.4. Based on the planned infrastructure, as given by the literature, assumptions on all the applicable costs associated with the diesel generators will be made and presented within section 4.5.

### 4.1 Ring of Fire

The Ontario ROF is an area within the James Bay Lowlands of Northern Ontario [14]. The James Bay Lowlands area is one of the largest wetlands in Northern America, serving as an important ecological region including species of birds of prey, seabirds, woodland caribou, polar bears and Arctic foxes. Simultaneously, due to its extensive peat bogs, the region serves as a major carbon storage [15].

In terms of distance, the ROF is located 500 kilometers northeast of Thunder Bay and 300 kilometers from the nearest road. The closest communities to the proposed Eagle's Nest mine, which will be located in the south-eastern regions of the ROF, are Webequie First Nation, 80 kilometers to the west and Marten Falls First Nation, 120 kilometers to the south [16]. The complete ROF, and its location within Ontario are presented in Figure 4.1.

#### Ring of Fire history

The ROF has been under investigation since 1959. Back then, the focus was mainly placed on diamond mining and prospecting. In the early 2000s, the focus shifted to mineral mining after the discovery of kimberlites. These kimberlites awakened the interest of prospectors and further research by follow-up drilling discovered volcanogenic massive sulphide (VMS) deposits. Further research exposed six additional VMS deposits in 2003. Subsequent geophysical research in 2004-2006 highlighted the potential for Ni-Cu-Cr-PGE mineralization, which was confirmed by subsequent drilling in 2006 [18].

Additional aerial research in 2007 was followed by prospective drilling and the first mineral resource estimations. Condor Diamond Corp. drilled a horizontal prospective core (the Eagle One) in 2007, on what is now the Eagle's Nest claim. These early drilling operations revealed a high-grade copper-zinc deposit, sparking the first large interest in the region [13, 18].



**Figure 4.1:** *Geographical representation of the ROF within Northern Ontario [17]*

The directionally (horizontal) drilled core provided minerals, but only in limited quantities. After the advise was given to drill completely vertically, hole number 5 struck gold, figuratively speaking, drilling through one of the richest deposits known, and a legend was born. Noront Mining Ltd. acquired the Condor claims in May of 2007 and mobilized drilling rigs to the property, from here-on called the Eagle’s Nest. 116 out of a total of 124 holes intersected the deposit, confirming its potential [18, 13].

The deposits discovered in the ROF are of such high grade and volume that they are deemed to be the largest in Canadian history. It is stated that [19, 20]:

”The ROF is the most promising mining opportunity in Canada in a century”

The ROF owes its mineral-rich nature to its geological features. It was formed due to an ultra-mafic outcrop which, after overturning, resulted in the layering found today. The features and riches of the area were discovered later, as the region is completely covered with overburden. A simplified example of the regional geology is visualized in Figure 4.2.

## 4.2 Planned development

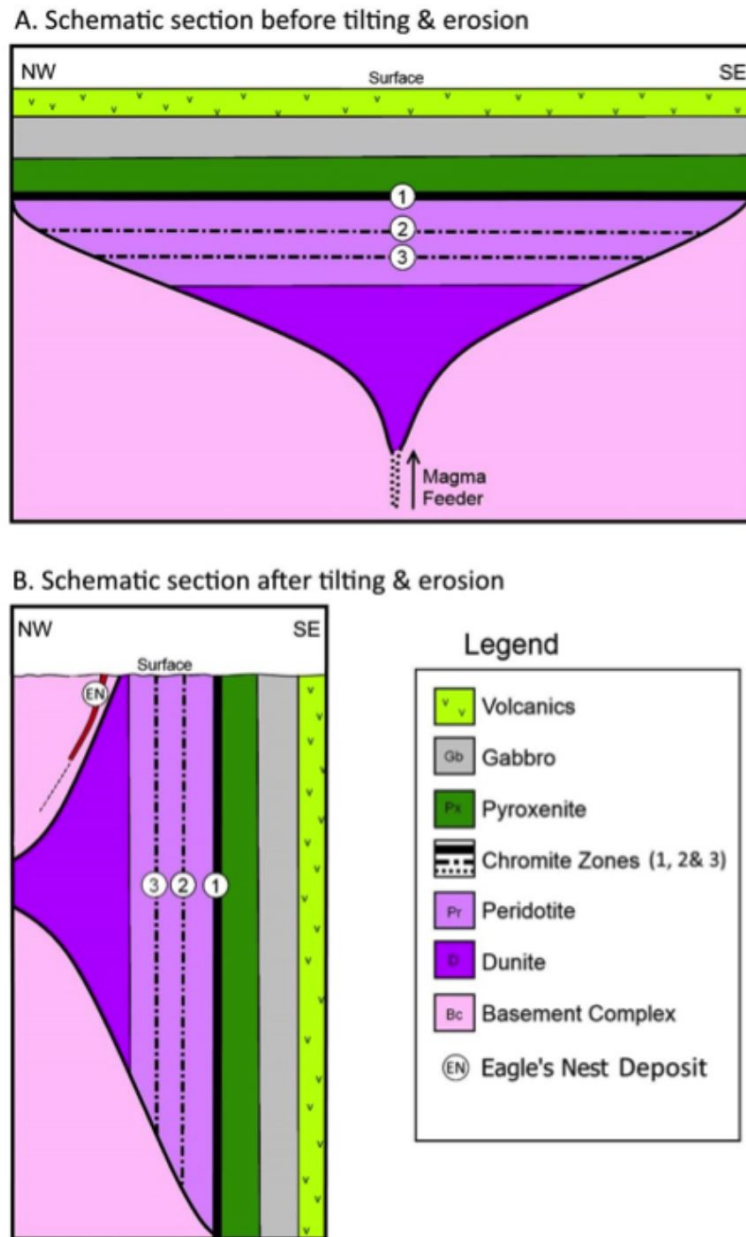
The first necessity for development of the region is accessibility. Provided the delicate ecosystem in which the ROF is located, infrastructural development of the region should proceed with the highest amount of scrutiny. Previously, infrastructural development was unnecessary, as other mines in the area are predominantly diamond and gold mines. The commodities produced by these mines are of such low volume that the small amounts of produced goods can be economically flown out to the market. For these mines, winter roads for equipment are all that is needed. The latitudes of the ROF places the region within the subarctic climate, providing long and cold winters with moderate summers, making these ice roads a viable option [22].

The proposed PGE- and chromite mines within the ROF are expected to produce ore in a high amount, which will require transportation by hauling-truck (or, as previously proposed, rail) to smelters. These high tonnage trucks require all-year, high-load capable roads. Finally, after years of consideration with local communities, the government of Ontario decided to push forward with the required infrastructure, which will mark the start of the development of the ROF [23].

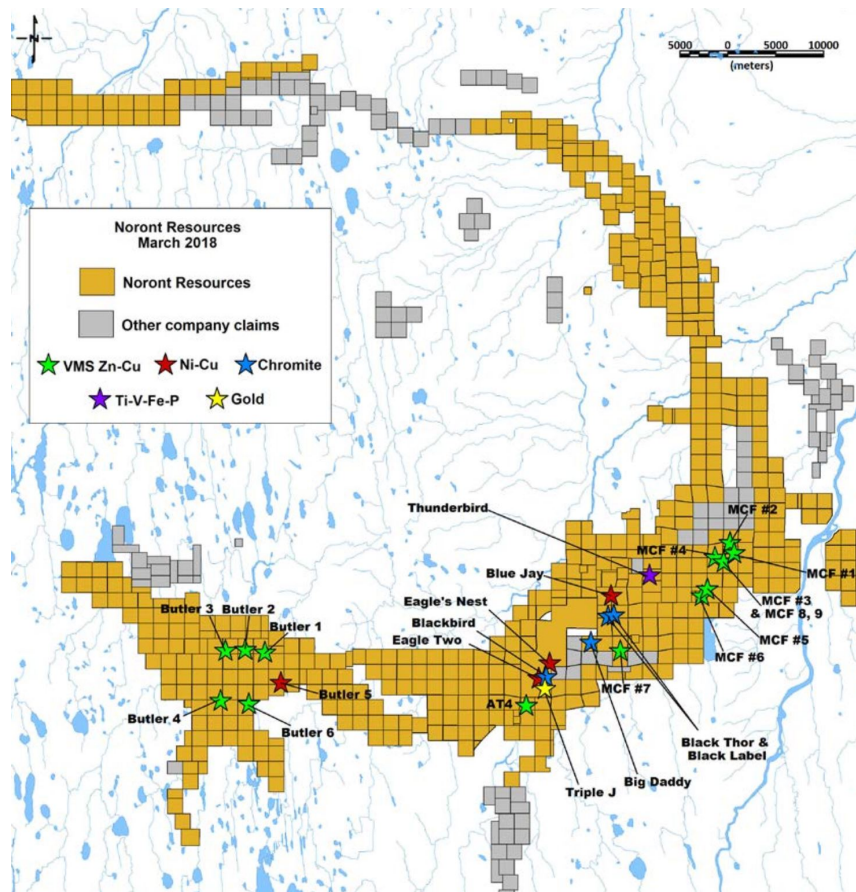
With the start of opening up the area through infrastructural development, the actual claims in the region can be turned into mines. As of August 2, 2016, there are approximately 10.040 active claims, held by 15 companies, covering a total area of 1606 km<sup>2</sup>. Noront Resources covers the majority of the claims, as can be seen in Figure 4.3 [15].

The Eagle’s Nest is the first mine to go through the licensing process. However, there are multiple propositions for additional mines, for chromite ore, within the direct vicinity of the Eagle’s Nest. Within 5 km of the Eagle’s Nest, Noront has serious plans to construct three more mines, Blackbird, Black Thor and Black Label (as seen in Figure 4.4), with Blackbird being chronologically the next mine which is planned to go through the development phase.

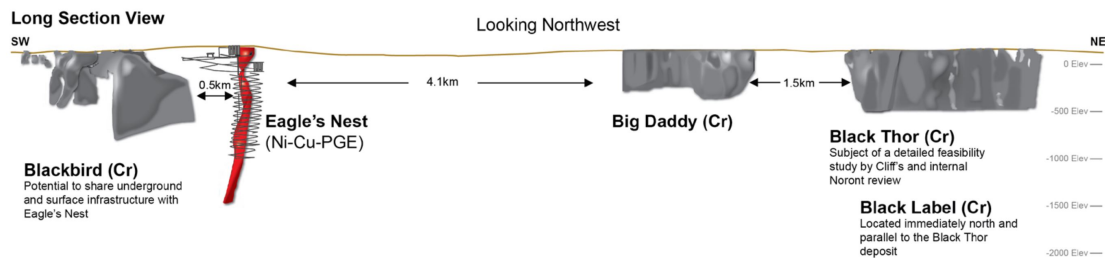
As can be seen in Figure 4.3, there are more promising mining developments within the same area, on top of the three stated chromite mines. These mines are in such close proximity that they warrant research into the possible sharing of surface infrastructure with the Eagle’s Nest, with great opportunities for sharing the electrical infrastructure.



**Figure 4.2:** Simplified representation of the local ROF geology. Visualized is the local stratification. The different geological layers were created from the same magmatic feeder system, forming the local intrusion. After tilting and erosion, the current vertical orientation of the system came to be. The PGE deposit is completely detached from the intrusion, but is expected to be from the same magma chamber, indicating that future additional discoveries are likely. This visualization is created by Micon International Ltd. [21].



**Figure 4.3:** Map providing an overview of the claims owned by Noront within the Ring of Fire, complete with the most promising mining locations, as of (Q4) 2017 [24]



**Figure 4.4:** Overview of all additional planned mines in the direct vicinity of the Eagle's Nest. With current estimates, it will be these mines which will go through licensing after the Eagle's Nest. [24]

**Table 4.1:** *Overview of expected mine statistics [8]*

Key mine plan statistics	
Mine life	10.2 years
Mine Construction	3 years
Daily ore production	3,000 t/d
Daily rock production	1,500 t/d
Workforce	162
Productivity	27 t/person-shift

### 4.3 The Eagle’s Nest development

The Eagle’s Nest project will take approximately three years to develop, before mining and processing of the actual ore will commence. Current estimates place the start of the development phase in 2020. A total overview of the expected mine statistics and production rate is given in Table 4.1. The Eagle’s Nest itself will be a complete subsurface mine. While the ore bodies reach all the way to the surface and would warrant open-pit mining, Noront has decided to go with the shaft-mining approach, especially after concerns expressed by the local communities, limiting the impact on the surrounding environment. A complete overview of the expected mine statistics is given in Table 4.1 [8, 25].

The utilized method will place all processes below grade, except for concentrate filtration. The concentrated ore will then be hauled from the mine and transported to the processing facilities out of the region. The trailings, including those from the above ground concentrate filtration plant, will be transported back into the mine and used to plug the voids, eliminating the need for trailing mounts and ponds on the surface.

The only parts of the infrastructure placed above ground will be:

- Process plant buildings
- Ancillary Buildings
- Maintenance complex
- Camp facilities
- Explosives storage area
- Airstrip
- Fuel storage (three tanks, total volume 2550 M<sup>3</sup>)
- Power supply and distribution
- Waste management facility
- Water supply and distribution
- Surface water management
- Sewage treatment and disposal

### 4.4 Planned energy infrastructure

The proposed project site currently is completely devoid of access to modern infrastructure, including the main utility grid. There have been past propositions about linking the region to the

**Table 4.2:** *Expected power requirements in MW and MVA per site-location[8]*

Area	Peak Load		Average Load	
	MW	MVA	MW	MVA
Process plant	14.74	17.33	11.08	13.06
Site surface infrastructure	1.95	2.3	1.96	2.3
Ramp and mine	5.35	6.29	4.55	5.35
Total	22.05	25.93	17.59	20.71

national grid. A proposed expanding project cites the costs as 1.9 billion C\$ for 1800 km [26]. An alternative proposition was the creation and extension of a ROF sub-grid, at the cost of C\$ 1,300 million (2014) [27]. At the time of writing, no fundamental plans for a grid extension exist, and the description of the mine still proposes a local diesel fuel powered power plant as the prime method of creating power, for the entire intended lifetime of the mine [8].

#### 4.4.1 Power plant

Power to the site will be supplied by a dedicated above ground power plant in a N+2 configuration (8 generators running, 2 on stand-by) to account for routine maintenance and/or equipment breakdown. Eight diesel generators will supply the 21.3 MW continuous output. As such, a total of 10 diesel generators is to be expected, having a capacity factor of  $\sim 0.8$  over-all. The "Catalog of CHP technologies" (Darrow, 2017), states that diesel generators operate with a capacity factor of 0.97, the assumed number within this study. Additional information on the importance of the capacity factor (CF), and why 0.8 was omitted, can be found in section 8.3. The expected power requirements can be found in Table 4.2. [8, 28].

The mine is expected to require 3 years of development, after which 11 years of production will take place. On top of these 11 years of indicated production there is the possibility to extend this period for an additional 9 years, depending on ore grade and market prices. The development term indicates that for the first three years, (electrical) energy consumption will be below the estimated average for the production years, as production facilities will not yet be in operation. The feasibility study provides some possible insight in the amount of energy required for these first years. It is an assumption that power requirements would grow in incremental steps, while the infrastructure and mine would grow and equipment would be tested.

As an assumption, for the first year, the power will be estimated by the requirements for the site surface and infrastructure. The power for the second year will be estimated by adding 75% of the estimated load requirements of the ramp and mine. The third year will be accounted for by using the full amount of these components.

If calculated as such, the total amount of energy needed per year is estimated as seen in Table 4.3. For the long term calculations, power requirements would be deemed constant as from 2033 onwards.

previous research, performed by Hatch (2016), indicates the use of Peak Power for the mine assessment. Therefore, this study commits to the additional use of the same values for a possible comparison of the results. These assumptions are provided in Table 4.4 [2].

**Table 4.3:** *The assumed average power requirements during each phase of the mine for the period 2023-2033. The values are given on a per-year basis*

	2020	2021	2022	2023-2033
MW	1.95	5.37	6.51	21.3
MWh	17,082	47,063	57,027	186,588

**Table 4.4:** *The assumed average power requirements, as per previous study, during each phase of the mine for the period 2023-2033. The values are given on a per-year basis*

	2020	2021	2022	2023-2033
MW	1.95	5.96	7.3	22.05
MWh	17,082	52,231	63,948	193,158

#### 4.4.2 On-site distribution

Electrical power on site will be distributed through the mine at 13.8 kV, to switchgear located at the primary crushing electrical room, 175 m below grade. Substations will lower the voltage from 13.8 kV to 5 kV and 600 V where required. Main operational equipment (such as electric motors for the mills) will require 5 kV of power. There will be a dedicated electrical system below ground, in the form of an overhead trolley line, for the operation of six electrical 60t Kiruna trucks. These trucks can revert back to diesel power when exiting the mine for overhaul. The overall assumption is that, due to the small nature of the grid, distribution losses will be negligible.

### 4.5 Diesel power cost estimation

It proves difficult to acquire reliable and consistent data on the cost components which account for energy production for proposed mines relying on diesel generators (within Northern Ontario). This section will describe every assumption made while estimating the final cost per component of the energy system for the diesel gensets.

First the power plant will be assessed for both its CAPEX and OPEX within subsection 4.5.1. After considering the power plant itself, the cost for the diesel fuel will be estimated within subsection 4.5.2. A possible extra expenditure for the system might arise from the planned implementation of a CO<sub>2</sub> cap-and-trade system. The possible extra costs that would be enforced due to such a system are estimated within subsection 4.5.3.

#### 4.5.1 Power Plant

A first assumption has to be made on the capital investment costs (CAPEX) for the power plant itself. After the CAPEX, the operational costs are assessed (OPEX).

**Table 4.5:** *Prices for Diesel generators, as given by different sources. All values are calculated to 2017-USD, with CPI development provided by the Bureau of Labor and Statistics [29]*

Source	Year	Price \$	Power (MW)	Specific investment US-\$/kW	Specific investment (2017)US-\$/kW
Energy and Mines [30]	2017	824,000	1	824	824
Hatch [2]	2016	NA	NA	1,648	1,689
Moore [3]	2015	23,000,000	10	2,300	2,390
NT Energy [31]	2013	NA	NA	2,472	2,606
Yukon Energy Company [32]	2011	824,000	1	824	909
University of Alaska [33]	2011	NA	NA	2,575	2,839
Eagle Plain [34]	2010	988,800	1	988.8	1,108
ESMAP [35]	2008	NA	NA	680	782
Average		-	-	-	1,643
Excl. ESMAP		-	-	-	1,766

### Capital expenditures

The investment costs for the diesel gensets are estimated in \$/kW. Within this research, it was attempted to estimate the price by assessment of other projects in the northern regions, and by assessment of related research. In total, 8 sources were found. These sources however contained estimates with a relatively large spread within the data. Table 4.5 gives the value according to each source.

ESMAP, the source with the lowest \$/kWh estimate, has done an estimation for utility scale diesel generators on a global level. They found multiple values in a reversed function (a larger generator costs more in the specific value of \$/kWh), as larger generators are often custom-build. As ESMAP provides different values, the generator size most applicable to the mining site was chosen for its value. Therefore, taking into account that ESMAP might not reflect the same scale of generators and the added costs for deployment in the remote north, an average of \$1750 was chosen as the specific investment cost for the Eagle's Nest generators.

### Operational expenditures

The fixed O&M and variable O&M costs separate values within TIMES. Limited data was found online within all resources. For the variable O&M costs, fuel has been taken out of the equation, as the procurement of fuel is treated as a separate process within the model (for the estimated fuel prices, see subsection 4.5.2). Variable O&M therefore can be costs such as oil changes (once for every X hours of operational time). Fixed O&M on the other hand might be recurring expenses, even while not operating, such as time-based periodic maintenance.

Three values for the O&M costs were obtained. One was provided by the Hatch research, one was calculated based on the literature from Moore and the Qulliq Energy Corporation (QEC). The final value was retrieved from the Catalog of CHP Technologies, as provided by the US Environmental Protection Agency (EPA).

Hatch provides an estimate of 15 \$/MWh for non-fuel O&M costs, based on in-house knowledge. In comparison, Moore provides a value of 25.21 \$/MWh for O&M costs by use of the QEC numbers.

This value however includes additional costs on salaries, amortization, bad debt, interest and travel and accommodations. While these costs can partially be justified, not all of them will apply to a mining site. The QEC average yearly costs on supplies and services is only 16.5% of their total expenditures. If the value given by Moore is recalculated to just 'supplies and services', the cost drops to 9.3 \$/MWh. This value is, however, not taking into account any additional costs which would also be applicable to a mining site, a markup is therefore warranted [36, 37, 38, 3].

Finally, the EPA states the values of utility-scale non-fuel O&M costs as between 9 and 25 \$/MWh [28].

As all values were given in \$/MWh, the final assumption was made to solely utilize a variable O&M of 15 \$/MWh, accounting for all diesel generated variable costs within this research. Fixed O&M costs were therefor assumed to be part of the variable O&M costs.

### 4.5.2 Diesel

Diesel generators are usually relatively inexpensive to build, but expensive to operate. Most of the LCOE of diesel power comes from the diesel fuel itself. It is therefore important to provide a realistic value for the expected expenditures on diesel fuel within the model.

The short-term diesel price fluctuations (2017-2018) can be found in Figure 4.5. The monthly values of diesel average to C\$ 0.781/liter, or US\$ 0.644/liter. Importantly, these numbers are wholesale prices and do not include taxes.

To check if this is a valid assumption, the long-term price development has been taken into account, as seen in Figure 4.6. It shows the high volatility of diesel fuel prices (retail) over the last years. In addition, it shows that current prices, compared to recent history, are slightly lower than the average trend. Therefore, the assumed value of US \$ 0.644/liter is a valid, despite slightly optimistic, value.

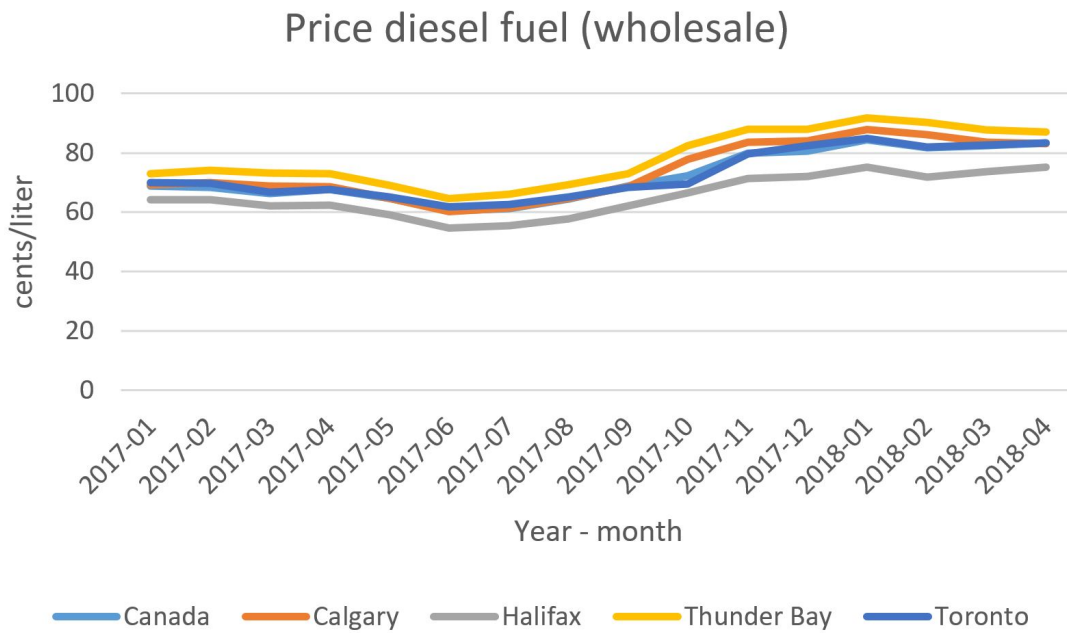
### 4.5.3 Carbon tax

The Carbon Tax has been estimated based upon the long-term carbon price forecast (LTCPF) as given in the "Long-Term Carbon Price Forecast Report" written by ICF Consulting Canada Inc. for the Ontario Energy Board (OEB) [41].

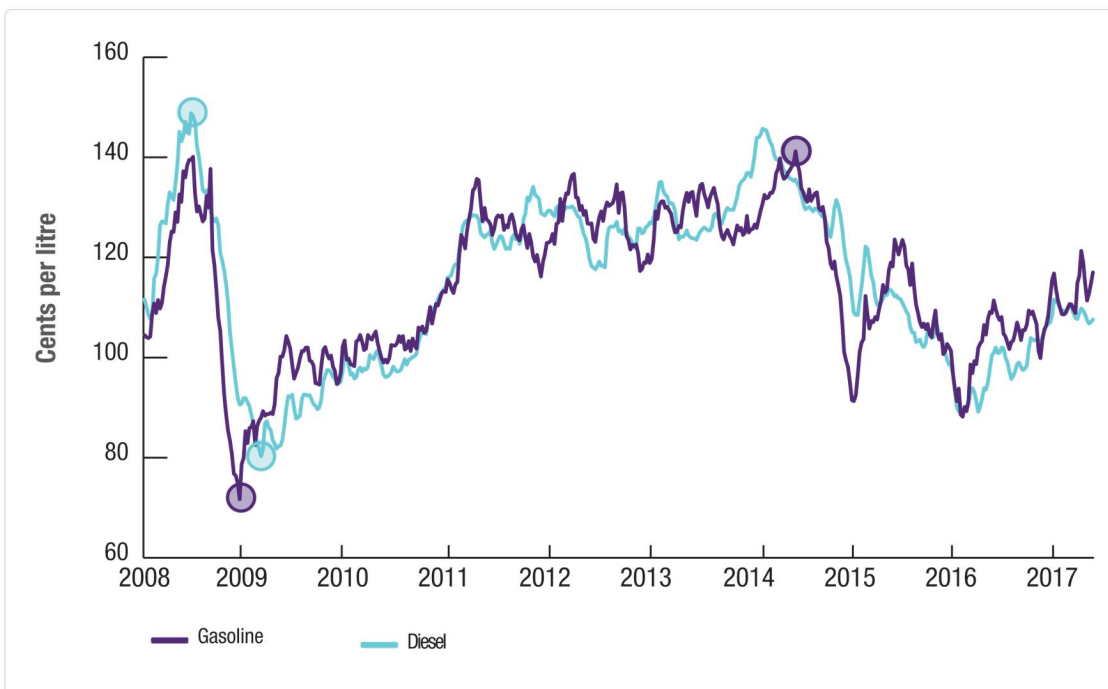
The report estimates the LTCPF within Ontario, based upon three possible scenarios. For the purpose of this research, the middle scenario was chosen and extrapolated over the lifetime of the mine. The graphs depicting the carbon tax, as seen in Figure 4.7 and Figure 4.8, are built up from three different data sets. The blue and orange data points are retrieved from the ICF-report. The gray data points describe the extrapolated values within of the graph.

In total, two future options were considered; One in which the carbon price would rise at a linear rate and one in which the carbon price would rise at an exponential rate.

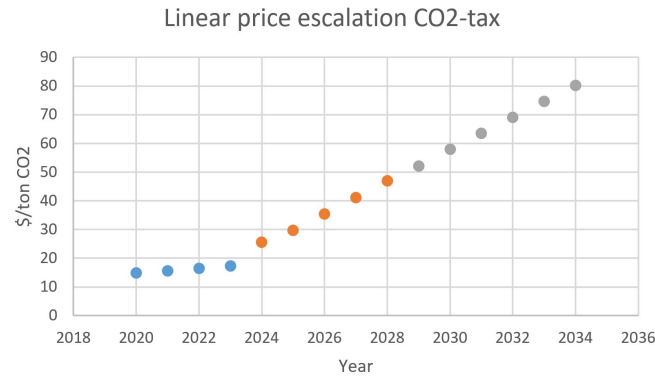
The linear-growth curve, as presented in Figure 4.7 is based upon the secondary part of the given data set (the orange data points), where the ICF foresees a shortage in allowances. This shortage will start in the year 2024, the reason why prices start to rise at an increased rate. The blue data points describe growth when the allowances are still in excess of demand, creating a reduced price development. The incentives behind the different growth rates explain the necessity to only use the



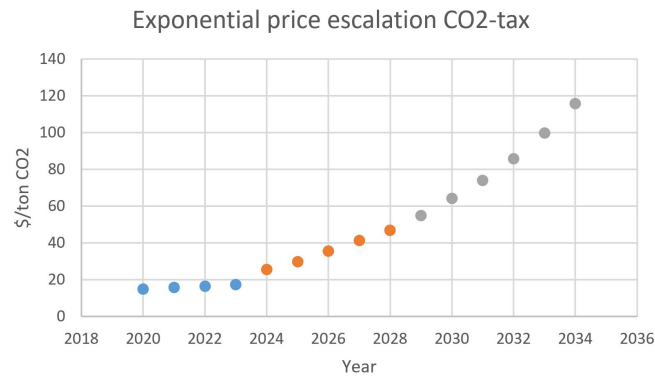
**Figure 4.5:** Wholesale price of diesel fuel in key areas in Canada, from the last 16 months (values are in CAD). Thunder Bay is the location closest to the Eagle's Nest [39]



**Figure 4.6:** Historical prices of diesel and gas (retail values), as an average for Canada. Values are in CAD [40].



**Figure 4.7:** Price estimation for a linearly evolving carbon tax, based on the medium case described by ICF consulting [41]



**Figure 4.8:** Price estimation for an exponentially evolving carbon tax, based on the medium case described by ICF consulting [41]

orange data for future price predictions.

The reason for the comparison of a linear growth rate and an exponential growth rate is that the use of a  $R^2$ -check for the exponential growth curve, dictates that it would have a slightly better fit. The exponential growth curve is also created with the secondary part of the data-set, describing the shortage in allowances.

The exponential growth would lead to extremely high prices in the latter years of case study for the Eagle's Nest, especially in the case of extended mining operations. These extremely high prices are deemed unlikely, as long term forecasts internationally stay within a more linear growth regime as for example the EU-ETS [42]. The exponential growth curve for the expected lifetime of the mine can be found in Figure 4.8

## 5 | The (v)SMR alternative

The small modular reactor (SMR) and its smaller derivative, the very small modular reactor (vSMR, <15MWe), are new nuclear technologies under development, with the intention to provide nuclear power in a smaller, more accessible configuration. These smaller reactors intend to ensure a reduced up-front cost, increased nuclear safety, and easy and fast transportation and placement. With the promise of increased transportability and affordability, SMR and vSMR technologies promise to provide the reliability of nuclear power in a safe and affordable way to be operators in far-off locations which now still rely on expensive fossil fuels.

To understand the aim and development of these new technologies, their recent history is provided in section 5.1, subsection 5.1.1. Additionally, subsection 5.1.2 provides information on the current developments, with a main focus on Canada.

To fit the boundaries of the intended study area, a selection of applicable SMR and vSMR systems was made. The entire selection criteria and the final list of selected technologies are provided in section 5.3. To utilize these technologies in the TIMES environment, economic data had to be obtained or derived. These assumptions and findings are explained within section 5.4.

### 5.1 Development history and current status

While the SMR and vSMR are a new development, they do have a long operational history leading up to their development. A short version of this history is given in subsection 5.1.1. After this historical background, the present day developments will be given in subsection 5.1.2

#### 5.1.1 History

With the International Atomic Energy Agency (IAEA) describing small power units as below 300 MW, and medium as up to 700 MW (SMR stands in this case for small and medium reactors, not to be confused with small modular reactors), SMR technology as given by its official description is not new. Early nuclear reactor designs only had tens to a couple hundred of MW of electrical power. But since their establishment in the 1950's, reactor size has steadily grown to more than 1600 MWe per reactor (size is a description of performance in the industry, as generally the physical size scales with the power output of the system) [43].

Even today, a lot of operational power units still fall into these small to medium power ranges. However, the current change within reactor technology is not necessarily about size. Smaller reactors are still built and in use today, mainly for naval purposes (with power output up to 190 MWth). The main change in design philosophy is described by the M in SMR, which stands for "modular". The modular design philosophy tries to materialize a reactor which can be produced in series with the use of prefabricated reactor components, sometimes with the intention to create a turn-key solution right off the manufacturing line. This design philosophy tries to reach its economies of scale not by increasing the total amount of power from each reactor, but from the total amount of reactors produced [43].

There are examples of early small reactors designed to be modular and transportable, including ones used in hard-to-reach places. A prime example is the reactor used on Antarctica, powering McMurdo Station. For over a decade, from 1962 to 1972, reactor PM-3A (meaning: Portable Medium power - nr. 3, field installation (A)) provided the Antarctic base with power and fresh water (through desalination utilizing the excess steam). PM-3A was the result of an early experiment to power forward bases with nuclear power as an alternative to conventional fuel oil. Before installing the nuclear reactor, half of the supplies hauled to the Antarctic station consisted of fuel oil, creating a massive burden on the Antarctic research budget. The PM-3A was designed to be hauled to Antarctica on a C-130 Hercules, while providing 1.8 MW of power for 20 years. PM-3A produced 78 million kWh, and 13 million gallons of fresh water, at a capacity factor of 0.76 during its lifetime at the Antarctic base [44].

### 5.1.2 Current status

Interest in new nuclear power, through SMR technology, is high and driven by two major factors; possible economic benefits and fossil fuel replacement.

#### The financial problems

The first important factor are the economics affiliated with the promise of portable nuclear power. Conventional-built reactors are multi-billion dollar projects which are often over time and over budget, creating financial problems within today's volatile financial markets. These high costs and cost escalations pose a major problem for nuclear cost competitiveness through its capital costs, of which the induced costs of financing can be a large percentage. Financing costs are determined by:

- Interest rates on total debt
- Risk premium
- Debt-equity ratio
- Differences between local markets, a regulated market has different dynamics
- Construction time

The total amount of costs accrued over a nuclear project can result in the financial costs correspond to a high percentage of the total overnight costs. A 2004 study by the university of Chicago showed that the interest costs accrued during construction can be as high as 30% of the overall expenditures, escalating to 40% if applied over a 7-year build schedule [45].

These financing costs are so high that they can only be afforded by the biggest of utilities. Even then, the money involved can represent a large portion of the utilities' market capitalization. This leads to extra risks for the company as a whole, leading to a reduced credit worthiness and further escalation of the interest rates [5].

SMR-technology tries to combat these problems by providing a smaller investment at a lower risk. By automating the production, risks of running into delays are severely reduced. Furthermore, the different technologies involved in the reactor design are intended to lower operational risks, through simplified designs and increased security. These measures should increase the capacity factor, as less shut-downs are foreseen, increasing revenue. All these features are intended to lower the total financial burden of interest rates and the risk premium. In addition, because of the modular design

philosophy, it is possible that a power plant is comprised of multiple units, instead of one giant reactor. This has the additional benefit that one unit can already start producing power and create a positive cash flow before other units are completed.

### **Canada and the move away from fossil fuels**

The other point of interest comes from rising incentives to move away from fossil fuels. This move away is especially difficult for places which rely up to a high degree on fossil fuels as their primary source of reliable energy, such as the mines and communities in the remote northern regions of Canada. These energy systems are costly and polluting, but a necessity for life in these inhospitable places.

As stated, a reliable source of energy is a necessity for life in the North. Currently, this fossil fueled power is delivered by diesel generators. While a hybrid energy systems, combining renewable energy with fossil fuel, can mitigate some of the fuel consumption, the current unreliable nature of renewable energy and lack of affordable storage means that it can not (yet) replace fossil fuel.

Nuclear power generation has the advantage of being a reliable source of energy, which can be operated 24/7 under all conditions. An additional benefit of nuclear power is that while the investment costs are high, the operating costs low and constant (as compared to volatile fossil fuel prices).

Canada sees itself as the prime location for the development of SMR technology, and current expectations regarding SMR technology are high, both for off-grid and on-grid applications. The CNL has even taken the task upon itself to demonstrate the commercial viability of SMR technology and plans to have the first small modular reactor operating by the year 2026. After a request for expression of interest, 19 different SMR concepts were received, ranging between 2 and 1000 MWe (the author of this report must note here that 1000 MWe does not particularly qualify as "small"), although the majority (11) of the designs were set within the 1-99 MWe category [46, 47].

Future research will focus on a further understanding of the possibilities of SMR technology for energy production in the north. On the 6th of April, 2018, Bruce Power, MIRARCO Mining Innovation and Laurentian University have signed a Memorandum of Understanding that will enhance strategic research opportunities, including the long-term potential for Small Modular Reactors to generate clean, low-cost and reliable electricity in rural/remote regions [6].

## 5.2 Types of SMRs and the choice between them

Not all SMR designs are applicable for this research. It is therefore necessary to limit the amount of reactors to be considered, based upon the boundaries of the intended deployment location. The selection process of applicable reactors is described within section 5.3. After identification of applicable reactors, the economics of each chosen design have to be derived. This process and all final assumptions can be found within section 5.4.

## 5.3 (v)SMR selection

With the large amount of different designs and technologies for SMR's, it is important to create a selection of applicable SMR's within the boundaries of this case study. Currently, there are at least 57 SMR designs being developed around the globe. The IAEA provides information on 45 designs within their 2016 leaflet. 10 other designs were retrieved from the "Pre-Licensing Vendor Design Review", as given by the Canadian Nuclear Safety Commission (CNSC). Finally, two designs were retrieved from the report "Task Force on Energy Systems for Forward/Remote Operating Bases" written by the Department of Defense Science Board [48, 49, 50].

Out of these 57 designs, a first selection was made based on the total electric power output ( $<25$  MWe). The cut-off point of 25 MW was chosen as it fits within the boundaries applicable for the "Eagle's Nest". This selection provides a total of 17 applicable SMR and vSMR designs, as given in Table 5.1.

After identifying 17 reactors that deliver up to 25 MWe in electrical power, and fit within the scope this research, a second reduction was made based on available economic data. Even applicable reactor designs will be omitted if there is similar technology with given economical data. For example, the "eVinci Micro Reactor" is a new promising system, but without any economic data at the time of writing. The "MegaPower" reactor operates utilizing the same basic reactor technology. Therefore, the "MegaPower" is used to create a final economic assumption, which for the time being will be applied to all reactors which use the same technology and do not have an independent economic evaluation. It is assumed that for the purpose of this study, the economic assumption could be used interchangeably between identical technologies. The results can be found in Table 5.2.

## 5.4 SMR cost assumptions

The cost assumptions for the SMR technologies are a challenge, as all technologies are still predominantly in the development phase. This implies that there is no available real-world economic data. All economical values are therefore assumptions by their very nature. To estimate the investment costs for these systems, both the economic data and performance data had to be retrieved.

The author tried to retrieve economic data from sources provided by either respectable institutions (such as the IAEA and the US department of defense (DoD)) or from the vendors themselves. All values were then converted to 2017 USD through the use of the Statistics Bureau of Labor and Statistics, CPI Inflation Calculator. As every SMR is a vastly different system, every SMR has to be treated individually. In cases where no economic data was available, or the range within the economic data was large, the assumptions for the final values are well described.

**Table 5.1:** The following table provides all applicable SMR designs by source, name, vendor, country of origin, reactor-type and electric output in MWe. This selection was only created by the criteria of an output up to 25 MWe. Abbreviations; high temperature gas reactor (HTGR), pressurized water reactor (PWR), integral pressurized water reactor (IPWR), liquid-metal-cooled fast-reactor (LMCFR), the preposition (M) stands for Marine

CNSC	Name	Vendor	Country	Type	MWe
1	eVinci Micro Reactor	Westinghouse	USA	Heat Pipe	1.6
2	MMR-5	Ultra Safe Nuclear Corp.	USA	HTGR	5
3	MMR-10	Ultra Safe Nuclear Corp.	USA	HTGR	10
4	U-battery	URENCO (Consortium)	UK	HTGR	4
5	Starcore Module	StarCore Nuclear	Canada	HTGR	10
6	SEALER	LeadCold Nuclear Inc.	Sweden	Molten Lead	10

IAEA	Name	Vendor	Country	Type	MWe
7	SHELF	NIKIET	Russia	(M)IPWR	6.4
8	ABV-6E	OKBM Afrikantov	Russia	(M)PWR	9
	ABV-6E (Cogen)	OKBM Afrikantov	Russia	(M)PWR	6
9	HTR-10	INET/Tsinghua University	China	HTGR	10
10	CAREM-25	CNEA	Argentina	IPWR	25
11	LEADIR	Northern Nuclear Industries Inc.	Canada	LMCFR	11
12	4S	Toshiba	Japan	LMCFR	10
13	G4M	Gen4 Energy inc.	USA	LMCFR	25
14	UNITHERM	NIKIET	Russia	PWR	6.6
15	ELENA	Kurchatov	Russia	PWR	0.068

DoD	Name	Vendor	Country	Type	MWe
16	MegaPower	Los Alamos/NASA/DoE laboratories	USA	Heat Pipe	2
17	HOLOS	Holos Gen	USA	HTGR	13

**Table 5.2:** Every reactor design was judged based upon its applicability as a mining site power generator and the availability of economic data

Nr	Name	Applicable	Economics	Note	Included
1	MegaPower	V	FOAK		V
2	U-battery	V	V		V
3	HOLOS	V	FOAK		V
4	4S*	V	V		V
5	SEALER	V	V		V
6	UNITHERM**	V	X		V
7	ABV-6E	V	V		V
8	ABV-6E***	V	V		V
-	Starcore Module****	V	V		X
-	G4M	V	X		X
-	SHELF	X	V	Marine module	X
-	eVinci Micro Reactor	V	X		X
-	MMR-5	V	X		X
-	MMR-10	V	X		X
-	HTR-10	X	X	Prototype	X
-	CAREM-25	X	X	Prototype	X
-	LEADIR	V	X		X
-	ELENA	X	V	Not applicable	X
* The Toshiba 4S is well documented, but there is no news regarding development status since Toshiba/Westinghouse filed for bankruptcy					
** The UNITHERM has no documented economical assumption. These values will be derived from other PWR's (see subsection 5.4.6).					
*** The ABV-6E is a marine PWR, with land capabilities. Current Economical estimates are for marine operation. Furthermore, the ABV-6E has a different production profile when utilized in a condensing configuration. The increased output (9 MW) is accounted for at the same total cost as the cogen (combined heat and power) option, as there is no additional economical information.					
**** The only economical data on the Starcore Module states that it would be at least 25% below an off-grid solution through a PPA.					

The systems are presented in the following order; The Los Alamos "MegaPower" (subsection 5.4.1); the Urenco "U-Battery" (subsection 5.4.2); the Holos Gen "HOLOS" (subsection 5.4.3); the Toshiba "Toshiba - 4S" (subsection 5.4.4); the LeadCold Nuclear Inc. "SEALER" (subsection 5.4.5); the NIKIET "UNITHERM" (subsection 5.4.6); and finally the OKBM Afrikantov "ABV-6E" (subsection 5.4.7).

### 5.4.1 MegaPower

The MegaPower vSMR is estimated to produce between 0.5 and 5 MWe of electrical power [51]. The preliminary assessment of the system by the Idaho National Laboratory states expected production as 2 MWe. 2 MWe is the more commonly cited output, and as such is the value used by the US-DoD [50]. As this is the most cited power output, 2 MWe is the value used within this study.

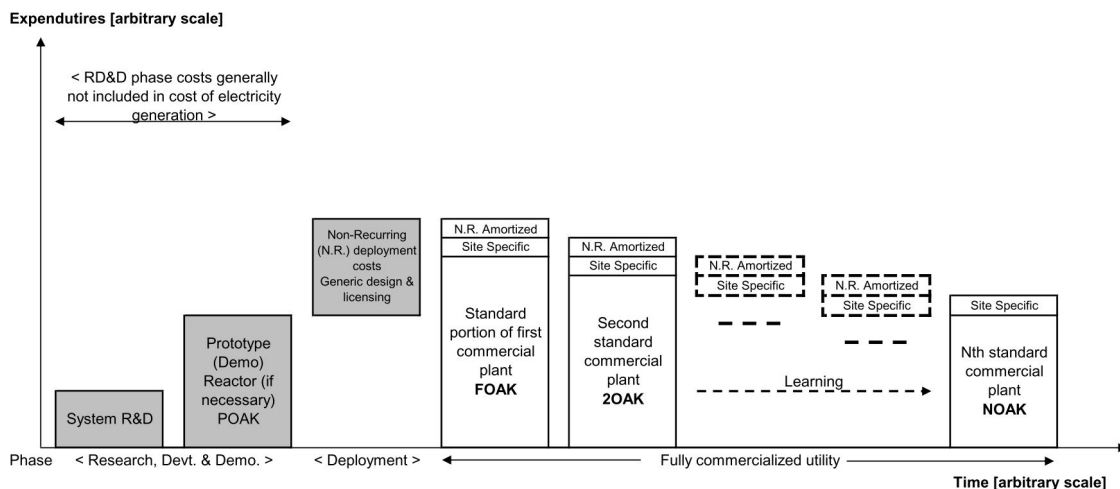
Its structure is comprised of a monolithic fuel block, with heat-pipes to transport the produced heat from the fuel block to the external condenser. Electricity conversion is done through a open-air recuperated Brayton cycle [52]. It is indicated by Westinghouse that the same general technology is going to be used in the eVinci Micro reactor, albeit being at a larger scale as it is expected to deliver between 10-25 MWe [53, 54]. For the purpose of this study, as there is no economic data as of this moment on the eVinci micro reactor, these two designs are treated as interchangeable and with the same economics, therefore only the MegaPower is taken into consideration.

The MegaPower reactor comes with only one, very rough, economic evaluation. A further complication is that the fundamental basis of this economic evaluation assesses only the FOAK reactor module. The estimates as given by the DoD indicate that a FOAK-reactor should cost between 140 and 325 million USD.

In order to make a proper comparison, the FOAK-cost estimate has to be recalculated into a NOAK-estimate, which implies a more mature state of the technology. The "Cost Estimating Guidelines for Generation IV Nuclear Energy Systems" provides a way to estimate the NOAK-expenditures. It states that due to the learning factor in modular systems, with every doubling of reactor construction experience, the total cost is reduced by a factor of 0.94. An illustration explaining the difference between expenditures for a FOAK-nuclear system and a NOAK-nuclear system is given in Figure 5.1 [55].

Using the guidelines, the costs for a 8th-of-a-kind-reactor were calculated to fall between 116.2 and 282.4 million USD for a single unit. The final expected retail value was calculated using the HOLOS vSMR system (see subsection 5.4.3). The HOLOS' economic data provides a lower and upper expected selling price, in combination with an expected retail price. The expected final retail price is not just a mere average of the lower and upper bounds. The difference between lower and upper bound was linearized. This linearization was expressed between 0 - 100%. The final results showed that the expected retail price would be 23.5% above the lower bound.

The same linearization is applied between the lower and upper bounds given for the MegaPower. This provides the final value of 155.4 million USD/reactor, or 77706 M\$/GW. A final assumption is that this price includes all additional costs.



**Figure 5.1:** Illustrative example with temporal relationships of research, development, demonstration, deployment, and standard plant costs, in the transition from FOAK to NOAK, as provided by the "Cost Estimating Guidelines for Generation IV Nuclear Energy Systems" [55]

## 5.4.2 U-Battery

The Urenco U-battery is the vSMR with the most comprehensive economic calculation. In the report "Design of a U-Battery", a complete lifetime economic assessment is provided.

Within the report, a total cost estimate of the CAPEX provides an estimate of 72.9 million euro for two reactor cores (it is expected that a U-battery system is built utilizing a minimum of two cores). In addition, for the first 10 years, operating costs comprised of fuel costs, auxiliary materials, security and O&M are expected to be in the range of 29.2 million euro. Decommissioning costs and possible salvage values are currently neglected [56].

These values are converted to 2017 USD, which results in 12,055 M\$/GW (TIMES utilizes values in the Giga-Watt range) and a fixed O&M cost of 15.3 M\$/MWa.

## 5.4.3 HOLOS

The HOLOS-vSMR has economic data provided by two independent sources, the US-DoD and HOLOS's vendor website. The US-DoD estimates the price of a FOAK reactor to be between 60.5 and 187 million USD. If this is brought to a 8th of a kind reactor, the cost is estimated to be between 50.25 and 155.3 million USD for each individual 13 MWe system. The HOLOS website provides an estimated sale price of 75 million USD per 13 MWe unit. As this number falls between the lower and upper bound of the 8th-of a kind estimate, it is assumed to be reasonable and the value is deemed useable for the TIMES calculations [57, 50].

Additionally, the website indicates that this price includes all costs for the HOLOS unit, making it impossible to allocate a price for fixed and variable operating costs. The final price per GW for TIMES equals to 5769 M\$/GW.

#### 5.4.4 Toshiba 4S

It is currently unknown if there is still progress being made with the Toshiba 4S vSMR. After the Toshiba/Westinghouse bankruptcy, the news surrounding the 4S system has died off and at the moment, no indication of further development can be found. Nonetheless, the sodium-cooled reactor provides a well documented case to be used for the assessment of other sodium-cooled designs.

The Toshiba 4S targeted a construction cost of 10.000 USD/kWe and O&M-costs of 4.5 ¢/kWh. Corrected to 2017 USD, provides the user with a value of 10,250 M\$/GW and 12.8 M\$/MWa.

#### 5.4.5 SEALER

The SEALER comes with the same cost estimation as the HOLOS. It is estimated by the vendor that a reactor would cost 100 million CAD, without stating any costs for the O&M. It is assumed that all related costs accrued over the lifetime of the reactor, are included in this retail price. The total price is then calculated as 27778 M\$/GW [58].

#### 5.4.6 UNITHERM

The UNITHERM reactor does not have any economic data, however, the economical data is estimated in the same way as done by Moore, by using a large scale light water reactor (LWR) to estimate the price of a scaled down LWR. By the same methodology, we use the value of \$4,910 million USD for a modern LWR-nuclear power plant (NPP) and the value of 0,55 for the scaling factor  $n$ . The estimation for a 6.6 MW LWR-reactor then becomes [3]:

$$\text{Overnight Cost (SMR \$M)} = \text{Cost(Large-NPP \$M)} \cdot \left( \frac{\text{SMR-MWe}}{\text{NPP-MWe}} \right)^n = \quad (5.1)$$

$$\$4910 \cdot \left( \frac{6.6 \text{ MW}}{1000 \text{ MW}} \right)^{0.55} = 310 \text{ M\$}$$

Which equals to 47027 M\$/GW, assuming all O&M costs are included.

#### 5.4.7 ABV-6E

The ABV-6E is a marine SMR, but has the capability to be used deployed on land as an independent system. The cost estimations for this technology are derived from the marine-based system, as currently no separate economic data for the land-based system is provided. The system can be used as a cogeneration or as a condensing unit. In the cogeneration setup each reactor provides 6 MWe and 14 MWth. In the condensing setup, each reactor provides 9 MWe and no thermal output [48].

The economic data provided by the IAEA states that the ABV-6E would be built at an average specific cost of 8,500 \$/kW in the case of a serial power unit. Corrected for inflation for 2017 USD, this amounts to 8713 M\$/GW [48].

Additionally, it is stated that "the contribution of the serial power unit to the prime cost of electricity is around 0.14 \$/kWh" It is estimated that this accounts for all O&M costs. Correcting this value to 2017 USD this provides a variable O&M of 39.86 M\$/PJ (TIMES uses the the value of M\$/PJ for its variable O&M).

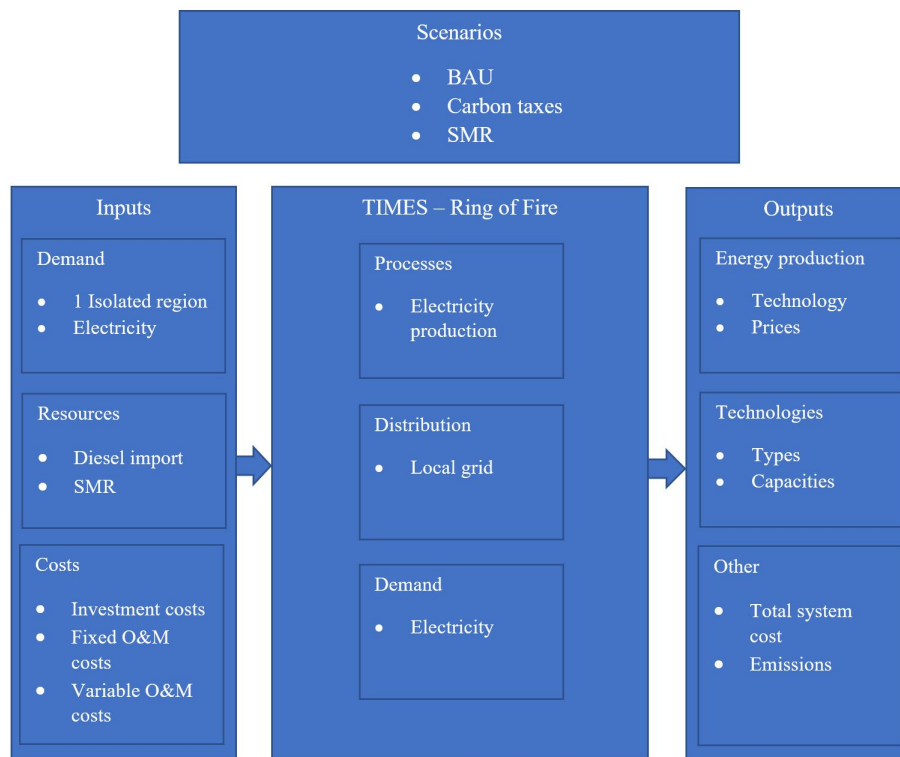
For the condensing units, all costs are estimated in the same way, albeit with 9 MWe production capacity. This provides 5808 M\$/GW in CAPEX and 26.57 M\$/PJ for OPEX.

## 6 | The TIMES - Ring Of Fire model

The TIMES-Ring Of Fire (TIMES-RoF) model is build as a variant of the models provided by Richard Loulou [59]. Within this chapter, the general build, use and calibration of the model will be described. At first, the general structure and use of the model will be explained within section 6.1. This section is divided into the scenario's (subsection 6.1.1), the inputs (subsection 6.1.2), the model itself (subsection 6.1.3), and the outputs (subsection 6.1.4). Finally, the calibration of the model will be explained within section 6.2.

### 6.1 Structure

The structure of TIMES-ROF is visualized in Figure 6.1, and is adopted from the TIMES-Noway report by Lind et al. [1]. The model can basically be divided into 4 sections; the scenarios, the inputs, the actual model and the outputs. The scenarios can be used simultaneously (e.g. a tax and the new technologies) for the desired outcomes.



**Figure 6.1:** Visual representation of the TIMES-ROF model structure, as adopted from the TIMES-Noway report by Lind et al. (2013) [1]

### 6.1.1 The scenarios

The model scenario's, describing each a path for possible future development, will run the model. The scenarios used:

- BAU scenario
  - Presenting the expected development of the mine as would be the case without the use of new technologies.
- Carbon tax scenario
  - Two separate scenarios. One of them assuming a linear carbon tax growth forecast, the other one assuming an exponential growth forecast. The absence of both of these scenarios implicitly creates a third scenario, the "no-tax" case.
- (v)SMR scenario
  - With this scenario, all SMR technologies are added to the model, providing TIMES with the 8 applicable SMR technologies, to choose from.
- Peak power
  - The Peak power scenario provides TIMES with the order to reserve 20% of total installed capacity for peak power purposes (in addition, this power can be used during maintenance, breakdowns or refueling of other generators or the SMRs alike).

### 6.1.2 Inputs

TIMES was provided with one region, the Eagle's Nest, which is modeled for its electricity demand. The region is set up as if comprised of 5 different sectors to describe all processes, as adopted from Loulou, 2016 [59]:

1. Electricity
2. Industrial
3. Primary energy
4. Residential, Commercial, Agrarian
5. Transportation

For the current study, the electricity, industrial and primary energy sectors are used. Primary energy describes the primary energy going into the model, for TIMES-RoF this would be the import of diesel and uranium. Uranium was given an arbitrary low price (for computational purposes, as a price of 0 would trigger a maximum import), as the price of uranium as a fuel is already incorporated in the O&M costs as given by the vendors (if applicable).

The electricity sector provides the model with the energy generation and conversion efficiencies of each process. For the SMR the total efficiency is given as 100%, as all induced costs are already directly calculated from the electrical output. With the fuel price already included in the O&M costs, efficiency for the SMRs should be ignored, as any additional efficiency penalty would trigger the additional costs from the import of uranium. For the SMRs the capacity factor taken is the minimum stated by the vendors. Only for the MegaPower, no capacity factor could be found. The system operates without any moving parts and therefore should have a high reliability, limiting

breakdowns and maintenance. To account for these technical features, a capacity factor of 0.97 was used, on par with the other SMR systems.

The industrial sector is the only sector with demand requirements within this study. The feasibility study only dictates a total energy requirement for the entire mine, which therefor can be summarized in the form of one demand projection. Both sectors "Residential, Commercial, Agrarian" and "Transportation" remain empty (no energy demands within these sectors), but are put in place for further future expansion.

The demand over the years is exogenously provided by the user and deemed fixed (TIMES does not influence demands). The model scenarios are run using the time period from 2020 to 2033 and from 2020 to 2042 respectively, the expected normal and extended lifetime of the mine (3 years of construction, 11 years of production and 9 year of possible extension). For this entire time-span, a discount rate of 8% is applied, as provided by the Noront [8]. All prices are given in 2017 USD.

The resources for TIMES to choose from are exogenously provided. These resources are the import of diesel fuel, or the use of SMR technology. To complement these resources, the user has exogenously provided the costs associated with each technology; investment costs (OPEX), fixed O&M costs and variable O&M costs (collectively referred to as CAPEX).

### 6.1.3 TIMES - Ring of Fire

The processes of energy production, distribution and the electricity demand are defined within the model. This means that when possible the efficiency of each process is filed into the model. This is currently only done for the diesel generators as the nuclear power plants were provided with their MWe capacity and fuel was included. Distribution is set to an efficiency of 100%, as no information was provided except for end use demand. Finally, the electricity demand, as given in Table 4.3 (subsection 4.4.1), is provided exogenously.

The use of discrete investment. TIMES is provided the possibility to make decisions every year, regarding investments, retirements, and the use of every technology. However, TIMES is restricted in its investment opportunities for the SMR technologies. As the described system is of such a small size, it is not realistic to have TIMES invest in arbitrary amounts of generation capacity when discrete increments regarding the reactors are the only real-life possibility. Therefore, TIMES is forced to work through lumpy investments, with each incremental growth-step being the size of one reactor.

The TIMES-ROF model currently utilizes only the ANNUAL level for electricity demand. The model has time-slices coded within its structure, on a daily basis for both summer and winter days, but given the data for the project, these are currently not in use. For this project, all given load data describe the energy demand during operations as relatively constant. The Eagle's Nest is scheduled to work 24/7 for 365 days a year, requiring constant power production, at the rate of 21.3 MW, with the additional capacity reserved for peak power.

**Table 6.1:** *Yearly efficiency vales as retrieved from the operation diesel generators used by the QEC, for the years 2014 until 2016. Values are based upon 39MJ/l, or 10.83 kW/l, for diesel fuel [36, 37, 38].*

Year	kWh/l	Efficiency (%)
2016	3.77	34.8%
2015	3.73	34.4%
2014	3.71	34.2%

### 6.1.4 Outputs

TIMES, after processing the inputs provided through Vesatile Data Analyst - Front End (VEDA-FE), delivers the results into Versatile Data Analyst - Back End (VEDA-BE), for post processing by the user. Within these results the user identified the following important parameters for this study:

- Energy production
  - Both the source (diesel and/or nuclear) and the total cost of production, for each given year.
- Technologies
  - The type of generator, build capacity and total investment cost for each given year
  - The O&M cost per technology, per year
- Others
  - The emissions from the entire system, per year
  - The total system costs

## 6.2 Calibration

Calibration of the model was carried out based on information from the feasibility study with regards to future energy use and expected energy costs, as there is no given base year to tie the calibration to. In the case of the current model, the data available is only given on a yearly basis, with expected fuel consumption and total expected yearly expenditures.

The amount of diesel that will be consumed by the generators to provide this amount of power is given as 5,8 m<sup>3</sup>/hr. This seems to be a conservative estimate. Looking into the three yearly rappsorts of the QEC (Nunavut) provides the possibility to check the estimate given by Noront. The reports provide efficiency as a yearly average value, as seen in Table 6.1 [8, 36, 37, 38].

The QEC states that their equipment is aging, indicating that their gensets are older, and therefor should have a relatively low average efficiency. Another assumption is that these gensets do throttle more during each diurnal cycle, as the demand profile of a community is vastly different from a continuous demanding mine. While the Eagle’s Nest is assumed to provide base-load during the full 24 hours, the demand curve of a typical community is usually characterized by a double peak. Energy consumption is high in the morning and evening, medium during the day and low during the night. Throttling of the diesel generators is necessary to follow these load curves. Throttling

lowers the average efficiency of a genset even further, as the optimal energy efficiency is usually found at the designed (maximum) load. It is therefore that the efficiency as stated by QEC should on average be below the efficiency of the proposed generators at the Eagle's Nest.

Knowing the expected energy demand and the assuming an efficiency for the diesel generators, provides the possibility to calculate the diesel consumption per hour. It is given that the mine is expected to use 21300 kWh per hour (the energy production of 21.3 MW for one hour). Based on the numbers of the QEC, the average efficiency of the diesel generators is assumed to be 34.5%. The consumption per hour should equal to  $\sim 5,700$  l/hr, which would be a conservative estimate based on the QEC numbers.

There is however another possibility, in which the stated amount would be the average including peak power. While the mine is designed to operate at a steady 21.3 MW, the inclusion of peak power might account for the difference. If the total expected peak power of 22.05 MW is used instead of the average load, the demand for diesel becomes 5,900 l/hr. It is therefore assumed that the 5,800 l/hr is an average consumption which includes peak power demand.

With regards to the economic side of the calibration, the financial outcomes should be compared to the feasibility study. In the "summary life of mine plan" on page 116 of the feasibility study [8], values are given for the total power costs. The values given in the table can however not represent the actual energy costs. Energy costs are given between 3,8 million and 7,1 million CAD, to account for the required power expenditures with regards to ore processing during operational years. This is in sharp contrast with the calculated values indicating expenditures in the range of  $\sim 32,1$  million USD/yr. This value does seem more in line with the operating costs, as depicted in chapter 21.1 of the Eagle's Nest feasibility study. Total lifetime costs for power are estimated at 324.257.000 CAD. Given the exchange rate (in 2012 the exchange rate was approximately  $\sim 1$  USD to 1 CAD) and recalculating this value into 2017 USD, this seems a reasonable assumption.



## 7 | Results

The results of the model will be discussed in four separate sections. Within section 7.1 the results will be provided for both the conventional system (subsection 7.1.1) and the SMR technologies (subsection 7.1.2). This analysis assumed the normal expected lifetime for the Eagle's Nest, setting the model horizon at 2033. A summary of the results can be found in Table 7.1, page 50. Expanding on the first results, section 7.2 will present the outcomes for the maximum life-time of the mine, placing the model horizon at 2042. The summary of these results can be found within Table 7.2, page 52. The third section will provide the results for the additional calculations based on the 22.05 MW demand profile section 7.3, with a summary of the results in Table 7.3, page 55. The fourth and last section will provide the extend-lifespan results for the increased power demand profile section 7.4, with a summary of the results in Table 7.4, page 57.

### 7.1 Normal expected lifetime analysis

Placing the model horizon at 2033, TIMES-RoF was analyzed for its intended conventional system (subsection 7.1.1) and the scenario in which TIMES has the possibility to replace the gensets with SMR technology (subsection 7.1.2).

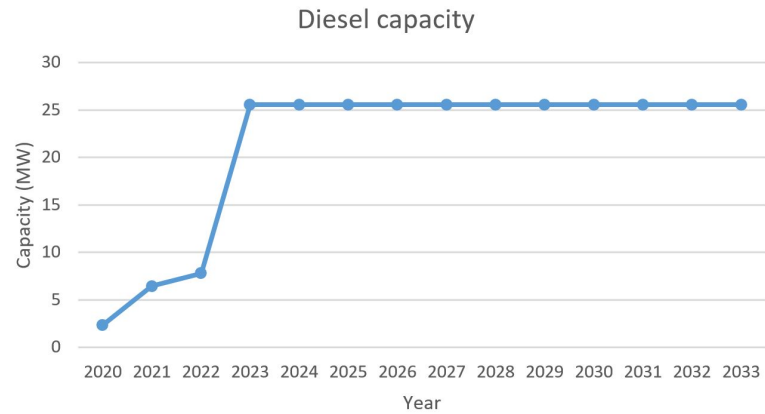
#### 7.1.1 Conventional system analysis

The first scenario to be processed contained the assumed values for the BAU-scenario, relying on diesel generation as its only production possibility. The scenario was run for both an 8% and 0% discount rate, with varying carbon tax possibilities.

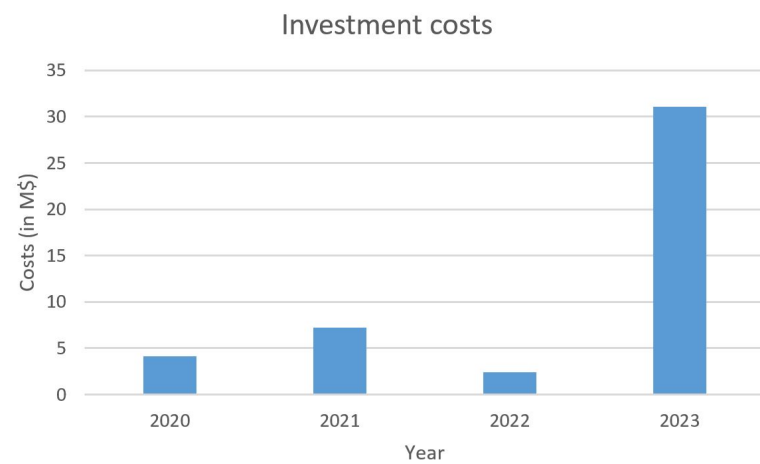
For these scenario's investment is not bound by a mandated incremental size regarding generator size (i.e. TIMES is allowed to allocate the optimum amount of generation per decision step). The resulting growth of the generation capacity in sync with the rising expected demand. During the first three years, installed capacity is low, as the total assumed demand is only necessary to power the development of the surface structures and the mine infrastructure. The fourth year sees the largest investments, as production commences and total demand reaches its maximum. Final generating capacity is 25.56 MW. Visual representation of the growth pattern, given in MWe total capacity per year, is provided in Figure 7.1. Associated investment costs per year, which accumulate to a total of 44.73 M\$, are shown in Figure 7.2.

The total OPEX for the diesel gensets is divided into two components; the fuel costs and the O&M costs. For the diesel generators the O&M is assumed to be a variable amount per MWh per year. Therefore, the total O&M expenditures per year rise depending on utilized generating diesel capacity. Yearly maintenance during full operations is of approximately ~2,8 M\$, accumulating to ~31,9 M\$ over the intended lifetime of the mine. These expenditures are visualized on a yearly and accumulative basis within Figure 7.3.

The major cost component for diesel-generated power comes from its fuel consumption. Fuel consumption is a function of power demand, and reaches its full consumptive capacity during full operations. The mine utilizes ~186.5 GWh per year. After accounting for efficiency losses, this



**Figure 7.1:** Visualized is the optimal available genset capacity development, as calculated by TIMES. Values are provided in MW



**Figure 7.2:** Shown are the investment costs for each year of new capacity installment. Gensets associated investment costs are given per year of installed capacity, in M\$



**Figure 7.3:** Visualized are the expected O&M expenditures, both per year and accumulated over the lifetime of the mine. Values are given in M\$

results in the consumption of  $\sim 536$  GWh of diesel per year (only utilizing conversion processes on-site, upstream processes and transport are neglected). 536GWh of diesel translates into just over 49.5 million liters of diesel fuel per year. Associated costs on a yearly basis are expected to be  $\sim 32$  M\$, and total expenses for fuel accumulate to  $\sim 371$  M\$. This is visualized in Figure 7.4.

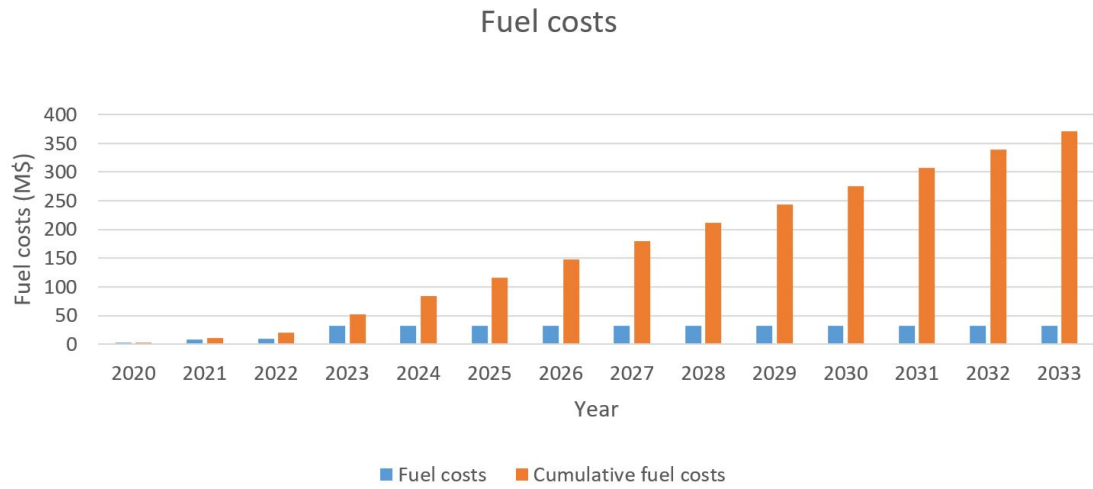
The diesel consumption associated  $\text{CO}_2$  emissions are  $\sim 131.7$  kt per year, during normal operations. Total diesel power generated electricity in the BAU-scenario results in a total of  $\sim 1534$  kt of  $\text{CO}_2$  emissions accumulated over the intended normal lifetime of the mine. Figure 7.5 presents the total amount of  $\text{CO}_2$  emissions.

These  $\text{CO}_2$  emissions are not just important for the environment, but also for the possible implications of the proposed carbon tax legislation. These total additional expenses are dependent on the tax-regimes (no tax, linear growth and exponential growth). The total expected additional costs from the carbon taxes with the linear growth scenario are  $\sim 69$  M\$. In the case of an exponential growing tax regime, total additional costs are estimated to be  $\sim 77$  M\$. These additional costs are visualized in Figure 7.6.

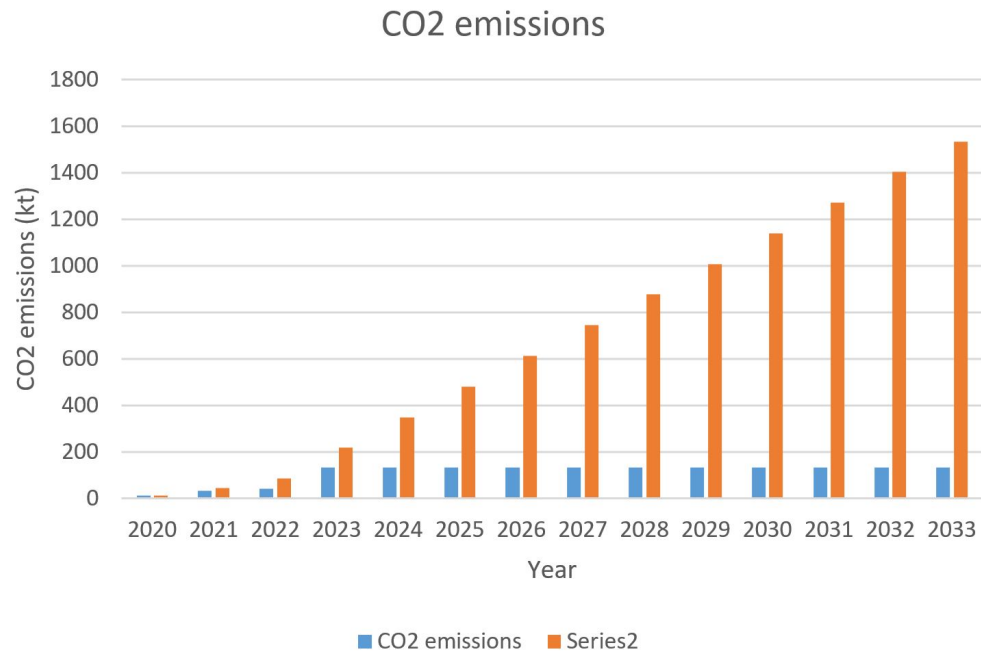
In total, the real system costs, without discount rate and additional carbon tax, accumulate to 449 million USD over the system lifetime. In case a tax is applied, the costs rise to either 518 M\$ (for a tax with linear growth assumption) or 526 M\$ (for a tax with exponential growth assumption). These total expenditures result in LCOE's ranging from 206\$/MWh, (0% discount rate and no tax) to 242 \$/MWh (8% discount rate and exponential tax). The total cost breakdown of the mine, excluding carbon taxes, can be found in Figure 7.7.

## Summary

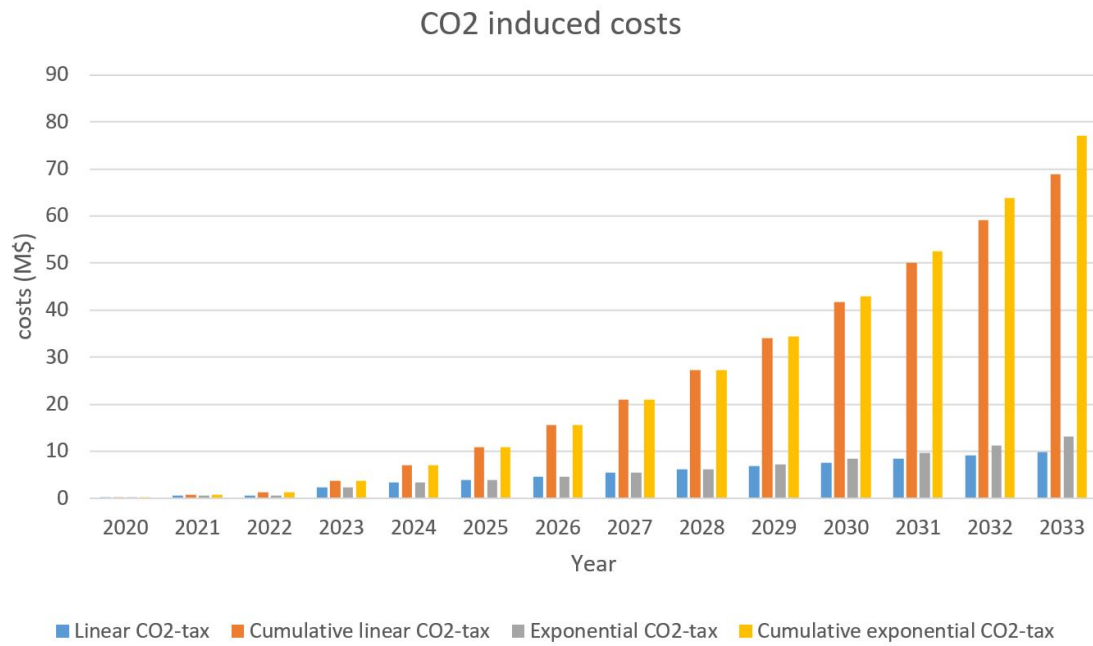
A complete overview of the most important parameters can be found in Table 7.1 (under "Diesel"). It is evident that the discount rate plays a large role in the assessment of an energy system. If on the over-all system the given discount rate of 8% is applied, the present value of the total lifetime



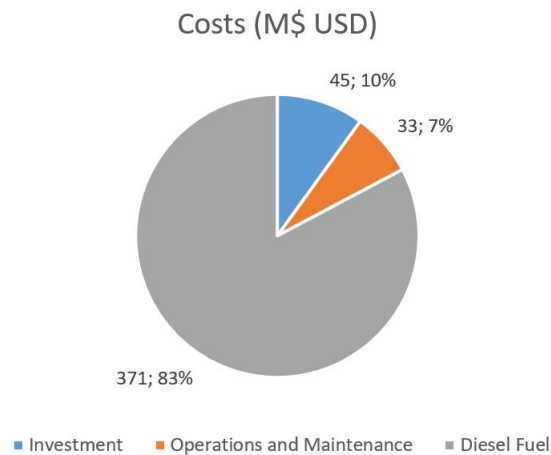
**Figure 7.4:** Diesel genset associated fuel expenditures. Expenditures are provided on a yearly and cumulative basis. Values are given in M\$



**Figure 7.5:** Total expected CO<sub>2</sub> emissions. Emissions are provided per year and cumulative over the life-time of the mine. Values are given in kt



**Figure 7.6:** The graph visualizes both the expected linear- and exponential carbon tax induced expenditures. Costs are provided on a year by year basis and a cumulative way. Values are given in kt.



**Figure 7.7:** Complete cost breakdown of the proposed diesel generated system, without additional carbon taxes. Values are given in \$/M

system drops from 449 M\$ to 272 M\$, without additional taxes applied. This large reduction for diesel generation arises from the fact that a large percentage of its life cycle costs ( $\sim 82.5\%$ ) is from fuel consumption, for which the associated costs are made in the future. Future expenses are discounted more when closer to the model horizon. A dollar spend on fuel in the last year of the model (2033) is only worth 36,8% of a dollar spent on fuel within the first year (as later discussed in section 8.7).

### 7.1.2 SMR analysis

For the SMR-analysis, two different sets were run. The first set included all vendors and all technologies, while the second was exclusively conducted with the U-Battery, which currently possesses the most comprehensive economic data. The additional scenario for peak power reservation was utilized to make sure that the system as a whole would invest in enough power to cover the peak load demands and the projected maintenance outages.

As expected, if TIMES has the opportunity to choose between all technologies, it will choose the system with the lowest over-all costs, in this case, the HOLOS. The HOLOS has the lowest investment costs (per MW of installed capacity), while simultaneously stating that all additional costs are already incorporated within this final amount, resulting in a one-time investment and no additional life-time costs.

The results, as found in Table 7.1 below "All vendors", describe the situation clearly. The results for all scenarios with a 8% discount rate are the same, as there is no usage of diesel. This provides an outcome in which there is no tax to be levied as the SMR does not emit CO<sub>2</sub>. Total system cost is expected to be 156 M\$, and the LCOE is calculated at 125 \$/MWh.

It is important to note the sudden decrease in LCOE as the interest rate drops to 0% (69\$/MWh). This inherently originates from the LCOE formula (as seen in section 3.3, in which both the cost and production are discounted per year. As the entire investment is done during year one, this value is hardly discounted. Most of the production is however spread over multiple years, and therefore gets discounted, lowering its value and resulting in an increased LCOE-value. The impact of the discount rate in the denominator of the LCOE formula therefore has a large effect on the LCOE of nuclear power. Reducing the discount rate effectively values future energy at a higher rate in today's terms, reducing the total price per MWh, resulting in an improved LCOE.

As a final remark, the HOLOS has the lowest investment cost per MW and comes only in 13 MWe increments. This means that even with the stated demand of 20% of capacity reserved for peak power (and implicitly for possible breakdowns or maintenance), TIMES has enough room within the HOLOS' capabilities to allocate surplus power for this purpose. This created a situation where, through unrestricted calculations, no amount of additional diesel back-up is required. The user should take this into account during system assessment.

### U-Battery

As the U-Battery provides the most sophisticated economic evaluation, a special subset of evaluations was made with this vSMR-technology. TIMES is only allowed to invest in increments of 4 MWe and is demanded to have 20% of capacity available for peak power demands (or in case of a breakdown/maintenance). Where the HOLOS scenario did have excess power, resulting in more surplus power from the generators, the U-battery is more tailored to the situation, as it comes in

smaller increments. The final results for the "U-Battery" can be found in Table 7.1 (underneath U-Battery).

Applying the 8% discount rate to the system, the system's LCOE comes close to the BAU-scenario's LCOE (225-228 \$/MWh for the U-Battery scenario, as compared to 217-248 \$/MWh for the BAU-scenario). Therefore, TIMES uses slight variations to alter its technology-mix when altering the parameters.

For all scenarios with an 8% discount rate, TIMES invests 20 MW in the first year, which powers the entire mining site during the construction. In the fourth year however, TIMES allocates 5.56 MW of diesel capacity, to fill the remaining production gap and as additional reserves. This choice indicates that for the remaining demand, diesel is less expensive per unit of power than the commissioning of an additional reactor.

As seen in both the "all-vendors" and "U-Battery" calculations, discount rate has a particularly high impact on nuclear power in the LCOE calculation. As a comparison, and to quantify its impact, the same scenarios are re-run, with the discount rate set at 0%. The results now present a different picture. TIMES refrains from running diesel generators completely and solely invests in the U-Battery vSMR for production. TIMES allocates 24 MW of nuclear power in the first year, while allocating 1.56MW of diesel generators in the fourth year to fulfill the required back-up demands, stated by the user as 20% of total capacity. These back-up diesel generators are however (ideally) never run. Most importantly, with the reduction in discount rate, the LCOE drops to 137 \$/MWh, this is a reduction of 58%.

### Summary

Table 7.1 provides an overview of all important outcomes, for each run scenario.

**Table 7.1:** All results that apply to the normal expected lifetime of the mine, calculated for the 21.3 MW demand profile, are provided within this table. In each row, the used set of combined scenarios is given; stating the discount rate (DR), and the applied carbon tax.

Diesel	Nuclear (MWh)	Diesel (MWh)	System cost (M\$)	LCOE \$/MWh	CO2-emissions (kt)	Diesel capacity (MW)	Nuclear capacity (MW)
8%-tax linear	NA	2173641	307	245	1534	25.56	NA
8%-tax exponential	NA	2173641	310	248	1534	25.56	NA
8%-no tax	NA	2173641	272	217	1534	25.56	NA
0%-tax linear	NA	2173641	518	238	1534	25.56	NA
0%-tax exponential	NA	2173641	526	242	1534	25.56	NA
0%-no tax	NA	2173641	449	206	1534	25.56	NA

All vendors	Nuclear (MWh)	Diesel (MWh)	System cost (M\$)	LCOE \$/kWh	CO2-emissions (kt)	Diesel capacity (MW)	Nuclear capacity (MW)
8%-tax linear	2173641	0	156	125	0	0	26.00
8%-tax exponential	2173641	0	156	125	0	0	26.00
8%-no tax	2173641	0	156	125	0	0	26.00
0%-tax linear	2173641	0	150	69	0	0	26.00

U-Battery	Nuclear (MWh)	Diesel (MWh)	System cost (M\$)	LCOE \$/kWh	CO2-emissions (kt)	Diesel capacity (MW)	Nuclear capacity (MW)
8%-tax linear	1971285	202356	286	228	143	5.56	20.00
8%-tax exponential	1971285	202356	286	228	143	5.56	20.00
8%-no tax	1971285	202356	282	225	143	5.56	20.00
0%-tax linear	2173641	0	297	137	0	1.56	24.00
0%-no tax	2173641	0	297	137	0	1.56	24.00

## 7.2 Extended life-span analysis

The results of the U-Battery, at an 8% discount rate, being close to the the ones of the BAU-scenarios of diesel generators, warrants research into the scenario's of a life-time extension of the mine, extending the horizon of the model to 2042. The combined results of the calculations using this extended model horizon are summarized in Table 7.2.

The results found below "Diesel" describe the output of the TIMES model in the case of the BAU-scenario's. The exponentially growing carbon tax was omitted, as the induced costs were growing beyond justifiable levels and deemed unrealistic. For the results as calculated with the U-Battery vSMR, the use of the "no-tax scenario" gave the same results as the "linear-tax scenario".

The comparison between the U-Battery results from the intended model horizon (Table 7.1) and the long model horizon is of importance. Comparing, it is seen that as the model horizon is extended, the preference of TIMES moves towards the nuclear powered options, a feat explained by the results of the LCOE calculations.

While the LCOE of the diesel generators rises under the tax-regime (from 246 \$/MWh, to 256.5 MWh), and slightly drops under a no-tax regime (from 218 \$/MWh to 217.5 \$/MWH), the LCOE of the vSMR continues to decrease. For the 8% discount rate, the LCOE drops from 227 \$/MWh to 176.5 \$/MWh. Nuclear drops even further with lower discount rates, reaching a low of 75 \$/MWh at 0%, for the extended mining operations scenario. This is the result of the LCOE formula, as explained in section 3.3. Extending the model horizon adds more value to the denominator, while the numerator is hardly changed (the variable costs are almost negligible).

A final remark is that for the extended life-time of the mine, TIMES uses the same energy system set-up as with the intended life-time calculations. For the remaining 1.3 MW of necessary power (above the 20 MW delivered by the U-Batteries) it is more economical to invest in additional diesel power at an 8% discount rate and in an additional nuclear core at a 0% discount rate.

### Summary

Table 7.2 provides an overview of all important outcomes for each run scenario with the extended model horizon.

**Table 7.2:** All results for the possible extended lifetime of the mine, as calculated for the 21.3 MW demand profile, are provided within this table. Each row states the discount rate (DR), and which carbon tax was applied. Only the U-battery technology was used in comparison to BAU.

Diesel	Nuclear (MWh)	Diesel (MWh)	System cost (M\$)	LCOE \$/kWh	CO2-emissions (kt)	Diesel capacity (MW)	Nuclear capacity (MW)
8%-tax linear	0	3852933	417	248	2719	25.56	0
8%-no tax	0	3852933	351	209	2719	25.56	0
0%-tax linear	0	3852933	951	247	2719	25.56	0
0%-no tax	0	3852933	761	197	2719	25.56	0
U-Battery	Nuclear (MWh)	Diesel (MWh)	System cost (M\$)	LCOE \$/kWh	CO2-emissions (kt)	Diesel capacity (MW)	Nuclear capacity (MW)
8%-tax linear	3485013	367920	297	177	260	5.56	20
8%-tax exponential	3485013	367920	294	175	260	5.56	20
8%-no tax	3485013	367920	291	173	260	5.56	20
0%-tax linear	3852933	0	300	78	0	1.56	24

### 7.3 22.05 MW, intended life-time analysis

Previous research by Hatch focused on an base-load energy consumption of 22.05 MW. This research replicates this demand for comparison. All other calculations were conducted in the same manner and the results are presented in the same way.

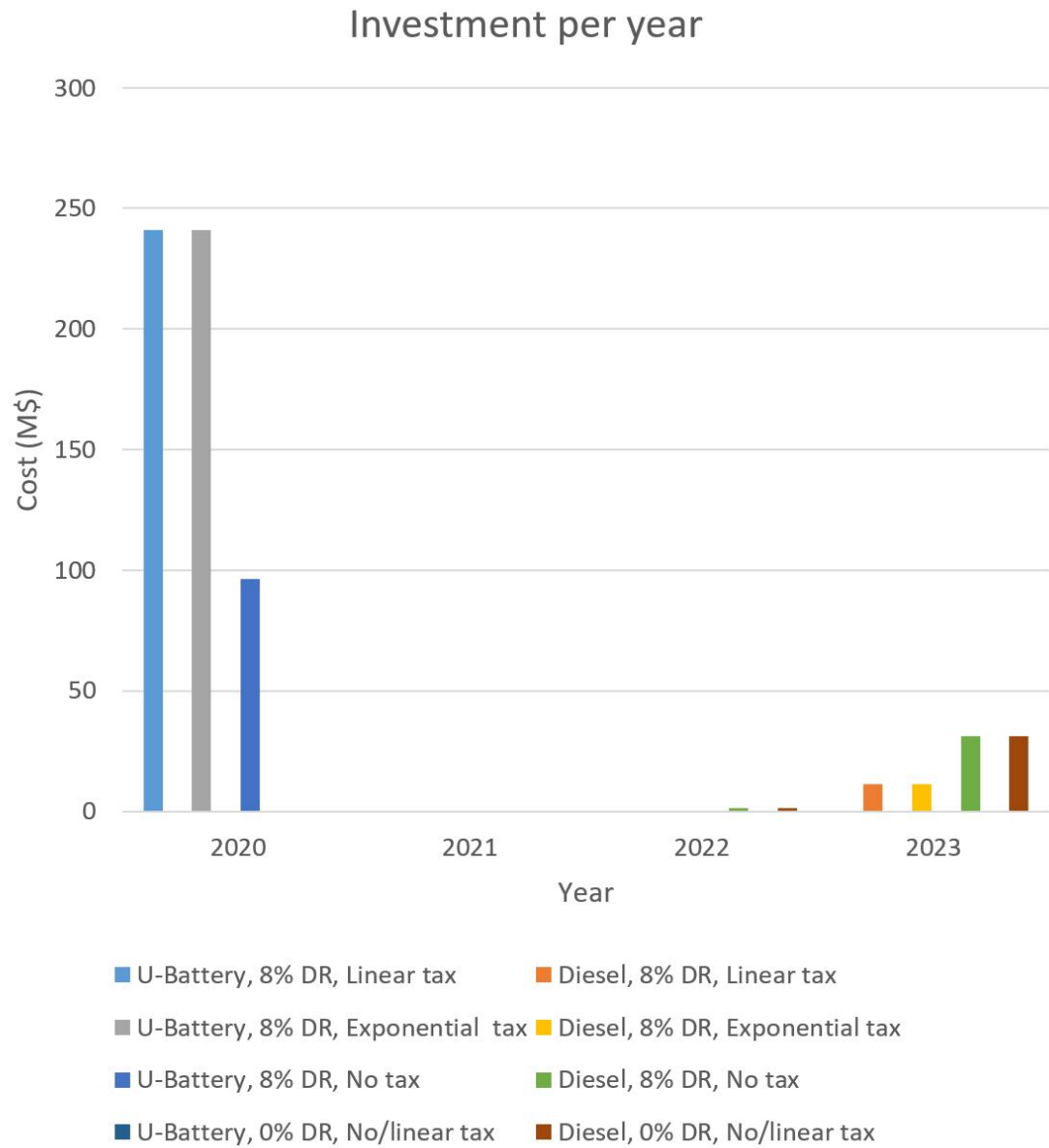
For the BAU-scenarios, the same range of values are found as within the 21.3 MW demand analysis. The same holds for the scenarios in which TIMES can choose between all nuclear vendors. An interesting result however arises from the analysis with the U-Battery.

For all scenarios with an 8% discount rate and either a linear or exponential carbon tax, TIMES invests 20 MW in the first year, which powers the entire mining site during the construction. In the fourth year however, TIMES allocates 5.56 MW of diesel capacity, to fill the remaining production gap and as additional reserves. This choice indicates that for the remaining demand, diesel is less expensive per unit of power than the commissioning of an additional reactor.

If the carbon tax is dropped altogether, the investment pattern of TIMES changes, and the investment into nuclear power is dropped to 8MW, which powers the mine for the first two years. In the third year, invisible in the graph, TIMES allocates 760 kW, at the cost of 1.3 million, to cover the small gap between demand and production. As this 760 kW of additional capacity is allocated within the 20% reserve margin, it is treated as backup generation and not utilized, being a mere precise outcome of TIMES' calculation between demand and capacity.

In the fourth year, TIMES allocates the remaining 17.7 MW of diesel production, which is used in addition to the 8 MW nuclear capacity. This additional diesel capacity is used as both base-load and as peak power and back-up capability. The U-Battery vSMR's are always used as base-load, as their power output is less expensive. A full visualization, comparing the different investment patterns, is provided in Figure 7.8.

The changes in allocation of technologies, between these three scenarios, are quite large, while at the same time, the LCOE of the different systems differ slightly. This also counts for a comparison to the BAU-scenarios. This indicates that with the current discount rate and the applied tax regimes, transitioning to SMR appears to be cheaper solution than diesel generated power. This is the region where the transition of the vSMR as a cheaper solution to diesel generated power, has been found.



**Figure 7.8:** The graph provides the investments in technologies under different scenarios. The investments are provided per year, per technology for each scenario. Values are provided in M\$

**Table 7.3:** All results that apply to the normal expected lifetime of the mine, calculated for the 22.05 MW demand profile, are provided within this table. In each row, the used set of combined scenarios is given; stating the discount rate (DR), and the applied carbon tax.

Diesel	Nuclear (MWh)	Diesel (MWh)	System cost (M\$)	LCOE \$/MWh	CO <sub>2</sub> -Emissions (kt)	Diesel capacity (MW)	Nuclear capacity (MW)
8% DR-linear tax	NA	2258000	319	245	1593	26.46	NA
8% DR-exponential tax	NA	2258000	323	248	1593	26.46	NA
8% DR-no tax	NA	2258000	282	217	1593	26.46	NA
0% DR-linear tax	NA	2258000	537	238	1593	26.46	NA
0% DR-exponential tax	NA	2258000	546	242	1593	26.46	NA
0% DR-no tax	NA	2258000	466	206	1593	26.46	NA

All vendors	Nuclear (MWh)	Diesel (MWh)	System cost (M\$)	LCOE \$/MWh	CO <sub>2</sub> -Emissions (kt)	Diesel capacity (MW)	Nuclear capacity (MW)
8% DR-linear tax	2258000	0	157	120	0	0.46	26
8% DR-exponential tax	2258000	0	157	120	0	0.46	26
8% DR-no tax	2258000	0	157	120	0	0.46	26
0% DR-linear tax	2258000	0	150	67	0	0.46	26

U-Battery	Nuclear (MWh)	Diesel (MWh)	System cost (M\$)	LCOE \$/MWh	CO <sub>2</sub> -Emissions (kt)	Diesel capacity (MW)	Nuclear capacity (MW)
8% DR-linear tax	1983374	274626	296	227	194	6.46	20
8% DR-exponential tax	1983374	274626	296	227	194	6.46	20
8% DR-no tax	873306	1384693	271	208	977	18.46	8
0% DR-linear tax	2258000	0	299	132	0	2.46	24
0% DR-no tax	2258000	0	299	132	0	2.46	24

## 7.4 Extended life-span analysis

The results found below "Diesel" describe the output of the TIMES model in the case of the BAU-scenario's for the 22.05 MW demand profile. Again, the exponentially growing carbon tax was omitted, as the induced costs were growing beyond justifiable levels and deemed unrealistic. For the results as calculated with the U-Battery vSMR, the use of the "no-tax scenario" gave the same results as the "linear-tax scenario".

An important comparison has to be made between the U-Battery results for the 21.3 MW and the 22.05 MW calculations. While TIMES still uses diesel power for the 8% discounted taxed scenarios for the 21.3 MW calculations, it utilizes only nuclear power for the 22.05 MW calculations. This indicates that within the difference of 0.75 MW between both calculations lies the point the fixed costs for the U-Battery system become less-expensive than the marginal expenses for diesel generation. Only in a situation where no tax is levied, TIMES uses diesel to produce a small portion of total power demand.

The further results of the calculation are the same and in line with the 21.3 MW calculations. it can be seen that as the model horizon is extended, the preference of TIMES move again towards the nuclear powered options. The LCOE of the diesel generators rise under the tax-regime if the life-time is expanded (from 245 \$/MWh, to 248 \$/MWh), and slightly drop under a no-tax regime (from 217 \$/MWh to 209 \$/MWh), the LCOE of the vSMR decreases again under influence of the LCOE formula. For the 8% discount rate, the LCOE drops from 227 \$/MWh to 177 \$/MWh. Nuclear drops further with a lower discount rate, reaching a low of 76 \$/MWh at 0%, for the extended mining operations scenario, with a 22.05 MW demand profile.

### Summary

Table 7.2 provides an overview of all important outcomes for each run scenario with the extended model horizon.

**Table 7.4:** All results for the possible extended lifetime of the mine, as calculated for the 22.05 MW demand profile, are provided within this table. Each row states the discount rate (DR), and which carbon tax was applied. Only the U-battery technology was used in comparison to BAU.

Diesel	Nuclear (MWh)	Diesel (MWh)	System cost (M\$)	LCOE \$/MWh	CO2-emissions (kt)	Diesel capacity (MW)	Nuclear capacity (MW)
8% DR-linear tax	0	3996422	433	248	2820	26.46	0
8% DR-no tax	0	3996422	365	209	2820	26.46	0
0% DR-linear tax	0	3996422	986	247	2820	26.46	0
0% DR-no tax	0	3996422	789	197	2820	26.46	0

U-Battery	Nuclear (MWh)	Diesel (MWh)	System cost (M\$)	LCOE \$/MWh	CO2-emissions (kt)	Diesel capacity (MW)	Nuclear capacity (MW)
8% DR-linear tax	3996422	0	308	177	0	2.46	24
8% DR-exponential tax	3996422	0	308	177	0	2.46	24
8% DR-no tax	3497102	499320	302	173	352	6.46	20
0% DR-linear tax	3996422	0	302	76	0	2.46	24
0% DR-no tax	3996422	0	302	76	0	2.46	24



## 8 | Discussion

The following points of discussion directly affect this report: the validity of the assumptions (section 8.1), the variables and allocation of the peak reserve (section 8.3), the use of discrete commitment (section 8.4), and the lack of data on the different time-scales (section 8.5). Topics of further importance are methodological possibilities beyond the scope of this report, such as additional parameters one could implement and the use of different software for future research and validation of this report (section 8.8).

### 8.1 Validity of assumptions

The most important parameters that will need additional work and an in-depth analysis are the economic and operational values, on both the diesel gensets and the vSMR technology. While no real-world data exist for the vSMR's, as their technology is experimental and unproven, a detailed economic analysis, as done for the Urenco U-Battery, might provide a better estimate for future capital and operation expenses.

Additional data on the economics of the gensets should be obtained through vendors and mining operators in the region, as prices can fluctuate based on the location of deployment and the place of purchase. This proved to be impossible within the time frame of this report. Collaboration with the mining sector will be an important way to assess the possibilities of retrieving real-world data in the future, and might be a valuable asset for both parties.

Another consideration is the validity of the final demand profile of the region, as used within the study. In this case the difference in demand might not influence the outcomes to a large extent as the study mainly is a comparison between generation technologies for priority-setting. This is confirmed as the results between the 21.3 MW and 22.05 MW demand profiles are coherent. However, the final values regarding real-world economics, consumption and emissions, if requested by a mining company or legislative body, are highly dependent on indicated energy consumption.

### 8.2 Salvage value

An additional important parameter, neglected within this study, is "salvage value". On diesel gensets the expected salvage value is not expected to be large compared to its initial value, nor is it expected to be of large influence due to the small proportion the equipment costs represent within the final cost analysis of a diesel system. The salvage value on the SMRs on the other hand can have a large influence. Some SMRs have a lifetime exceeding by far the model horizon for the proposed mine. Being small (and some of them also highly portable), the SMRs can possibly be relocated or taken back to the vendor for refurbishment. This might have additional benefits which should not be neglected.

### 8.3 Peak power reserve changes

In subsection 4.4.1, it was noted that the CF of 0.8, as stated by Noront, would be omitted. This comes from the fact that in the final calculations, if a user would have used the CF of 0.8 instead, it would have lead to incoherent results. Specifically, the final generating capacity within the results would not have been equal through all instances, the gensets would have seen an increase of  $\sim 5\%$  in their allocated generating capacity.

This disparity originates from a different way in calculating the final generation capacity. In case of the reactors, the CF was available in all cases. TIMES is tailored to use both a CF and peak power reserve as separate values. This makes multiplication of these values by hand unnecessary (and dangerous as assumed values can easily be forgotten in the large excel spreadsheets used by TIMES). Instead, a peak power reserve was used through the use of a "peak-power reserve" scenario. Peak power reserve is allocated as a percentage of total generating capacity.

A quick reference to the feasibility study shows that with 8 generators running and 10 in total, 20% of total capacity is to be mandated for additional generating capacity. However, by allocating a CF of 0.8 to the diesel generators (8 running, 2 offline) the program allocates 25% extra capacity, as it assumes the same capacity factor applies to the additional 20%. Therefore, one should consider the following:

1. The impact on the study. For this study, the extra capacity for the BAU-scenarios is small if one uses a CF of 0.8, (1 MW equals 1,75 million USD with current estimations). One might however reconsider an either change the CF for the diesel generators, as done within this study, or tweak the peak power reserve to create coherent results.
2. The reality is that one should manage each scenario individually, especially in such a small region. The best example is provided by the outcomes for the U-Battery in both the short-term and the long-term scenarios. While TIMES might create an "optimum" outcome, this outcome does not necessarily reflect the real-world optimum. In the results for the U-Battery, the short-term and the long-term scenarios, TIMES allocates 20% extra generation capacity, which comes from the output surplus of the U-battery system, and the reserve diesel generators. However, in this specific case, this creates an N+1 system. Only one U-Battery can go offline, with enough back-up available. A second failure would create a shortage. The most obvious solution is to buy more diesel generators serving as off-line back-up capacity (as the vSMR's produce enough and less expensive power). While TIMES can be tailored by tweaking the input parameters, increasing investments to create an N+2 system, for current calculations the missing capacity is a low-impact event (as the additional cost of diesel generators is low). It highlights however that the user should always consider and validate the answers, not just with the model, but also with the real-world demands and requirements.

### 8.4 Discrete commitment

While TIMES currently utilizes discrete investments for its technologies, discrete commitment was not yet applied due to time-constraints. The way discrete commitment is influencing the results can be described best by the results of the U-Battery scenarios, at a 0% discount rate (Table 7.1). TIMES allocates 2.46 MWh diesel capacity in addition to the surplus power from the U-Batteries (24 MWe total). TIMES applies the CF of the U-Battery (given as 0.96) to the production capacity

as a whole, implying that with the current spatial resolution (ANNUAL), 96% of capacity is always available.

This is however not a reasonable scenario. During refueling, an entire core of 4MWe has to be taken offline, leaving only 20 MW of nuclear power and making the use of diesel power an necessity (as 21.3 MW is required at all times). While the effects for the current calculations are small, this is something to consider for future, more detailed calculations.

## 8.5 Improving temporal resolution

### 8.5.1 Increasing time-slices

Another important consideration for the user to make is the use of different time-slices. While the first intentions of this study were to utilize monthly and hourly time-slices to cope with demand variations during the seasons and through each day, the available data did not provide the resolution to utilize this feature.

Another consideration is the use of sub-hourly data. In the case of small grids and generation units, load changes can be fairly sudden and large with respect to total demand. For example, the start or trip (the sudden shut-down) of a generator or mining equipment can cause large residual loads which in turn can lead to a shut-down of the entire system. Therefore, it is a necessity to take these loads into consideration while designing the power system.

Research has to be carried out to determine if the generators can cope with these sudden shifts in load demands, or which measures are necessary to mitigate these problems. Additional equipment might be an option, e.g. in the form of a flywheel or a capacitor unit, which can correct for the sudden change until the generator has changed its output accordingly. This technology can be added to TIMES as an extra process or possibly an added investment value to the affected generators. The use of additional equipment should be a consideration for the balance of the entire final energy system.

### 8.5.2 PLEXOS coupling

TIMES itself is technically capable, but not particularly suitable, for these sub-hourly analyses. A way to circumvent this is through the use of additional software. An example is the combination of TIMES and PLEXOS (a commercial software for energy power system modeling), as demonstrated by Alessandro Chiodi et al. (2011) [60]. Chiodi et. al. used PLEXOS to investigate the additional benefits of soft-linking the two systems through the use of the TIMES-Ireland model.

PLEXOS has a high time-slice density. Power system models only focus on the electrical power system (while TIMES, models all facets of an energy system, e.g. heat, power, industrial processes, etc). Power system modeling is tailored more specifically to assess the specific system challenges, as it can focus on higher resolutions.

Linking TIMES and alternative software, such as PLEXOS, creates the possibility to more correctly take into account highly variable loads and production, creating more detailed and realistic model outcomes.

## 8.6 Increasing demand functions

The model is currently relatively small, especially given the possibilities that TIMES offers. If the user can acquire additional data, the creation of a more detailed and enlarged model is possible, providing an increasingly better foundation to determine the priority-setting in regional and technological development.

Examples of possible implementations within this model are:

- Cost curve for diesel import
  - The import-price for diesel within this model is fixed. The user could define an expected cost-curve, or create different scenario's for different expected fuel prices.
  - For added complexity, the cost curve for the import of diesel could be linked to the total volume of imported diesel, as the price might be influenced by economies of scale.
- Alternative energy sources
  - The user should not be limited to just nuclear power and diesel fuel. While this can be a great opportunity for the development of nuclear power, and this study would warrant further research upon its results, one should not exempt other technologies. Renewable sources such as solar, wind, local small scale hydro or even local biomass (and the possible jobs it might create) can be modeled. for the modeling of intermittent resources, options as PLEXOS could be utilized, and even TIMES has the option to run stochastic models for renewables.
- Additional mining sites
  - With the planned development, additional mines can added to the model. As the most mines in the vicinity of the Eagle's Nest are also developed by Noront, it might be an idea to model each mine as a seperate region, using the 'trade' parameter within TIMES to assess the best method of supplying these mines energy. This trade can possess economic parameters describing the investment costs (for power lines), efficiency losses and the price of energy.
- Additional local communities
  - With local communities still running on expensive diesel fuel, the promise of a local sub-grid with less expensive, more sustainable power might be an option for future development. This could provide economical incentives for all parties, but also create more involvement and sympathies for the mining operation on the part of the local communities.
- Electric vehicles
  - The Eagle's Nest will utilize mostly electric vehicles below ground. But with the increased developments regarding electric heavy equipment, as for example the electric Komatsu HD 605-7 [61], it is possible to expand the model using demand functions for transport and equipment. Different scenarios can be constructed, in which the possibilities for the investment in or change to electrical equipment can be laid out.
- Additional demand-commodities, such as heat,
  - A commodity such as heat can be provided by the SMR technologies, but is being neglected at the moment. Especially in cold-climate regions, the additional price for fossil fuels used for heating can be substantial. The use of a cogen setup might be an additional extra incentive for SMR deployment.

**Table 8.1:** *Present value table, presenting the value of an arbitrary 1\$ per year, as function of time and the discount rate*

Year	Discount rate (%)									
(n)	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
1	0.990	0.980	0.971	0.962	0.952	0.943	0.935	0.926	0.917	0.909
2	0.980	0.961	0.943	0.925	0.907	0.890	0.873	0.857	0.842	0.826
3	0.971	0.942	0.915	0.889	0.864	0.840	0.816	0.794	0.772	0.751
4	0.961	0.924	0.888	0.855	0.823	0.792	0.763	0.735	0.708	0.683
5	0.951	0.906	0.863	0.822	0.784	0.747	0.713	0.681	0.650	0.621
6	0.942	0.888	0.837	0.790	0.746	0.705	0.666	0.630	0.596	0.564
7	0.933	0.871	0.813	0.760	0.711	0.665	0.623	0.583	0.547	0.513
8	0.923	0.853	0.789	0.731	0.677	0.627	0.582	0.540	0.502	0.467
9	0.914	0.837	0.766	0.703	0.645	0.592	0.544	0.500	0.460	0.424
10	0.905	0.820	0.744	0.676	0.614	0.558	0.508	0.463	0.422	0.386
11	0.896	0.804	0.722	0.650	0.585	0.527	0.475	0.429	0.388	0.350
12	0.887	0.788	0.701	0.625	0.557	0.497	0.444	0.397	0.356	0.319
13	0.879	0.773	0.681	0.601	0.530	0.469	0.415	0.368	0.326	0.290
14	0.870	0.758	0.661	0.577	0.505	0.442	0.388	0.340	0.299	0.263
15	0.861	0.743	0.642	0.555	0.481	0.417	0.362	0.315	0.275	0.239
16	0.853	0.728	0.623	0.534	0.458	0.394	0.339	0.292	0.252	0.218
17	0.844	0.714	0.605	0.513	0.436	0.371	0.317	0.270	0.231	0.198
18	0.836	0.700	0.587	0.494	0.416	0.350	0.296	0.250	0.212	0.180
19	0.828	0.686	0.570	0.475	0.396	0.331	0.277	0.232	0.194	0.164
20	0.820	0.673	0.554	0.456	0.377	0.312	0.258	0.215	0.178	0.149

## 8.7 Discount rate

An important parameter to consider is the discount rate which is applied to the system. A high discount rate is sensible for the entire mining endeavor, as it has a high risk profile. However, when applied to the costs of the project, especially for diesel generation, it causes the future costs to be discounted as well. At high discount rates, this means that over the long lifetimes of the proposed mines, expenditures in the future are discounted to marginal levels.

High discount rates are therefore good for fossil fuels. Most fossil fueled energy sources accrue most of their cost during their lifetime in the form of fuel expenditures. Nuclear and renewable sources alike have a different spending profile, spending most costs up-front in the form of capital costs. Table 8.1 provides an insight in how quickly costs are discounted at different discount rates. While fuel at a modest rate of 3% would still be at 66,1% of its current value in the future (given a lifetime of the mine of 14 years), at an 8% rate as used by Noront, this would only be 34%.

## 8.8 Modeling environment

Another consideration is the transition from TIMES to another modeling environment. TIMES is a proven framework, but requires financial resources due to its commercial software components and takes a substantial amount of time to learn. With the rise of open source modeling tools, these

barriers resulting from the capital cost and the necessary time to get acquainted with the program could be mitigated and the model could be more accessible to third parties (not requiring up front capital themselves), if required.

A few examples of modelling tools for consideration are:

- Python for Power System Analysis (PyPSA)
- Open Source Energy Modelling System (OSeMOSYS)
- Calliope

## 8.9 Extended scope

Finally, this study has been fixated on the techno-economic aspects of the deployment of SMR technologies, to determine future priority setting. However, far more facets of the deployment of nuclear power should be taken into consideration. Among many things to consider are, for example: legislation subsection 8.9.1, handling of nuclear materials on site (subsection 8.9.2) and the public opinion (subsection 8.9.3).

### 8.9.1 Legislation

Legislation is by far one of the most important considerations, while assessing the future deployment of SMR technology, and a large portion of the future priorities with regards to SMR commitment should come from this field. Just a few, but major legislation hurdles to consider are: licensing, non-proliferation and commissioning and decommissioning.

### 8.9.2 Materials handling

While for the purpose of this study, all technologies were treated equally, this does not make sense in reality. Some technologies are more capable of being handled on site than others. A drawback of easy handling might be the security of nuclear materials. Aspects to consider are: on-site or off-site refueling, access to nuclear materials and spent fuel, radiation safety on-site and the need for specialized personnel.

Systems like the HOLOS are designed to be the pinnacle of flexibility. They can be transported by air if necessary, and their spent fuel is easily packed inside a standard spent-fuel storage cask for storage. However, this transportability and availability comes with its own safety concerns which all should be considered, with regards to the nuclear safety of the system.

### 8.9.3 Public opinion

Finally, the public opinion is of utmost importance. The local population, mining company and other regional actors should be in support of the new technology in order to create a safe and prosperous endeavor.

## 9 | Conclusion

This study provides an in-depth and verifiable research, utilizing the Eagle's Nest as its study case to investigate the feasibility of SMR deployment into small isolated grids. Provided the final results of the model, they verify the previous work by Hatch and Moore ([2, 3], and it seems warranted to prioritize further research into the area of SMR development and deployment for this and similar regions and isolated grids.

While this study required a substantial amount of assumptions, resulting from hard-to-obtain data due to its sensitivity and the experimental state of the technologies, this study still provides the reader with an indication of the possible financial implications of SMR deployment. The following conclusion should be taken into account on top of the final results:

- The diesel generation capacity has been modeled with a low estimate for diesel prices. As diesel fuel makes up the largest portion of the total costs of these systems, the general conclusion can be that for the diesel gensets the final financial estimates are a low estimation.
- For the nuclear systems, the data provided by the different vendors proved to be variable and the lower and higher estimated values are often far apart. By the use of the best-documented system, the Urenco U-Battery, which investment costs was average in comparison to other technologies, a justifiable result could be retrieved.

The final conclusion of the study can be summarized as follows:

- The final financial results state that with the current estimations for the production of power through diesel gen-sets, SMRs can be a cost-effective option.
  - Extension of the lifetime of the energy system will be beneficial for the nuclear powered option. As the operation costs of the system are low, any additional power delivered lowers the over-all costs per MWh, and therefor its LCOE, accordingly.
  - The incentive for SMR deployment increases when the discount rate decreases. In the light of current estimates, an SMR becomes a viable option at a discount rate between 0-8%.
- The designed framework offers possibilities for future research into the development of the Eagle's Nest, the ROF-region as whole as well as other isolated systems.
  - If coupled with short term analysis software, the presented framework can contribute to the development of the technologies, provide improved cost estimates, and look into the deployment of other resources such as renewables.
- Provided the importance of the discount rate, the up-front capital is a major point of consideration for vendors (and operators). The differences in up-front capital between some of the SMR technologies are substantial. In order to be competitive, up-front capital should be as low as possible, or the risks minimized (lowering the discount rate).



## 10 | Recommendations

In recent years, research into SMR deployment has been carried out with numbers either justified by "in-house knowledge" or with a limited scope [2, 3]. The research at hand tried to verify past results by open-source data and provide a framework for future research. The author, based upon the conclusions and discussion, makes a number of recommendations.

In order to increase the validity of the results of this study, the author recommends to perform an in-depth analysis for the SMR technology with regards to their investment and operational costs for each considered system, to ensure more valid assumptions and results. One of the considerations is to perform a components-based analysis, if possible, as performed by Ding et. al. (2011) for the Urenco U-Battery. It is especially important to take into consideration the salvage values, which for the SMR technologies might provide substantial differences.

The same recommendations apply to the input parameters for the diesel gensets. While the deployment area will effect specific investment and maintenance costs, and differences between vendors should be considered, the values of this proven technology should be obtainable with a high amount of certainty.

Another consideration is the use of discrete commitment, in combination with the required peak power reserve. The use of this package will deliver a result better representing the total needed available capacity under all circumstances.

Additional improvements towards this specific study can be obtained by the use of additional commodity demand curves (for example heat). These additional demand profiles should ideally be defined per season and at an increased resolution. The increased quality data from the additional demand profiles would be able to better reflect the necessities of the region. This high quality data, can then be utilized for analysis with increased temporal resolution. In order to be able to use high resolution temporal data, the consideration should be made to use additional software for the sub-hourly time frame analysis.

Another consideration with regard to the demand side is to utilize a demand function, instead of the inelastic demands used at the moment. E.g. it can be expected that the price of diesel fluctuates with total volume (economies of scale), which will result in different model outcomes.

For future research expanding on the results of the present research, the author recommends the use of additional generation sources to offer a more extended energy mix. While this study merely focused on the disparities between the use of diesel and nuclear power, from a techno-economic perspective. However, no additional resources should be banned from the equation. The introduction of additional vendors and technologies, conventional, renewable and experimental, will only lead to a more comprehensive assessment of the different technologies and a well-considered energy system.

Important additional research should be performed beyond the scope of a mere techno-economic assessment. While economic numbers might warrant future research, that alone does not allow for future deployment. Legislative bodies, utilities and communities should be questioned regarding legislation and public acceptance, in order to be able to make the right decisions. While one technology on paper might be the best-performing on an economic level, that does not necessarily apply for licensing. A full assessment of each technology and its safety features has to be utilized in order to come to a decisive conclusion.

In conclusion, the author wants to provide the reader with some final words; "No technologies should be demonized based upon emotions and results from the past. In the development of a sustainable future, for both ourselves and the generations to come, mitigating both climate change and pollution should be our primary goal. Excluding any possible measures or promoting one single technology harms the pursuit of this goal. All technologies should be taken into consideration for the common good."

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# Glossary

**BAU** business as usual. 3, 38, 43, 45, 49, 51, 53, 56, 60

**BY** base-year. 82, 84

**CAPEX** capital expenditures. 12, 22, 34, 36, 39

**CF** capacity factor. 21, 59, 60

**CNL** Canadian nuclear laboratories. v, 29

**CNSC** Canadian Nuclear Safety Commission. 30

**DoD** department of defense. 30, 33, 34

**EFOM** Energy Flow Optimization Model. 78

**EIA** environmental impact assessment. 11

**EPA** Environmental Protection Agency. 23, 24

**ETSAP** Energy Technology Systems Analysis Programme. 78

**FESNS** Faculty of Energy Systems and Nuclear Sciences. v, vi

**FOAK** first of a kind. 1, 11, 33, 34

**GAMS** The General Algebraic Modeling System. 77

**GHG** greenhouse gas. 8, 77

**HTGR** high temperature gas reactor. 30

**IAEA** International Atomic Energy Agency. 27, 30, 35

**IEA** International Energy Agency. 78

**IPWR** integral pressurized water reactor. 30

**LACE** levelized avoided cost of energy. 12

**LCOE** levelized cost of energy. 12, 24, 45, 48, 49, 51, 56, 65

**LMCFR** liquid-metal-cooled fast-reactor. 30

**LTCPF** long-term carbon price forecast. 24

**LWR** light water reactor. 35

**MARKAL** market allocation. 78

**NOAK** Nth of a kind. 1, 11, 33

**O&M** operations and maintenance. vii, 23, 24, 34, 35, 38, 39, 40, 43, 83

**OEB** Ontario Energy Board. 24

**OECD** Organization for Economic Co-operation and Development. 78

**OPEX** operational expenditures. 12, 22, 36, 39, 43

**OSeMOSYS** Open Source Energy Modelling System. 64

**PGE** platinum group element. 15, 17

**PWR** pressurized water reactor. 30

**PyPSA** Python for Power System Analysis. 64

**QEC** Qulliq Energy Corporation. 23, 40, 41

**RES** Reference Energy System. 82, 84

**ROF** Ring of Fire. vii, 15, 17, 20, 65

**SMR** small modular reactor. v, 3, 7, 8, 9, 11, 12, 27, 28, 29, 30, 35, 38, 39, 43, 48, 53, 59, 62, 64, 65, 67

**TIMES** The Integrated MARKAL-EFOM System. 3, 11, 12, 23, 27, 34, 35, 38, 39, 40, 43, 48, 49, 51, 53, 56, 60, 61, 62, 63, 77, 78, 79, 80, 82, 83, 84

**VEDA-BE** Versatile Data Analyst - Back End. 40, 77

**VEDA-FE** Versatile Data Analyst - Front End. 40, 77

**VMS** volcanogenic massive sulphide. 15

**vSMR** very small modular reactor. v, 7, 9, 11, 27, 30, 33, 34, 48, 49, 51, 53, 56, 59, 60, 77

# A | The TIMES model generator

TIMES comes with an exhaustive documentation, which includes a full explanation of its underlying mathematical principles and a learning environment. Furthermore, it describes the organization of the TIMES modeling environment and The General Algebraic Modeling System (GAMS) control statements. The learning environment provides an introduction to the management software for the creation of the model (within the VEDA-FE) and the analysis of the results (within the VEDA-BE). The basic documentation is written by Loulou, Goldstein et al. (2016), and covers five parts [62, 63, 11, 64, 59]:

1. Part I - Provides a general description
2. Part II - Constitutes a comprehensive reference manual
3. Part III - Describes the organization of the TIMES modeling environment and GAMS control statements required to run the TIMES model
4. Part IV - Provides a step-by-step introduction to building a TIMES model in the VEDA-FE model management software
5. Part V - Describes the VEDA-BE software, which is widely used for analyzing results from TIMES models.

First, the usefulness of energy modelling will be explained in section A.1. Then, the short version of TIMES' history will be given in section A.2. Last, a summarized description regarding the TIMES-paradigm will be provided in section A.3.

## A.1 The usefulness of energy modeling

An energy model is a computer model of an energy system, recreating relevant aspects of its real-life counterpart in a simplified way in order to understand and analyze its processes. This allows for easier quantification, visualization and assessment of the system as a whole. As such, energy modeling provides means for the assessment and answering of complex questions. Subsequently, it makes energy modeling a diverse practice. Energy systems can be modeled on different scales and for different purposes.

Especially in energy systems, modeling is of increasing importance. With large scale utility projects often spanning multiple decades, a long term decision maker has to be well-informed. With rising global concerns regarding GHG emissions, increasing volatility in fossil fuel prices, and an increasing expectancy of a short-term return on investment, choices now can hold grave implications decades in the future for policy makers and utilities alike.

Within this study, the model is expected to quantify the financial and environmental impacts of possible vSMR deployment within the Eagle's Nest, while simultaneously providing the tools for (limited) technology assessment. This provides decision makers with the tools for informed priority setting and the creation of future mitigation measures, as the expected implications of vSMR-deployment can be quantified beforehand. In order to provide this long term analysis, the model

should be able to at least span the expected life-time of the Eagle’s Nest. TIMES, a proven model generator, was designed specifically for long-term energy system analysis.

## A.2 A (very) brief history of TIMES<sup>1</sup>

The very brief history of TIMES is summarized from the already short history of TIMES/MARKAL, written by Richard Loulou (2016) [11]. It provides insight in the development of the TIMES model generator, adding to the credibility of TIMES as a model generator and the preferred method for this research, especially for those who are unfamiliar with the TIMES-environment.

TIMES is an energy modeling framework, based upon the older market allocation (MARKAL) and Energy Flow Optimization Model (EFOM) frameworks. The creation of TIMES started with the decision by the International Energy Agency (IEA) to create a common tool for energy system analysis to be used the countries of the Organization for Economic Co-operation and Development (OECD). MARKAL became the first model generator to fulfill that role and was ready for use by the members of Energy Technology Systems Analysis Programme (ETSAP) by the year 1980. While MARKAL was used and evolved for over two decades, by the late 1990s, the necessity to gather all existing MARKAL features, and to create of new ones, led the ETSAP-community to the creation of TIMES[11].

Independently, EFOM was created in the 1970’s, when institutions had shown an increased interest in modeling as a direct result of the the first oil crisis. Governments required these models to quantify the interdependent effects of energy sector changes and were used to create mitigation possibilities (in the case of a new crisis). EFOM was created as an optimization model under restricted energy choices for the European Commission. It is a multi-period system optimization tool, based on linear programming, with the goal of minimizing the total discounted cost in order to meet the exogenously specified demand of a country. EFOM evolved into EFOM-ENV (for environmental), increasing its environmental capabilities, and as such it became a sister model within the MARKAL family of models. [65, 66].

When the necessity of new features and flexibility grew, TIMES was created from the the combination of MARKAL and EFOM. As MARKAL and EFOM encompassed the same modeling approach, the combination provided a more flexible and powerful tool [65]. At first, transition to TIMES proved slow, as many users had their databases tailored for use by MARKAL. Work however progressed and more features were added. After implementing a climate module in 2005 and the development of the first ”world multi-regional” TIMES model, ETSAP was able to participate in the Stanford Energy Modeling Forum, and conduct global climate change analysis. By the early 2010s, TIMES models were recognized as major contributors within the field of energy and climate change research, and the number of projects soared. Today it is estimated that MARKAL/TIMES is used by over 300 institutions in more than 80 countries, and is generally considered the benchmark integrated energy system optimization platform available for use around the world [11].

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<sup>1</sup>in commemoration of Professor Stephen Hawking (1942-2018)

## A.3 The core TIMES paradigm

This section will provide a description of the core TIMES paradigm, as described within chapter 3.2 of the documentation for the TIMES model, part I (2016) [11]

TIMES has one main goal [11]: ” TIMES aims to supply energy services at minimum global cost, or more accurately, at the minimum loss of total surplus.”

TIMES is a vertically integrated model of the entire extended energy system (from resources to emissions) and calculates its outcome by simultaneously making decisions on equipment investment and operation, primary energy supply, and energy trade for each region. The model is made up of producers and consumers of commodities, such as energy carriers, materials, energy services and emissions (e.g. industrial and residential heat demand, transportation, and CO<sub>2</sub> emissions and restrictions). As an example, when the heat demand within a model is expected to rise, TIMES can react in different ways. It can use current generating equipment more intensively or allocate more generation capacity, on the other hand, TIMES can also invest in alternative technologies on the demand side if the model is set up in the appropriate way. It is the user who provides TIMES with the existing stock of energy equipment and characteristics of technologies expected to be available in the future. The capacity to utilize future expected demand technologies illustrates the capacity of TIMES to extend beyond purely energy oriented issues [11].

TIMES assumes perfect market conditions between supply and demand (unless dictated otherwise by the user). Supply and demand are both treated as curves and the final answer is a supply-demand equilibrium defining the maximum net total surplus, within the (possible) constraints as given by the user. Features that can be introduced by the user, and in turn create an imperfect market, are called limitations. These limitations can influence technologies, stock or expected legislation (e.g. maximum amount of nuclear power, maximum amount of emissions and taxes or subsidies) [11].

The core mathematical models of TIMES are described by the following properties [11]:

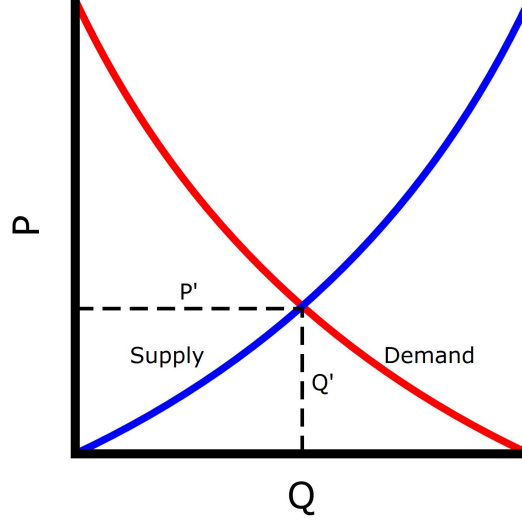
- Technologically explicit, integrated;
- Multi-regional (if required);
- Partial equilibrium (with price elastic demands for energy services) in competitive markets with perfect foresight. It will be seen that such an equilibrium entails marginal value pricing of all commodities.

### Technologically explicitness

Each technology is explicitly identified, and treated individually. Technologies describe every part of the energy system (procurement, conversion, production, processing, transmission, demand) for each individual region. The user can add or remove technologies at will, without having to alter the TIMES mathematical formulas, creating a (mostly) data driven program [11].

### Multi-regionality

Each TIMES model can encompass multiple regions, which can be seen as geographical areas of arbitrary size. These regions can be linked through the trade of energy and materials. This provides the possibility to establish a multi-regional model, creating more extensive ways to model



**Figure A.1:** Simple supply and demand curve. The quantity ( $Q$ ) on the  $X$ -axis is given against the Price ( $P$ ) on the  $Y$ -axis. [67]

energy policies over larger areas. A prime example is TIMES-Norway model, in which Norway is represented with different regions, one for each province [11, 1].

### Partial equilibrium

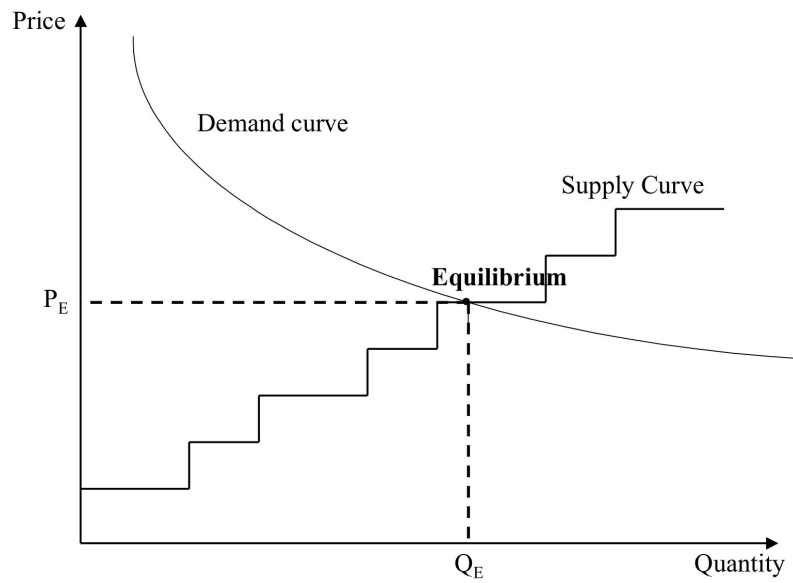
As a partial equilibrium model, TIMES can manipulate both the production and demand of commodities. In a perfect market, demand and supply can be visualized by two curves (given one requested commodity), as visualized within Figure A.1. These curves depict price ( $P$ ) on the vertical axis and quantity ( $Q$ ) on the horizontal axis. It is visible, and naturally expected, that with a low commodity price ( $P$ ) the will for suppliers to provide the commodity is low, while demand is high, explaining the gap between the two curves. As soon as demand  $Q$  and prices  $P$  are in equilibrium, the maximum economic surplus is reached.

While the curves presented in Figure A.1 are ideal, and therefore continuous in nature, this ideal supply and demand curve is practically impossible within an energy market. This is due to the fact that every increase in supply is dictated by either the same generating option, or a new supply option if the cheaper alternative is depleted. A generating option would be a real world power facility operating at its own marginal costs, which can ramp up and down production without varying costs for this additional or lesser production, creating stepped increments. This buildup of the total supply curve is called the merit order. An example of a stepped supply function is given in Figure A.2

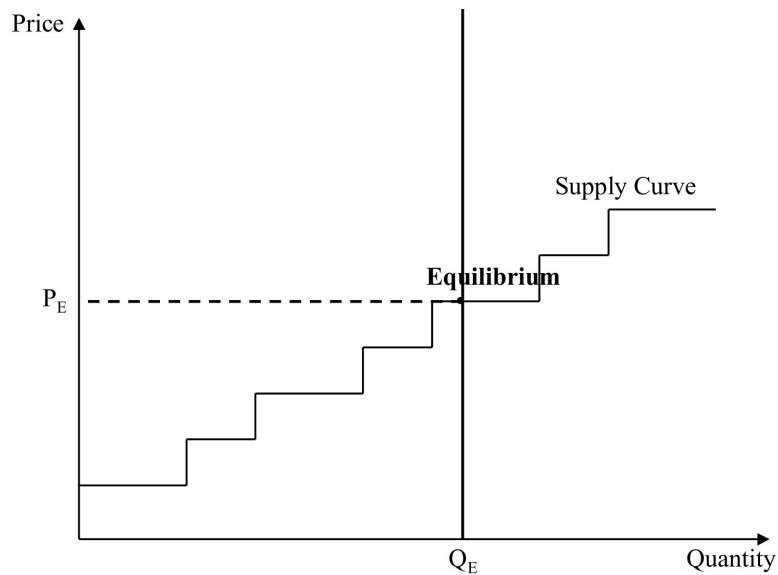
Within TIMES there are two demand curves possible. Either a smooth demand curve, as given by the user <sup>2</sup>. Or an endogenously created demand curve, which will become lumped. However, the demand curve can be almost straight, as energy demand can be an inelastic feature. Figure A.3 provides an visualization of a simplistic commodity (e.g. electricity) in which the supply is stepped, and the demand is inelastic and almost independent of the price.

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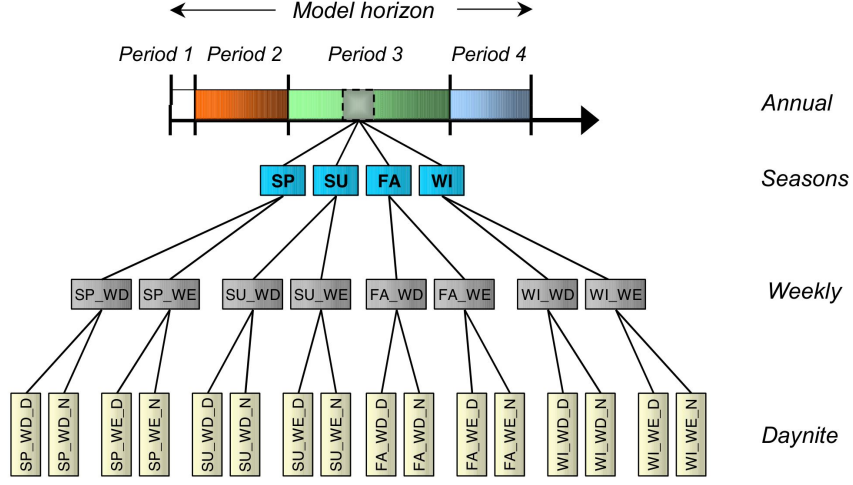
<sup>2</sup>A smooth curve will always become a stepped function, necessary for computational purposes [11].



**Figure A.2:** Every step is a generating capacity for the requested commodity. The width of the step is dictated by the constraints of the commodity, for example production capacity and/or resource stock limitations. [11]



**Figure A.3:** The merit order supply curve in combination with an inelastic demand curve. The inelasticity shows the demand being independent of the price[11]



**Figure A.4:** Time slices structure within TIMES [11]

### A.3.1 Time slices

As stated within section A.3, the demand section has to be defined exogenously by the user. The demand usually is provided in a demand curve, which changes over time, as energy demand is usually not a constant.

Energy demand changes per year (long term forecast for energy demand growth), season (the demand for heat is usually at highest during the winter), week (an vacation period usually sees a drop in demand) and day (weekends see a reduction in demand compared to weekdays).

By creating a discrete demand function, similar regions of the demand curve can be grouped. Each of these groups should use one time slice, describing the average demand. This creates the possibility to follow the demand curve within TIMES. The more time slices TIMES uses, the more accurately the demand curve can be approximated.

The time slices within TIMES are given on the annual, seasonal, weekly or daily level. However, any arbitrary amount of time slices is possible. An example of the time slices structure is given within Figure A.4

### A.3.2 Regions

Any TIMES model is filled by independent regions. Regions can be defined due to geographical boundaries, different policies, or other decisive factors. Regions however can interact by direct trade, as provided by the user.

Any region is represented by a Reference Energy System (RES). This RES provides a full oversight of all energy production and demand during the base-year (BY) of the model.

Regions can be defined by completely independent of other regions within a model, having its own internal processes, generating capacity and legislation. New processes can be defined either for all or per individual region.

A region also houses domestic energy sources, such as oil or gas. These resources can be quantified and expressed in production costs. The possibility exists to create the same reservoir with different prices, as one might assume that initial production of an oil field can be done at lesser expenses than advanced production at the end of life of an oil field.

### A.3.3 Cost assumptions

For the calculations within TIMES, specific values for each process are required. For energy related processes, there are three main economic values which are relevant:

1. Specific investment cost
2. Fixed O&M costs
3. Variable O&M costs

These values, combined with the resources needed for a process to function (e.g. fuels), will compute to the total cost of a process over its intended lifetime.

### A.3.4 Scenario's

TIMES is an applicable tool for the analysis of different possible energy futures. Each future would be represented by a unique scenario. As TIMES can model over long term horizons, econometrics would become unusable, leaving scenario's as the only option.

Scenario's differ from forecasts in the way that they do not assume foresight. They rely on a set of well *coherent assumptions* to drive the model. A scenarios is build with four types of input:

- Energy service demand curves
- Primary resource supply curve
- Policy setting
- The descriptions of a complete set of technologies

The energy service demand curves are created from the combination of drivers (e.g. population growth) and on the elasticities of the demands to the drivers and its own prices.

$$Demand = Driver^{Elasticity}$$

Primary resource supply curves consists of the stepped wise representation of the potential and availability of a resource at any given price. This amount can be given as a cumulative potential. A cumulative potential is usable in the case of fixed possible reserves, such as for fossil resources, but can also be used to map geographical constraints, on for example the available space for renewable production. Trade is also covered within the supply curve component of a scenario.

Policy setting are user defined constraints on the energy system. Policy can be defined on a micro measure level (e.g. defining portfolios or specific subsidies) or on a macro level (e.g. a broad carbon tax).

Finally, the descriptions of a complete set of technologies provides the techno-economic component of a scenario. Technologies describe all processes (converting energy resource into energy service). By providing different technologies and cost assumption into the future, TIMES forms a far more sophisticated development profile for each scenario.

As an example, a scenario can create the introduction of a carbon tax from any given year, or dictate a cap on a technology or investment. It is from within these scenarios where the flexibility of TIMES can be found. As soon as a model is created, it can be easily manipulated to assess different scenario's. This creates a possibility for priority-setting for all stakeholders.

### **A.3.5 Calibration**

After the TIMES is given the values for each technologies, it is important to calibrate the system. Calibration lets the user check if the values that are given to times produce answers that apply to the real world. Usually, this process is done through the calibration of the model to the BY. Through tweaking variables, such as the AF, the user tries to replicate the BY-outcome. Especially in systems with smaller time slices and more detail, calibration can be a tedious, but important, process, as it defines the validity of the model. Calibration is usually done through the use of an RES

### **A.3.6 Trade**

Trade is a parameter that allows interaction between different regions, or the "world" (then called import/export). Trade is characterized by a possible cap and import and export prices.