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Preface

This Master thesis was written during the spring semester of 2023, and concludes our Master degree in Industrial Economics at the University of Stavanger. Through our studies at the University we both discovered a strong interest in commodity markets thanks to subjects we attended along the way. The growing global focus on energy security and the technical processes involved in Uranium enrichment made this market our preferred focus of study. This process is highly technical, and therefore in our opinion also suitable for a thesis in Industrial Economics. Researching and writing this thesis has been challenging, but also highly rewarding. We have gained many valuable insights into the Uranium market, many of which we believe are transferable to commodity markets in general.

We would like to thank UxC LLC for allowing us access to their proprietary historical price data. The data is robust and extensive, and without it this thesis would not be the same. The Uranium market is opaque, and price data is often hard and expensive to access. As such, we are thankful for the generosity shown to us as it provides us with an opportunity to re-examine this commodity market with a novel approach.

We would also like to thank Ruth Beatriz Pincinato for the guidance she has given us. Her expertise and advice have both made us rethink our approaches, as well as given us confidence in our work and methodology.

For the convenience of the readers, we would also like to mention that this thesis is written in Latex. Because of this, acronyms, references to tables, figures and equations are linked and can be used to navigate the document when read digitally. We hope that you will find our work and results to be intriguing, and hopefully motivate you to expand on our work.

Stavanger, 15.06.2023.

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Rick Rule, legendary natural resource investor on Uranium:

"Either the price goes up, or the lights go out."

Abstract

In this thesis paper, we model price reactions to demand shocks for Uranium Oxide, U_3O_8. We argue that these demand shocks will emerge from operational decisions regarding the enrichment of Uranium for use in nuclear reactors, and that the ensuing price reactions should range from significant to extreme. In our calculations we employ the Equilibrium Displacement Model (EDM) to calculate how the endogenous variable $\%\Delta P$ changes as a result of demand shocks for U_3O_8, created by price increases for our exogenous variables. The exogenous variables are prices of the services that are required in the enrichment process, namely Conversion and Separative Work Unit, (SWU). The demand shocks we modeled, result from calculations of the December 2022 profit maximizing quantities of these services and U_3O_8. The calculations are based on recent market prices and potential future supply and demand scenarios.
The research aim of this thesis is to determine the magnitude of the increases in price for U_3O_8 caused by these exogenous variables in current, and possible future states of the Uranium market. Furthermore a secondary aim of the research is to determine whether or not the price reactions predicted by the EDM are supported by the fundamentals of the Uranium market.

The results in this thesis are derived primarily from the economics of Uranium enrichment, and focuses on the processes and costs required to enrich and produce Low Enriched Uranium, (LEU) for fuel fabrication. We begin by analyzing historical price data supplied by UxC LLC, and calculate the costs associated with enriching U_3O_8 at various tails assays. The purpose of this, is to quantify likely and possible demand shocks arising from the primary assumption of this thesis; That enrichment companies as well as utilities seek to maximize their profits by amongst other approaches, minimizing their fuel costs. In addition to the demand shock resulting from this strategy, we also determine other potential shocks to demand, based on a background and literature review. These demand shocks served as inputs into the EDM, with which we calculated price reactions to these shocks.

This thesis models three separate demand scenarios, one based on the current state of the market and two based on possible future states. The results for the most likely scenario show the price for U_3O_8 increasing to levels that should incentivize the expansion of mine capacity to sustainable levels. Currently this capacity is incapable of producing enough material to support neither the current, nor the future fleet of nuclear reactors. In the case of the two hypothetical scenarios the research show price reactions surpassing historical highs. Although some of the price-levels predicted by our research has never been seen, our research suggests they still could occur in the form of partial equlibria in the short term, and highly profitable levels for miners in the long term. When comparing our results to recent price increases for other industrial minerals and energy commodities like Lithium Carbonate and Gas, the results for these scenarios seem less extreme. Finally, based on the price data from UxC, we were also able to determine a theoretical crossprice-elasticity of demand for U_3O_8 in relation to SWU.

The implications of our research are clear. For extraction capacity to be able to meet the quantity requirements of both the current and future reactor fleet, price for U_3O_8 must rise significantly from the December 2022 levels. Due to the long lead-times and the high capital requirements for mining projects, this increased price must be reflected in long-term contracts signed with mining companies. Furthermore, the magnitude of committed purchases of U_3O_8 must be expanded if reliable supply of the mineral is going to be avaliable for the reactor requirements in the future.

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Acronyms

ATH	All Time High.
COGS	Cost of Good Sold.
EDM	Equilibrium Displacement Model.
IAEA	International Atomic Energy Agency.
IMF	International Monetary Fund.
LCOE	Levellized Cost of Electricity.
LEU	Low Enriched Uranium.
LWR	Light Water Reactor.
NEA	Nuclear Energy Agency.
SWU	Separative Work Unit.
UxC	UxC LLC.
WACC	Weighted Average Cost of Capital.
WNA	World Nuclear Association.

1 Introduction

Nuclear reactors provide a considerable amount of the global share of base-load electricity generation, and the number of reactors is set to expand at an accelerating rate in the coming decades. At this time there are increasing numbers of reactors under construction as well as expansive plans for future programs (World Nuclear Association [WNA], 2023b, sec. 1). Furthermore, in response to the Russian invasion of Ukraine and the ensuing energy crisis, energy policy is changing in what has been described as a nuclear renaissance. Several countries, like Japan, have decided to extend the lifetimes of their operating reactors and are currently restarting reactors that have been shut down (Reuters, 2022, sec. 1).

In order to be able to generate electricity, nuclear reactors require fuel which is almost exclusively made using U_3O_8. Today, practically all of the supply of U_3O_8 comes from mining operations (Nuclear Energy Agency [NEA], 2020, p. 66) as these are the only financially viable options at the current market price for the commodity (WNA, 2023a, sec. 1). The supply of U_3O_8 is therefore constrained by the cost to produce it and the market price, which we will show has been depressed for over a decade. This has resulted in mine closures and an investment drought in new capacity (NEA, 2023, p. 94). To incentivize increased production of U_3O_8, prices must rise (NEA, 2023, p. 95). Nuclear power is already important for global energy markets, and the future planned expansions of nuclear generation capacity is significant. This should increase the importance of, as well as our reliance on the availability of U_3O_8.

Before U_3O_8 can be used as fuel for nuclear reactors it must first be gassified and enriched, which require specialized services. Due to the physics of current enrichment technology, the inputs and services in the enrichment process can be varied in quantities and still produce the same amount of enriched uranium. This is in turn used in the final step of fuel fabrication. One can either choose to increase the amount of Uranium in the centrifuges, or increase the amount of enrichment work that is performed on a smaller amount of Uranium. Because of this there will always be a combination of quantities of U_3O_8 and these services that result in the least expensive reactor fuel. As we demonstrate in this thesis, the prices for conversion and enrichment services has risen significantly in 2022. Because of this we believe a change in pricing for U_3O_8 is coming, as less of the services are demanded in a profit maximizing strategy.

Our data and calculations show that in late 2022 the profit maximizing combination of inputs for making LEU favours increased demand for U_3O_8. This is a result of increased amounts of Uranium needing to be fed into centrifuges at enrichment facilities, as enrichers seek to maximize profits by decreasing their expenses on enrichment services. The operational decision causes a shock to demand for U_3O_8 that should exert upwards pressure on the price for the commodity. In a commodity market such as the one for U_3O_8 which is slow-moving, and the lead times between investment and production are substantial, the resulting price action can be violent.

In economic theory, price is determined in the intersection between the supply- and demand-curves. When one of these are shifted,a as we believe is the case for the demand curve for U_3O_8, equilibrium displacement models can be used to calculate the expected price responses resulting from the shocks. Based on this, we will in this thesis answer the research question:

> ***Which changes does the Equilibrium Displacement Model suggest will occur in the price of U_3O_8 in response to the identified demand shocks, and are market fundamentals supportive of these price changes?***

To answer the research question this thesis will explore three demand shock scenarios for uranium and calculate the predicted price responses using the EDM.

- The resulting demand shock should enrichers choose to overfeed at the December 2022 optimal tails assays. The resulting S_D of 10.83% is due to operational tails assays increasing from 0.14% to 0.20%
- The resulting demand shock should enrichers choose to overfeed at historical high optimal tails assays. The resulting S_D of 19.09% is due to operational tails assays increasing from 0.14% to 0.24%
- A loss of Russian enrichment capacity, forcing operational tails assays up due to constrained SWU supply. The resulting S_D of 34.52% is due to operational tails assays increasing from 0.14% to 0.30%

Previous research on price dynamics in the Uranium market has been focused on estimating future prices for the commodity, but as far as we could find these have all been based on simulated system dynamics models. Authors Kahouli and Considine created these models, and to quantify demand for U_3O_8 they both used functions of installed capacity to determine reactor requirements. Our research on the other hand, uses recent market prices to calculate the profit maximizing quantities of U_3O_8 and the services required for enriching U_3O_8 used in nuclear fuel fabrication. These profit maximizing quantities are what cause the demand shocks modeled in this thesis, and it also represents the novelty of it. Additionally, we also present an estimate of the cross-price elasticity of demand for U_3O_8 in relation to the price of enrichment capacity, something we have not been able to find in published research.

Our research relies heavily on historical price data supplied to us by UxC LLC however, the time horizon of this data ends in December of 2022. As such, the current prices for Conversion and SWU may have changed from the last data-points we have access to. Spot prices for U_3O_8 are more transparently reported through open sources and as such we know that this price has yet to experience the appreciation that the EDM proposes in our research. Due to the opaque nature of this market, a delimitation for this paper is that we will only consider price data ending in December 2022. Furthermore, the time constraints for the Master thesis made us limit the research to only employ one model for calculating price responses to the demand shocks. This is another delimitation of our thesis.

Before presenting our results, discussion and conclusion we will explain concepts and theory that are essential to understand the results, starting with a background chapter. The uranium market is not broadly known and the nuclear fuel value-chain is complex and technical. This paper uses terminology and concepts specific to the Uranium market and its various industries. The research question itself arises from one of the processes in the nuclear fuel cycle, and therefore we believe a fundamental understanding of this process is necessary. For this reason we have spent considerable time to explain the concepts necessary to understand our results and discussion.

2 Background

The uranium market is the global market for the production, sale, and trade of uranium, which is a naturally occurring radioactive element used primarily as fuel for nuclear reactors. The demand for uranium is primarily driven by the use of nuclear power plants to generate electricity (NEA, 2023, p. 100). The uranium market is characterized by a relatively small number of producers, with the majority of global supply coming from a handful of countries such as Kazakhstan, Australia, Namibia and Canada (NEA, 2023, p. 77).

This chapter is a chronological presentation of the milestones in the development of the Uranium market. It is intended as a brief introduction to the origins of the Uranium market, and aims to bring the reader up to speed on the market as well as its current state. Furthermore we will explain important terms and topics from the nuclear fuel cycle to the extent necessary to answer the research question of this thesis, as well as aid in the readers understanding of what is a topic that has not garnered much attention from the commodity-focused academic writing of late.

2.1 Development of The Uranium Market

The foundations for the Uranium market emerged as a consequence of military weapons research during the later phases of World War 2. In The 1960s civilian use-cases for uranium, mainly its potential for production of electricity was developed, leading to a significant increase in demand which was followed by an even larger increase in production. This caused prices for Uranium (U_3O_8) in the 1980s to decline below production costs, forcing producers to lower production. The spot price of U_3O_8 later recovered from 2003 to 2008 but has since experienced a prolonged period of lower prices (WNA, 2022d). In the following years the demand for nuclear power has fluctuated along with public opinion, which has been significantly impacted by reactor accidents like the ones in Three Mile Island(1979) and Fukushima(2011). Public opinion has been mirrored in governmental policies, resulting in the decommissioning of multiple reactors. These policy changes have resulted in stagnant growth for nuclear power generation capacity, and an oversupply of uranium. This has for a prolonged period resulted in sustained low uranium prices and reduced investments in new mining projects as well as shutdowns of existing mines.

The Russian invasion of Ukraine on the 24th of February 2022 and the following developments in global energy markets has preceded changes in policies regarding nuclear power. The ongoing global energy crisis has demonstrated the need for reliable base-load energy generation, and energy security is now guiding many countries in their energy policies. From slowly shutting down reactors from 2009 several countries have now invested in, restarted and extended the lifetime of their reactors (Reuters, 2022, sec. 3). Furthermore, an increasing number of new capacity is being planned. More and more environmentalists and governments are beginning to see nuclear power plants as the fastest and only solution to carbon neutrality as well as meeting their increasing energy demands(Berliner, 2022, Sec. 1).

The market for Uranium, and the services required to transform the naturally occurring element into usable reactor fuel is highly complex. Supply, demand and price dynamics in the market result in shifting prices for U_3O_8, its intermediaries and the services required to process it into fuel. For the remainder of this chapter we will explain in further detail what these products and services are, and which roles they play in the nuclear fuel cycle.

2.2 Nuclear Fuel Cycle

The International Atomic Energy Agency describes the nuclear fuel cycle as:

> "[...] an industrial process involving various activities to produce electricity from uranium in nuclear power reactors. The cycle starts with the mining of uranium and ends with the disposal of spent fuel and other radioactive waste" (International Atomic Energy Agency [IAEA], 2018, p. 2).

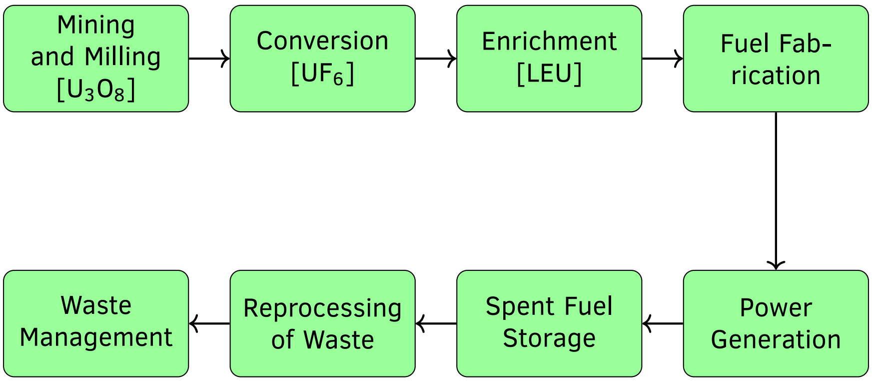

Figure 1: The Nuclear Fuel Cycle

One might also include other operations in the fuel cycle such as exploration, that is drilling and analyzing samples for their content of natural Uranium. The International Atomic Energy Agency does however not include exploration, and by their definition the fuel cycle is as described in figure 1. In this paper we will focus on the parts of the fuel cycle which affect the pricing of U_3O_8, namely mining, conversion, enrichment and nuclear power generation.

2.3 Mining and Milling

Mining and Milling, henceforth referred to as mining, is the process of extracting natural Uranium from solids. Uranium is a relatively common metal in nature and can be found is most rocks, solids, and even in rivers and seawater. Its abundance in nature is approximately 500 times that of Gold, but even though it is a common metal the concentration and economic feasibility of extraction varies widely around the world. Uranium is generally extracted either by traditional mining or a process known as "in-situ leaching". After purification of the extracted material both methods result in "Yellow-Cake", a powdered form of U_3O_8 with a Uranium concentration of over 80% which is later transported to a conversion facility (IAEA, 2018, pp. 2–3).

2.4 Conversion

Although some nuclear reactors do not require enriched uranium fuel, the vast majority of reactors do (IAEA, 2018, p. 4). In order to achieve this by current enrichment technology, the Uranium is needed in a gaseous form.

At conversion facilities, the Yellow-Cake is converted to Uranium Hexaflouride (UF_6) which is a gas at relatively low temperatures, but is cooled to a solid for transport to an enrichment facility (IAEA, 2018, p. 4). After arriving at an enrichment facility, the solid UF_6 is reheated to a gas and fed into centrifuges, where the enrichment process is performed.

Conversion is a service supplied from specialized facilities and there is a fixed total capacity for this service globally. A scarcity of conversion capacity can act as a barrier to overfeeding, as enrichers are unable to acquire UF_6.

2.5 Enrichment

Isotopes of the same element share many of the same chemical properties, but due to the isotopes not having the same number of neutrons in their nucleus, their mass and physical properties differ(IAEA, 2023, sec. 3). Critical for nuclear fission power generation is the fact that the isotope ^{235}U is highly fissile, and it can sustain a nuclear chain reaction

Natural Uranium consist mainly of two isotopes, approximately 99,3% ^{238}U and approximately 0,7% ^{235}U. Of these two isotopes, ^{235}U is the main driver of the Nuclear Fission process, and since modern reactors require fuel with a ^{235}U concentration of between 3 and 5% the proportion of this isotope needs to be increased through the enrichment process (IAEA, 2018, p. 5). This level of enrichment is usually referred to as Low Enriched Uranium, or LEU and is what most modern reactors use. Modern enrichment facilities accomplish this by feeding UF_6 gas into centrifuges which spin to separate parts of the ^{238}U from the mix, until the concentration of ^{235}U reaches the desired level. Historically Gaseous Diffusion has been another process used for uranium enrichment, but due to rising costs of electricity this process is no longer economically competitive with centrifuge technology(Rothwell, 2009, p. 6). Once the enrichment process is complete, the Uranium can be formed into fuel rods and shipped to a nuclear reactor for power generation.
Enrichment facilities are usually owned and operated by private companies like *Urenco* and *Rosatom*, who sell enrichment capacity to the market in the form of Separative Work Unit.

2.5.1 Separative Work Unit

Separative Work Unit, or SWU is the standard unit of measure for the enrichment effort to separate the isotopes ^{235}U and ^{238}U(Urenco, 2023, sec. 1). Each enrichment facility has a fixed SWU capacity, and as such this is a good which appreciates and depreciates in price as a function of supply of and demand for enrichment. SWU can be sold as a service to buyers, or be an internal cost for the enrichers when they are contracted to produce specific amounts of LEU. In this case, the internal cost is related to electricity costs as modern gas centrifuge plants require approximately 50 kWh per unit of SWU(WNA, 2022b, sec. 4).

2.5.2 Tails Assays

Buyers of enrichment capacity can specify several terms in the contracts they sign with enrichment companies, one of them being the tails assays. This number specifies the amount of ^{235}U left in the remaining UF_6 material after the enrichment process is complete, and the enriched uranium has been extracted. Lately enrichers have likely operated with tails assays of 0.14%. Enrichment facilities can operate at different operational tails assays than what contracts stipulate, but the contractual tails assays determine the amount of uranium supplied to the enrichment facility by the client.

2.5.3 Enrichment Economics

Utilities contract enrichers to produce specific amounts of LEU at contractual tails assays. In order to produce a certain amount of LEU an enricher can vary either the amount of feedstock in the form of UF_6, or the amount of SWU(Urenco, 2023). A lower amount of feedstock requires more separative work to be performed on the gas in order to separate enough ^{238}U and the resulting tails assays will be low. Another choice is to purchase more feedstock for enrichment, use less SWU and have higher tails assays when producing equal amounts of Low Enriched Uranium. The total cost to produce the resulting LEU will be a sum product of amounts and prices for U_3O_8, UF_6, conversion services, and energy for SWU. From a profit seeking perspective, enrichers will maximize profits by minimizing total costs of producing LEU. These two strategies of enrichment are often referred to as *underfeeding* and *overerfeeding*.

2.5.4 Underfeeding

When an enrichment facility is underfeeding, its operational tails assays are lower than the contractual assays. This is logically performed when SWU is inexpensive and supply of SWU is not constrained. Underfeeding results in enrichers building inventory of uranium either in the form of UF_6 or LEU which they can sell on the spot market, creating secondary supply of uranium (NEA, 2020, p. 103).

A practical example of underfeeding can be:

- An enricher has signed a contract to deliver X amounts of LEU, at Y tails assays. This means that the client supplies a certain amount of uranium, and the enricher will have to spend a certain amount of SWU in order fulfill the terms of the contract.
- If SWU capacity is either abundant or inexpensive, or a combination of both this presents an opportunity for profit.
- The enricher chooses, from a profit maximizing perspective to operate at operational tails assays lower than specified by the contract. SWU is in this case abundant and cheap, and the capacity should therefore not be left idle.
- The choice of underfeeding allows the enricher to produce the contracted amount of LEU by using more of a cheap and abundant recource in SWU, while having to use less of the uranium supplied by the client.
- As a by-product of underfeeding, the enricher ends up with excess inventory of uranium which can be stored, sold or enriched and sold as LEU on the spot market, increasing profits and secondary supply.

2.5.5 Overfeeding

The process of overfeeding is when operational tails assays are higher than contracted, resulting in increased demand for uranium as enrichers must purchase additional material apart from what was supplied by the utilities. Overfeeding can be a profit maximizing strategy if internal costs of SWU are high, or the available capacity is limited.

The practical example of overfeeding would be the opposite of underfeeding. If the internal cost of SWU is high or supply is constricted, the enricher can choose to purchase additional uranium feed-stock and run the plant at operational tails assays higher than contracted. This will produce the contracted amount of LEU, but can be financially beneficial to the enricher due to lower total SWU costs. If enrichers choose to overfeed, secondary derived demand for U_3O_8 emerges.

2.6 Nuclear Power Generation

The operation and principle of a nuclear fission power plant is a complicated balance of physics, and is in no way simply explained. For the purposes of this thesis however, a deep understanding of the physics behind this process is not required. For our usage, we can view nuclear power generation as a process where nuclear fission creates heat. This heat is used to turn water into steam, which again drives a turbine that generates electricity.

3 Literature Review

In this chapter we present a thematic literature review of the uranium market. The aim is to review existing research and statistics that contain relevant findings four our research question. The scope of the review includes Uranium market trends, elasticities and shocks. Supplemented with the latest changes regarding supply and demand.

3.1 Studies and research

Various measures of quantities are used in the uranium markets. When referring to mining and trade of U_3O_8, pounds, tonnes U_3O_8 or tU_3O_8 are often used. In terms of conversion, enrichment and reactor requirements, tonnes of Uranium, or tU is commonly used in the sources we have reviewed. For clarity, equation (1) describes conversion between these measures (WNA, 2023b, sec. 3).

$$1\ kgU = 1.1792\ kg\mathrm{U_3O_8} = 2.6\ pounds\ \mathrm{U_3O_8} \tag{1}$$

3.1.1 Primary supply and demand for U_3O_8

According to the World Nuclear Association, global production of U_3O_8 was 56 995 Tonnes in 2021 (WNA, 2022e, sec. 1) while at the same time, the total installed capacity of nuclear fission power plants required 73 698 Tonnes of U_3O_8 to fill their fuel requirements. Resulting in a net primary supply deficit of 16 703 tonnes U_3O_8 (WNA, 2023b, sec. 3). A deficit in this range has existed since 2018, as primary production of U_3O_8 has not been able to meet the yearly reactor requirements(NEA, 2023, p. 76). Low market prices for U_3O_8 has caused many mines to be shut down or idled, starting before 2018 and continuing through 2020, resulting in a net decrease of primary supply (NEA, 2023, p. 94). The deficit has likely been met by secondary supply like inventories and underfeeding. The quantity demanded of U_3O_8 is derived from the amount that the global fleet of reactors expends each year. In terms of LEU, a typical 1GW Light Water Reactor requires approximately 27 tonnes of enriched Uranium (Marques, 2010, p. 3).

As of January 2023, reactors currently under construction accounts for an increase of 16.3% in the generation capacity compared to the operational fleet (WNA, 2023b, sec. 1). Some of the currently operational reactors were planned to be shut down, but a significant portion of these have recently had their lives extended which effectively limitis the negative demand-effect for U_3O_8 (Reuters, 2022, sec. 1).

If prices for U_3O_8 are low, or utilities are not entering into sufficient long term contracts, it is reasonable for mines to be idled. In such market conditions, low cost mines like Cameco's McArthur River can still be restarted when conditions are favorable, as it did in November of 2022 (Cameco, 2023, p. 13).

The increase in market prices for U_3O_8 from 2020 to 2022 will likely have caused low-cost idled mines to have been restarted. Even so, during the previous five years the amount of contracted production of U_3O_8 has been cumulatively outpaced by what reactors have spent by 345 million pounds (Cameco, 2023, p. 15). These types of long-term contracts are important for mining companies in their decision regarding restarting mines or investing in new ones.

Supply and demand data - 2021	
Primary mine production [U_3O_8] (WNA, 2022e, sec. 1)	56 996 Tonnes
Reactor demand [U_3O_8] (WNA, 2023b, sec. 3)	73 698 Tonnes
Capacity growth[GW], reactors under construction (WNA, 2023b, sec. 1)	16.3%
5-year trailing contracted deficit[U_3O_8] (Cameco, 2023, p. 13)	132 692 Tonnes

Table 1: Various supply and demand data - 2021

3.1.2 Secondary sources of supply of U_3O_8

A number of different sources of supply is required to meet the demand for Uranium, the largest of which is primary mining of U_3O_8. The supply gap separating primary supply and demand from reactors has for several years been filled by secondary sources of uranium. This secondary supply is primarily comprised of stockpiles, down-blending of weapons-grade plutonium, reprocessing of spent fuel, underfeeding and re-enrichment of depleted tails (NEA, 2020, p. 94). These secondary sources of supply can have significant implications in volume but are however, economically viable at different price levels (Rooney, Nuttall & Kazantzis, 2015, p. 2).

Re-enrichment of depleted tails can be placed in a separate category. Depleted tails require enrichment in order to reach the concentrations of ^{235}U necessary for nuclear fission reactors. The result of this is that this source of secondary supply is only relevant and economically viable when spare enrichment capacity is available and operating costs of enrichment are low (NEA, 2020, p. 102). Underfeeding is another source of supply that logically disappear when enrichment capacity is limited or costly, as we will explain later in this thesis.
Recycling and reprocessing of spent fuel is an expensive process that requires specialized conversion and enrichment facilities. Currently this secondary source of supply stands for only 1% of annual consumption and is only produced in France and Russia (NEA, 2020, p. 100).
That leaves two major sources of secondary supply identified by the Nuclear Energy Agency; stockpiles and down-blending of weapons-grade plutonium.

Between 1950 and 1990, production of U_3O_8 exceeded demand due to lower than expected growth rate of nuclear generation as well as large quantities being destined for strategic inventory. Since then the situation has been reversed, with demand outstripping primary supply and the resulting inventories are declining. The theoretical maximum amount of remaining U_3O_8 equivalents was approximately 500 000 tonnes in 2020. These volumes are split between military strategic stockpiles and civilian inventory, however it is uncertain how much of these inventories that are available for purchase on the spot-market (NEA, 2020, p. 97). The numbers for theoretical global inventories of U_3O_8 equivalent are significant, and if they are available for sale this source of supply could prevent any significant divergence of supply and demand. The inventories, though significant have been declining for decades. In recent years, the emergence of financial entities like Sprott Physical Uranium Trust and Yellowcacke PLC have removed approximately 80 million pounds of U_3O_8(Sprott Inc., 2023) (Yellowcacke PLC, 2023, p. 1). Furthermore the USA, as well as other entities have begun rebuilding their strategic reserves of uranium (Energy Fuels INC, 2022).

Down-blending of weapons grade plutonium was conducted both in the US and Russia following an agreement between the two nations in 2000, however the projects in both countries have since been terminated (NEA, 2020, p. 102).

3.1.3 Supply of Conversion services

Conversion, is the industrial process of converting U_3O_8 into UF_6, which is necessary to be able to enrich Uranium with current technology for use in nuclear fission reactors (IAEA, 2018, p. 4). According to the World Nuclear Association, the global capacity for conversion services was 62 000 tU in 2020. The capacity is split between several countries as shown in Table 2 (WNA, 2022a, sec. 1).

2020 Global Conversion capacity [tU] (WNA, 2022a, sec. 1)		
Country	**Company**	**Capacity**
France	Orano	15 000
China	CNNC	15 000
Russia	Rosatom	15 000
Canada	Cameco	12 500
USA	ConverDyn	7 000
	Total	62 000

Table 2: 2020 Global conversion capacity

Of the capacities listed in Table 2, the ConverDyn facility has been idled since 2016, but will resume operation in 2023. Furthermore, Orano's capacity will not reach full capacity until their new facility is operational, which is expected to be in 2023 (WNA, 2022a, sec. 1).

3.1.4 Supply of SWU

In 2020 the total operational and planned enrichment capacity of the world was 60,1 million SWU, with capacity stipulated to grow to 62,3 million SWU by 2025. Of this capacity, as can be seen in Table 3, Russia controls approximately 46% of the global capacity (WNA, 2022c).

Enrichment capacity [000' SWU] (WNA, 2022c)		
Country	**Company**	**Capacity**
Russia	Rosatom	27 700
Germany, Netherlands, UK	Urenco	13 700
France	Orano	7 500
China	CNNC	6 300
USA	Urenco	4 900
Rest of World	Various	66
	Total	60 166

Table 3: 2020 Global enrichment capacity

Supply of enrichment capacity is a fixed number, as it describes the total amount of seperative work that can be performed. Demand though, is not quite as simple to describe as the total amount of SWU demanded is relative to the amount of Uranium that is fed into the enrichment plants. This is due to the fact that the required amount of separative work increases, as the concentration of ^{235}U decreases.

Russia controls a significant part of global enrichment capacity, and following the Russian invasion of Ukraine attempts to assert political pressure through restrictions on energy imports and exports have affected petroleum and gas markets. To this date, such restrictions on products in the nuclear fuel cycle have not yet occurred but they are a possibility. We will not discuss geopolitics in this thesis, but import bans such as the "Reduce Russian Uranium Imports Act"

(Senate Comittee on Energy & Natual Recources, 2023) could severely affect the availability of SWU, should they be voted in. Whether or not these types of bills will be accepted is not in the scope of this thesis but there seems to be some risk of Russian SWU capacity becoming unavailable to many countries, whether due to bans of their own creation, or as a result of Russia limiting exports.

3.1.5 Market dynamics

Simulations conducted by Kahouli in 2011 determined that a 1% increase in the price of U_3O_8 results in a decrease in demand of 0.039%. This equates to a short-run price elasticity of demand, E_D = 0.039, while the long-run elasticity of demand was determined to be E_D = 0.066 (Kahouli, 2011, pp. 10–11). This inelasticity for E_D was supported by Considine on page 7 of his 2019 study ‘The market impacts of US uranium import quotas’. Considine also determined price elasticities of supply, E_S for the US and the rest of the world at 1.35 and 1.578 (Considine, 2019, p. 8). Kahouli determined E_S to be 0.06 in the short-run and 0.153 in the long run (Kahouli, 2011, p. 10).
The figures for price elasticities of supply and demand in the studies conducted by both Kahouli and Considine have been determined by simulating the Uranium commodity market. Due to the opaqueness of this market, determining elasticities by use of observations may have questionable validity, and we therefore believe simulations to be a beneficial method of estimating these variables. We do however, tend to favor the figures estimated by Kahouli. Neither Kahouli nor Considine specify a definition for short-run and long-run when discussing elasticities, and thus we default to the definitions from *Agricultural Product Prices* described in the theory chapter.

In all mining projects, there is a significant time-lag between an investment decision and mine production. This should intuitively limit the extent to which supply can react to upward trends in price of U_3O_8 in the short- and medium term. Especially in the time-frames where the prices that caused the investment decision to be made remain elevated. We therefore utilize the estimates made by Kahouli in our Equilibrium Displacement Model.

Due to the global nature of the commodity market for U_3O_8, we would expect demand for the commodity to be influenced not only by developments internal to the nuclear fuel cycle. Furthermore since it is a commodity used for energy generation, it seems likely that demand for U_3O_8 is also influenced by the price dynamics of other energy commodities like oil, gas and coal. Kahouli investigated these effects in her 2011 paper, and determined the crossprice-elasticity of U_3O_8 to price changes for coal to be 1.025 in the short-run and 3.439 in the long run (Kahouli, 2011, p. 11). Kahouli also investigated how price changes for oil affected demand for U_3O_8, but found the results to not be statistically significant (Kahouli, 2011, p. 11). Although it does not speak of the statistical significance of the link between oil prices and uranium demand, UxC LLC stated in volume 21 of ‘*Uranium and Oil Don’t Mix*’ that there is essentially no crossprice-elasticity between oil and uranium, suggesting that any measure of the crossprice-elasticity between these two commodities has low confidence (UxC LLC, 2007, p. 2).

3.1.6 Trade and price discovery

Uranium is predominantly purchased through long-term contracts where price details can be confidential, with only approximately 15% of volumes are traded on the spot market. While spot prices result from short-term supply and demand imbalances, long-term pricing is affected by the production cost of the material. Even so, these prices influence one another as contracts

can be linked to spot prices, along with other effects (Rooney et al., 2015, p. 3).
Cameco, one of the world largest producers of U_3O_8 usually plans their contracted volumes to slightly exceed planned production, and have been net buyers of spot volumes in order to meet contracted volumes (Cameco, 2023, p. 25). This practice, amongst others can serve to connect the spot and long-term market, as spot purchases in order to meet contracted volumes make financial sense until the spot price equals the contracted price.

Like many other commodities, demand for Uranium is cyclical. Unlike most of them however, Uranium is not traded on a public exchange in meaningful amounts, with the spot market primarily serving discretionary demand. In general, periods of elevated uranium prices creates a perception of scarcity that motivate buyers to expand their long-term contracting. This again drives investments into high-cost production of Uranium which due to prolonged development timelines can miss the window of elevated demand. Production from these projects only come available for sale after the demand has already been met by proven producers. The resulting oversupply is then exposed to a low-volume spot market, causing prices to crash and also to create the perception of Uranium being abundant. The ensuing lack of demand for long-term contracting cause investment into new production capacity to decline and create the prerequisites for elevated prices, and for the cycle to restart (Cameco, 2023, p. 14). This description of the cyclicality in uranium markets seems to imply that the availability of spot volumes can serve to affect willingness to enter into long-term contracts both positively and negatively.

2017 estimates by UXC LLC stated production costs for U_3O_8 in currently operating mines, to be on average 40$ per pound, with a standard deviation of 15$. They also stated a maximum production cost of 82$ (Considine, 2019, p. 8). Data from the IMF suggests world inflation from 2017 to 2023 to total 39%, significantly affected by 2022 and 2023 (International Monetary Fund [IMF], 2023). If we adjust the 2017 estimates from UxC for this inflation, production cost in 2023 should on average equal 55.50$ per pound and have a maximum cost of 114$.
These numbers are not necessarily accurate, however they do imply that a significant number of active Uranium mines are currently producing U_3O_8 at a higher cost than current market prices, as the production cost represent the miners COGS. These high cost mines may have signed long-term contracts at higher than current prices, resulting in the mining companies not operating at a loss.
These numbers also imply that numerous mines that have had their production temporarily shut down will require significant price increases in order to be restarted. Furthermore, both reactivating existing mines and investing in new capacity requires mining companies to include Weighted Average Cost of Capital in their calculations. In order for expansion to be economically viable, mining companies need to make a profit, adjusted for their WACC.

3.1.7 Market development and technology

Successful development of laser enrichment technology could potentially result in large positive supply shocks, negatively affecting prices for U_3O_8. Although this technology could dramatically affect supply of LEU, GE-Hitachi Global Laser Enrichment has slowed development of the technology due to poor market conditions (NEA, 2020, p. 103). Successful development of this technology would cause a surplus of U_3O_8 as it would provide more efficient enrichment, requiring less U_3O_8 to produce the same amount of LEU. This type of shock was investigated in a 2015 study, *'A dynamic model of the global uranium market and the nuclear fuel cycle'*. Rooney et al. simulated the effects of negative supply and demand shocks on the price of uranium. Their results suggest that even though a negative supply shock result in significantly higher prices for uranium than the negative demand shock, both types can result in prices far exceeding current spot and long-term prices (Rooney et al., 2015, p. 7). It may sound illogical for a decrease in demand to result in higher prices, but the simulations conducted by Rooney et al. is based on a system dynamics model, incorporating equations for future supply and demand. The study asserts that this would cause future price spikes to be lower, though it does not investigate the short-term effects. Regardless, this study exemplifies the effect that shocks to either supply or demand have on the uranium market.

During 2022, prices for enrichment measured in SWU have approximately doubled as can be seen in Figure 2, incurring higher costs for enrichment facilities as well as those entering into long-term contracts for Low Enriched Uranium. Figure 2 is created using the UxC data.

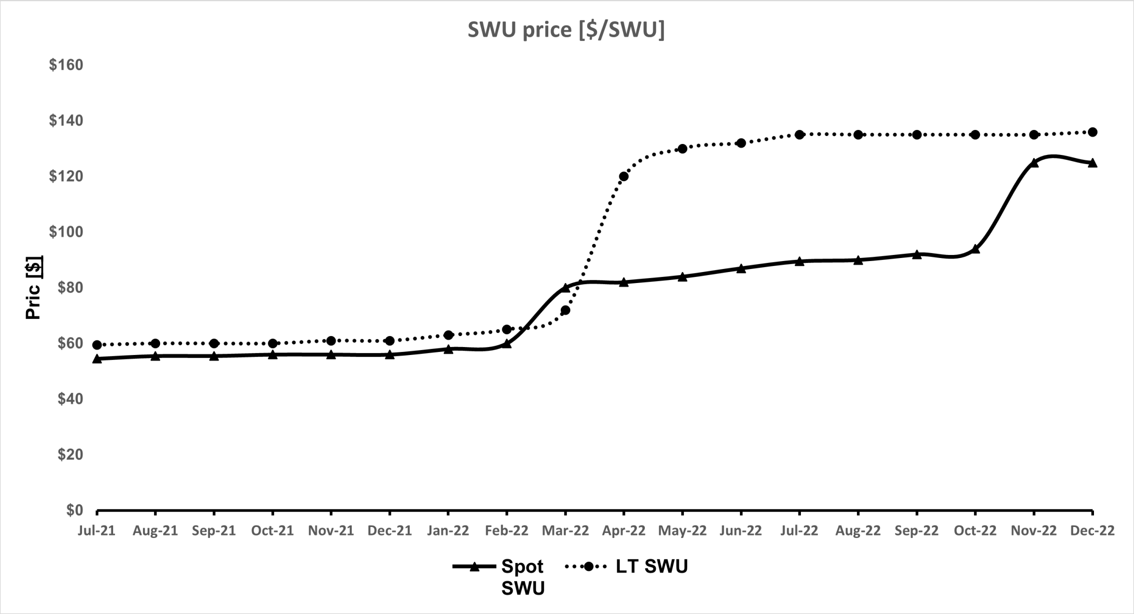

Figure 2: Recent price developments for SWU

3.1.8 Nuclear power generation costs

The costs of generating nuclear power is dominated by capital costs and costs relating to operations and maintenance which together account for approximately 80-85% of Levellized Cost of Electricity. The remainder of the costs can be attributed to fuel cycle costs, which in addition to fuel costs include storage, disposal and recycling of nuclear waste (Kahouli, 2011, pp. 1–2). Due to the low fuel costs relative to LCOE, nuclear power plants are only slightly affected by large increases in fuel costs. In fact Lorenczik et al. estimated that a 50% increase in fuel cost only causes an 8% increase in total costs (Lorenczik et al., 2020, pp. 88–89). These fuel cost are again a combination of the prices of U_3O_8, conversion, enrichment and fuel fabrication, of which U_3O_8 only represents a small percentage.

3.2 Literature Conclusion

Based on the referenced research, the commodity market for natural Uranium exhibits significantly inelastic behaviour to price changes both in the short and long term. We assess this to be accurate, as nuclear power often provide nations with base-load power. Further strengthening our belief that the price elasticities of supply and demand identified by Kahouli are realistic. The fuel costs are very low relative to capital- and operations & maintenance costs. The cost of U_3O_8 is only a portion of fuel costs and although the price of U_3O_8 has appreciated, this has been dwarfed by the recent price increases for SWU and Conversion services. We also note the crossprice-elasticity of U_3O_8 to coal, which we denote as E_{UC}, while we disregard any measure of this effect between U_3O_8 and oil due to it's low statistical significance. Kim studied the effects of price changes in Coal, Natural Gas and Oil for Nuclear Power, however the results solely represent the effects on nuclear power generation observed in South Korea (Kim, 2019, p. 1). Therefore we do not believe the results are reliable for estimating the effects on the global market for U_3O_8.

Elasticities

	Short-run	Long-run
E_S	0.06	0.153
E_D	0.039	0.066
E_{UC}	1.025	3.439

Table 4: Price-elasticities of U_3O_8

Due to the rising costs of enrichment capacity we find it reasonable to assume that both enrichment facilities and operators of nuclear fission generators will seek to maximize their profits by limiting this expenditure. As we explained previously, it is possible to limit the required amount of SWU used to produce equal amounts of LEU if one increases the amount of feed-stock. We believe rising SWU costs, will cause profit-maximizing enrichers and operators to increase the amount of Uranium that is fed into enrichment facilities, and that this will cause a demand-shock for the commodity. We intend to model the price-effect this can have on U_3O_8, which we expect to cause an upward move in price. This will likely serve to incentivize expansion of primary supply as well as make secondary sources of supply financially viable. We will therefore include supply as a variable in both the short- and long-term, to account for the uncertainty of secondary supply and to quantify the extent to which this will affect price-responses to our demand shocks.

A loss of Russian enrichment capacity would significantly decrease supply of SWU, and even though it may be more of a worst-case scenario for Uranium prices we find it prudent to model a scenario where Russian capacity is unavailable to many purchasers of LEU. If a lower supply of SWU is avaliable, operational as well as contractual tails assays could be forced significantly higher, resulting in demand shocks for U_3O_8.

Based on the statistics and reports we reviewed, there is a significant shortfall between current primary supply of and primary demand for U_3O_8. Secondary supply may offset this shortfall, but the extent to which this available for purchase is uncertain. What appears clear to us is that increased long-term contracting is necessary to fill the long term fuel demand of the global reactor fleet, and to incentivize this increase prices need to rise.

4 Theory

In this chapter we will describe relevant theory employed to answer the research question of this thesis.

4.1 Equilibrium Displacement Model

Price discovery in commodity markets explained crudely, is a function of quantity supplied and quantity demanded. Shifts to either of these curves cause the price discovery process to restart, resulting in price changes.
We do not, however, need to know the exact curves, according to Bailey (2008):

> "To forecast price and quantity changes, you do not need to know the exact supply and demand curves; all you need are elasticity estimates, which are more readily available. By incorporating elasticities into something called an equilibrium displacement model, one can calculate price and quantity changes due to a number of outside events." (p. 78).

Equilibrium Displacement Models group all the variables affecting supply and demand for a good into endogenous and exogenous variables. For a model based on supply and demand curves, price and quantity of a good is determined within the model and are therefore endogenous variables. Variables that causes shifts in either of the curves are external to the model, and are therefor called exogenous variables (Bailey, 2008, pp. 78–79).

In this thesis we will use an Equilibrium Displacement Model as described by Bailey(2008) in pages 78-80 of *Agricultural Marketing and Price Analysis*. Equations (2) and (3) represents the demand and supply curves. Here, $\%\Delta Q_D$ and $\%\Delta Q_S$ represent changes in quantity demanded and supplied. E_D and E_S represent the own-price elasticities of supply and demand, $\%\Delta P$ the price change and S_D and S_S the demand and supply shocks.

$$\%\Delta Q_D = E_D(\%\Delta P) + S_D \tag{2}$$

$$\%\Delta Q_S = E_S(\%\Delta P) + S_S \tag{3}$$

Price and quantity is determined in the cross-section, or the equilibrium between these two curves, represented by equation (4).

$$\%\Delta Q_D = \%\Delta Q_S \tag{4}$$

If we substitute both sides of equation (4) with (2) and (3), the resulting equation is (5), with which we can determine price reactions and changes in quantities supplied or demanded, following shifts in the supply or demand curves for a good.

$$E_D(\%\Delta P) + S_D = E_S(\%\Delta P) + S_S \tag{5}$$

4.2 Price Elasticity of Supply

The price elasticity of supply, denoted as E_S describes how supplied quantities, Q_S of a good responds to a change in price of the good, P_A. Specifically it describes the percentage change in quantity supplied in response to a one percent change in price (Tomek, 2014, p. 57).

$$E_S = \frac{\%\Delta Q_S}{\%\Delta P_A} \tag{6}$$

The price elasticity is always non-negative and can generally be characterized in one of three categories, Perfectly inelastic, inelastic and elastic. Perfectly inelastic supply, when E_S = 0 is when supply is fixed and does not respond to changes in price, which is generally only observed in the very short run. Inelastic supply, where E_S takes values between 0 and 1 is an area where the percentage change in quantity supplied is smaller than the percentage change in price. Finally, price elastic supply, where $E_S \geq$ 1 determines a percentage change in quantity to be greater than the corresponding percentage change in price (Tomek, 2014, p. 57).

4.3 Price Elasticity of Demand

The price elasticity of demand, denoted as E_D describes how quantities demanded, Q_D of a good responds to a change in price of the good, P_A. Specifically it describes the percentage change in quantity supplied in response to a one percent change in price (Tomek, 2014, p. 57).

$$E_D = \frac{\%\Delta Q_D}{\%\Delta P_A} \tag{7}$$

The price elasticity of demand is characterized similarly to the price elasticity of supply, except from the quantity responding to changes in price is quantity demanded.

4.4 Long-run supply and demand

The term long-run when used to describe supply and demand is usually defined as the time period required for a complete readjustment of quantities supplied and demanded, in response to a price change for a good. This time period is not fixed, but however dependant on the time required to complete the change in production or consumption, and is usually longer for storable goods than for perishable ones (Tomek, 2014, pp. 22–23).

4.5 Short-run supply and demand

The short-run time period in relation to supply and demand, is the time period where the initial quantity response to a change in price for a good, appears. The short-run response to a price change, would then be the change in quantity supplied or demanded in response to a change in price the same day, week or month depending on the unit of observation (Tomek, 2014, p. 23).

4.6 Crossprice-elasticity of demand

The crossprice-elasticity of demand $E_{D,B}$ describes how demand of one good Q_D can be affected by a change in price on another good P_B. In other words calculating the responsiveness of quantity demanded of one good to a change in the price of another (Tomek, 2014, p. 60). The crossprice-elasticity of demand $E_{U,B}$ is given by:

$$E_{D,B} = \frac{\%\Delta Q_D}{\%\Delta P_B} \tag{8}$$

If $E_{D,B} > 0$ the two goods are substitutes. If $E_{D,B} < 0$ they are complements. For goods that are substitutes, the quantity demanded of one good is positively related to the change in price of the other. For complementary goods on the other hand, P_B and Q_D usually exhibit a inverse correlation (Tomek, 2014, p. 20). This is due to complementary goods often being used together, while for substitutes one good can partially or wholly replace the other.

5 Data

This chapter presents a description of the data used in the thesis, as well as the tools, sources and techniques used to collect and analyze the data. Our data has been retrieved from both public and proprietary sources, and thus the data from UxC can not be directly published in this paper due to its proprietary nature. This chapter will therefore describe the data from UxC LLC and the other data used to answer our research question. This includes prices for Lithium Carbonate, TTF Gas and API2 Coal which are all used in the discussion of our results.

5.1 Sampling Strategy

Price data supplied by UxC LLC is based on non-probability sampling, as it depicts month-end and week-end prices for various products in the nuclear fuel cycle. This sampling strategy also applies to the collection of data regarding future supply and demand. We have chosen this method of sampling, because sampling at random time intervals in the population of data describing supply and demand of U_3O_8 would not serve to answer our research question. In order to accomplish this, we need to establish what this balance will be in the future. The supply of U_3O_8 is a function of, amongst other factors the number of producing mines times the production output of each mine. The first term of this equation increases and decreases following a time-lag as investment decisions are made. The demand side is subject to the same time lag from an investment decision, and increases when new reactors are completed, or existing reactors have their lifetime extended. Sampling this data at random intervals would in our opinion not depict future supply and demand meaningfully, and thus a non-probability sampling strategy has been chosen. This same sampling strategy also applies for the Argus/McCloskey's Coal Price Index, API2, as well as price data for Lithium Carbonate and TTF Gas.

5.2 Data collection

This thesis makes use of a quantitative data collection method, with data collected from various sources. Historical price data is provided by UxC LLC and data regarding supply and demand of the different products in the nuclear fuel cycle has been collected from public websites, news releases and scientific articles.

Data regarding the Argus/McCloskey's Coal Price Index, API2 as well as prices for Lithium Carbonate and TTF Gas have been collected through the public websites *investing.com* and *cmegroup.com*.

5.3 Data statistics

To analyse the data set from UxC LLC we will use descriptive statistics. This allows us to summarize and explore possible trends, as well as frequency and variability that can be used to support our research question. Furthermore we will make use of inferential statistics to make predictions for the data set. This predictions will be crucial to determine if the samples is representative for the uranium population and for input to our EDM predictions. During phase one, where the bulk of the analysis of the historical price data is conducted we will primarily use Microsoft Excel. Table 5 summarizes selected data statistics from the UxC data.

	U_3O_8 Spot	NA Conv	NA UF_6 Value	Spot SWU
Unit of measure	[$/pound]	[$/kgU]	[$/kgU UF_6]	[$/SWU]
Median	$ 20.00	$ 7.25	$ 86.79	$ 95.00
Maximum	$ 136.00	$ 40.00	$ 366.85	$ 163.00
SD	$ 20.69	$ 6.55	$ 58.50	$ 35.29
Excess Kurtosis	4.15	6.47	2.70	-0.84
Skewness	1.70	2.27	1.29	0.06
Data Start	03/30/1987	11/28/1994	12/26/1994	11/28/1994
Data End	12/26/2022	12/26/2022	12/26/2022	12/26/2022
Frequency	Monthly	Monthly	Monthly	Monthly

Table 5: Data Statistics - UxC Data

5.4 Description of historical price data

The price data made available to us by UxC LLC describe prices for various products and services in the nuclear fuel cycle between March 1987 and December 2022. Although the data spans a large time-frame, not all of the data categories have been recorded since 1987. For example, the data only describes prices for NA UF_6 Value starting in January 2005.
Definitions of the various data categories can be viewed at *https://www.uxc.com/p/prices/UxCPrices.aspx?currency=EUR&print=true&pdf=true*, and the categories we have used in the writing of this thesis will be explained in detail below. UxC LLC is a leading research and analysis company in the nuclear industry, providing consulting and information services regarding the entire nuclear fuel cycle. the company was founded in 1994 as an extension of The Uranium Exchange Company, providing data services for the nuclear fuel cycle (UxC LLC, 2023b, Sec. 1). The long history of the company, as well as it being a trusted source for actors in the nuclear industry results in the historical data provided to us by them having high reliability.

The UxC data exists in two versions, one spreadsheet with a weekly sampling frequency and one with a monthly frequency. The version we use for our research is the one with the monthly sampling frequency. This is due to the monthly data containing data categories that the weekly version does not. Examples of these are *Spot SWU* and *NA UF_6 Value* which are essential for our purposes. Table 6 describes how the historical price data from UxC LLC appears in the spreadsheet containing it. The description in table 6 does not show the full extent of the data, only the data categories most relevant for our research. A description of the complete dataset is available to read at: *https://www.uxc.com/p/prices/UxCPrices.aspx?currency=EUR&print=true&pdf=true*.

Date	U_3O_8 Spot	NA Conv	NA UF_6 Value	Spot SWU	Unused data...
Dec/2022	$ -	$ -	$ -	$ -	$ -
Nov/2022	$ -	$ -	$ -	$ -	$ -
Oct/2022	$ -	$ -	$ -	$ -	$ -
Sep/2022	$ -	$ -	$ -	$ -	$ -
:	$ -	$ -	$ -	$ -	$ -
:	$ -	$ -	$ -	$ -	$ -

Table 6: Example of UxC Data

U_3O_8 Spot
The weekly and monthly spot price for $\geq$ 100.000 pounds of U_3O_8, measured in US Dollars per pound. The data contains entries for the month-end price from March 1987 to December 2022.

NA Conv

The spot price for conversion of $1kgU$ of U_3O_8 into UF_6, measured in US Dollars and with delivery in North America(NA). This data category represents the price of the conversion service in isolation, however this cost is incorporated into the data category *NA UF_6 Value*. The month-end price of NA Conv is recorded in the data from November 1994 to December 2022.

NA UF_6 Value

A calculated US Dollar price for purchase of U_3O_8 and conversion services necessary to result in $1kgU$ of UF_6. This value is a sum of the components U_3O_8, multiplied by 2.61285 to convert pounds U_3O_8 into $1kgU$, and the spot price of the conversion services to result in $1kgU$ in UF_6 form. This category is recorded in the data from December 1994 to December 2022.

Spot SWU

The spot price for enrichment services in the form of one Separative Work Unit, measured in US Dollars. The month-end price of Spot SWU is recorded in the data from November 1994 to December 2022.

5.5 Supporting price data

In addition to the historical price data from UxC LLC, we have also used price data for other energy commodities and industrial chemicals in our research and discussion. The commodities in question are Coal, Natual Gas and Lithium Carbonate.

Price data regarding historical API2 coal prices and futures, as well as prices for Lithium Carbonate and Dutch TTF Gas are publicly available online. The data can be viewed and accessed through the links provided in the bibliography, and are referenced throuhout this thesis.

API2 Coal Price Index

The Argus/McClosky API2 Coal Price Index is the benchmark price reference, for coal imported to northwestern Europe. Approximately 90% of all Coal derivatives are priced against this and the API4 Index (Argus Media Group, 2023, Sec. 1).

Dutch TTF Gas Price

The price of futures contracts for physical delivery of Natural Gas in Europe. Contracts are traded in 1MW contract sizes, an as such measured in Euros per MW (Intercontinental Exchange Inc. [ICE], 2023, Sec. 1).

Lithium Carbonate 99.5% Price

Lithium Carbonate of 99.5% purity is the standard battery grade of the material (Targray, 2023, Sec. 1). The prices are measured in Chinese Yen, ¥per tonne.

6 Method

6.1 Research introduction

In this chapter we will describe the method used in the writing of this thesis, and the reasoning behind the chosen method. The intended aim of using the described method is to determine the theoretical price-effect of demand shocks by use of the Equilibrium Displacement Model in the commodity market for natural Uranium, as well as whether Uranium market fundamentals allow for the theoretical price reactions determined by our research to materialize. The research question of this thesis requires us to determine the magnitude of the demand shocks, the price responses to these demand shocks, and the factors affecting how the market responds to these changes in price. Because of this, we have structured the research of this thesis into three main phases.

The calculations that were used to arrive at the results presented in the next chapter are reliant on operational tails assays changing from a reference level. In this thesis, a reference tails assay level of 0.14% has been used. This is because our calculations show that for most of the period between 2018 and 2022, this has been the profit maximizing tails assay when enriching U_3O_8 to LEU. We do not have access to data which unambiguously confirms which tails assays were in use at each point in time where the price data from UxC applies, we can only use the price data to infer what levels enrichers should have been using to maximize their profits.

6.2 Research design

To answer the questions above for each of our three scenarios, we have structured our method and research design into three phases. Phase 1 focused on analysing the historical price data from UxC LLC and served as the foundation for calculating the demand shocks modeled in our three demand scenarios. In phase 2 we implemented the EDM and calculated the price responses for our three scenarios, as suggested by the model. The phase 3 research was further subsectioned into two parts. During part one of phase 3 we explored how the larger energy market affects demand for U_3O_8, specifically how the price for coal can affect this demand. While the first part focused on how external price changes in energy markets affect demand for U_3O_8, the second part focused on internal price dynamics of the nuclear fuel cycle. In the second part of our phase 3 research, we used our results from phase 1 and 2 to calculate a theoretical cross-price elasticity of demand for U_3O_8 to SWU. During phases 1 and 2 we found both the price change $\%\Delta P$ for SWU, and the $\%\Delta Q_D$ that should occur for U_3O_8, assuming that quantity demanded is optimized for profit maximization. We decided to separate this phase structurally between the internal and external relationships, to increase the readability.

6.2.1 Research philosophy

The research philosophy in this thesis is positivism as described by Creswell in *Qualitative, quantitative and mixed methods approaches*, p. 36. All the data collected and used for the thesis is factual in nature and provides an objective measure of prices, supply and demand of products in the nuclear fuel cycle at various points in time. We also make use of existing theory to calculate responses to demand shocks in the U_3O_8 market. Although the price responses calculated using the theory are theoretical, whether or not market fundamentals are supportive of these price changes are grounded in factual data, accurately portraying the reality of uranium markets.

6.2.2 Research type

In order to accomplish the research aim of this thesis we used a quantitative deductive research method. Based on price data provided by UxC LLC and the current state of market supply and demand we identified potential future states of the Uranium market, where the occurrence of demand shocks seemed probable. These demand shocks were the basis for the research question of this thesis. We then used deductive research by applying the EDM and discuss weather or not the results produced by the model has the possibility of materializing given the current and likely future state of the Uranium market.

We believe that a quantitative deductive research method is well suited, given our positivist research philosophy and choice of data. Furthermore, our research question requires us to quantify current and future measures of supply and demand of the products in the nuclear fuel cycle, as well as supply and demand shocks.

6.2.3 Time horizon

Methodologically, the time horizon in this thesis is both longitudinal and cross-sectional. In phase one of our research we analyze the price data from UxC LLC, which is longitudinal data. During this phase we analyze how prices for products in the nuclear fuel cycle evolve over time, and a cross-sectional approach would not yield relevant insights in this phase. During phase two, we calculate price changes by use of EDM in response to shocks in supply and demand. As we in this phase are modeling specific states of supply and demand, this phase uses a cross-sectional time horizon. During the third phase, a hybrid approach is used. In this phase we look at longitudinal price data and use this to calculate what this data implies for demand at a cross-sectional point in time.

We have chosen this approach due to the slow moving nature of the uranium market, but also the inherent volatility in prices for the products in the fuel cycle. Long lead times from an investment decision to a change in supply or demand cause the balance between them to evolve slowly. At the same time singular events like enrichers shifting to overfeeding or geopolitical events, can cause shocks in either side of this balance.

6.2.4 Methodological limitations

In writing a Master's Thesis, time is a limiting factor. The scarcity of time results in our decision to model the uranium market with existing theory. This represents a methodological limitation in several ways. Firstly, since we are applying general theory to a specific market there is a possibility that the validity of the price responses this theory suggests are low. Furthermore, time has caused us to chose to model market reactions with only one model, where several models may produce a more nuanced picture of the future. Another potential weakness in the methodology is related to how we calculate demand-shocks for use in the EDM. In order to directly link increasing tails-assays to demand for U_3O_8, we assume that conversion capacity is not a limiting factor. When beginning the work for this thesis, conversion was a limiting factor but additional western capacity is coming online in 2023 and onwards.

A potential methodological weakness is our chosen research philosophy. This is a positivistic thesis written based partly on analysis of spot market prices for products in the fuel cycle. As we have mentioned, most of the volumes of U_3O_8 is traded on the long term market. The prices in the spot and long-term market are closely linked, but they can at times diverge which introduces the possibility of data-points to not accurately depict reality. This limitation in our methodology is in our opinion necessary due to the opaqueness of the uranium market.

Our quantitative deductive strategy might introduce confirmation bias into our research(Onwuegbuzie & Daniel, 2003, p. 9). Any researcher biases regarding the research question, data collection or statistical analysis can invalidate the results. Furthermore, by focusing on numbers and statistical relationships, we run the risk of disregarding important decision factors regarding nuclear energy. Examples of this can be energy security, fear, geopolitics and several others directly affecting supply of and demand for U_3O_8.
Finally, the methodology used in this thesis to calculate price reactions only result in calculations to what the partial equilibria should be according to the EDM. In reality, over time a general equilibrium should evolve in part due to the price impulses from the partial equilibria which we have determined.

6.3 Research Strategy

6.3.1 Phase 1

The first phase consisted of collecting and performing exploratory data analysis of longitudinal price data describing pricing of various commodities and services in the nuclear fuel cycle. In order to gain access to this historical data we contacted UxC LLC by e-mail, requesting access to the data for academic purposes. This request was granted with the restrictions that we were not allowed to publish the raw data in any other form than graphically, as the data is proprietary and is normally only accessible at a high cost.
In order to provide answers to our research question, we needed to determine the extent of the demand shocks in our three scenarios as well as what is driving these shocks. The following methodology describes how we went about accomplishing this.

While conducting our literature review and studying topics for the background chapter, we realized the importance of the enrichers decisions in the nuclear fuel cycle. Enrichers are profit maximizing actors in the market. Fluctuating inputs prices affect their operational decisions. Inputs that are relevant in the profit maximizing desicions made by enrichers are the price for U_3O_8, Conversion and SWU. The last two of which have experienced significant increases during 2022, as can be seen in figure 3 in the Results chapter. In order to visualize this data, we plot $NA\ Conv$ and $Spot\ SWU$ from the UxC data against time using Microsoft Excel.

When enriching Uranium, the amounts required of inputs are dependant on the tails assays and this directly affects the total cost for each 1kg of LEU. In order to calculate, and then plot Spot LEU cost we began by collecting information regarding the input quantities of UF_6 and SWU required to enrich 1 kg of LEU at 4.4% ^{235}U. These quantities represent the amounts required when enriching at operational tails assays between 0.10% and 0.30%, increasing by 0.01% at each step. As stated in the background chapter, LWR require fuel enriched to between 3% and 5% ^{235}U. Various designs may require higher or lower concentrations, but we chose to use 4.4% as this was the level proposed as standard by the SWU Calculator from Urenco.
The quantities were acquired by employing Urenco's SWU calculator accessible at *https://www.urenco.com/swu-calculator* and are represented in table 10.
The feed assay used in our calculations was set to 0.711% ^{235}U. This is the same concentration

contained in naturally occurring U_3O_8, and the quantities in table 10 hence depict necessary amounts when enriching with mined uranium.

The cost of enriching 1 kg of LEU at time t, was calculated as a sum-product of the amounts of each component at tails assays n, and the prices for one unit of the components at time t. In this equation, the terms with a subscript n refer to quantities and the terms with subscript t refers to prices. $(kgU\ \ UF_6)_n$ thus represents the quantity of UF_6 measured in kgU. $(NA\ \ UF_6\ Value)_t$ represents the price at time t for the necessary U_3O_8 and conversion services to result in 1kgU of UF_6, measured in $/kgU. The same goes for the SWU terms with subscript n and t.

$$LEU\ Cost_t = (kgU\ \ UF_6)_n * (NA\ \ UF_6\ Value)_t + (SWU)_n * (SWU\ Spot)_t \tag{9}$$

We calculated LEU cost for each tails assays described in table 10 in a spreadsheet, ending at December 2022 and beginning at January 2005 as this is the first occurrence of $NA\ \ UF_6$ in the data-set.

Date	NA UF_6 Value	Spot SWU	LEU Cost, n=a	LEU Cost, n=a + k*0.01
Month - Year	$ -	$ -	$ -	$ -
Month - Year	$ -	$ -	$ -	$ -
Month - Year	$ -	$ -	$ -	$ -
Month - Year	$ -	$ -	$ -	$ -
Month - Year	$ -	$ -	$ -	$ -

Table 7: Example of calculating LEU Cost

From the literature review, we already knew that enrichers have the freedom to operate at whatever tails assays they prefer, and the calculations for LEU Cost were made to quantify the value of the choice of doing this. Our calculations also allow us to graphically demonstrate the monetary value of operational choices regarding tails assays.

For each data-point in the time-series there will be a profit maximizing combination of components based on market prices at the time in question. We believed that this serve as a powerful motivator for operational choices made at enrichment facilities, as well as by utilities. To find the optimal operational tails assays, the waste concentration of ^{235}U resulting in the lowest LEU cost at each point in time we used equation (10) in an excel spreadsheet expanding on table 7. In the equation, $E$5:$Y$5 and E6:Y6 represent the area where the total LEU Cost had been calculated for each tails assays level, at each point in time.

$$Optimal\ Tails_t\ =\ INDEX(\$E\$5 : \$Y\$5, MATCH(MIN(E6 : Y6), E6 : Y6, 0)) \tag{10}$$

Table 8 is an example of how our spreadsheet appeared. Four our purposes, which are to show that management of operational tails assays does have a financial impact for enrichers, as well as to approximate the demand shocks this creates, a precision of two decimal points is sufficient. It is although possible to control the operational tails assays even further, but this was determined to be superfluous for the purposes of this thesis. Therefore, the actual optimal tails assays at the time periods calculated in figure 6 may in fact be slightly different.

Date	**NA UF_6 Value**	**Spot SWU**	**Optimal Tails**	**LEU Cost, n=a**	**LEU Cost, ...**
Month - Year	$ -	$ -	-	$ -	$ -
Month - Year	$ -	$ -	-	$ -	$ -
Month - Year	$ -	$ -	-	$ -	$ -
Month - Year	$ -	$ -	-	$ -	$ -
Month - Year	$ -	$ -	-	$ -	$ -

Table 8: Example of calculating Optimal Tails Assays

Plotting the resulting data against time in Microsoft Excel resulted in figure 6 seen in the Results chapter.

Due to the fact that the differences in total LEU cost between the various tails assays are relatively low compared to the total LEU cost, we decided to visualize only a selected sample of the tails assays in figure 4 and 5. This was done to allow for readability of the graphs, and the tails assays were selected based on the results in figure 6. The tails assays visualized in figures 4 and 5 were selected based on the current optimal tails, and approximations of the previous highest and previous lowest optimal tails assays, as well as an additional lower level of tails assays in order to visualize the financial effect of actively managing operational tails assays at enrichment facilities.
The calculated LEU costs for the selected tails assays were then plotted against time, using Microsoft Excel.

Figures 4 and 5 visualize how total LEU Cost varies over time, but the choice regarding which operational tails assay an enrichment facility operates at, is dependant on the costs of the inputs at the moment of decision. As demonstrated by figure 6, in December 2022 the optimal tails assay was 0.20%. We expanded upon the formula for LEU Cost to calculate the monetary gain from enriching at the optimal tails assays, G_n, compared to the other levels described in earlier tables. This was accomplished by subtracting the LEU Cost at optimal tails assays, 0.20% from the total LEU Cost for each tails level. The numbers calculated by equation (11) are the dollar amount an enricher would gain by enriching at the December 2022 optimal tails assays, per 1kg LEU at the time of calculation, compared to enriching at tails assays n.

$$G_n = LEU\ Cost_n\ -\ LEU\ Cost_{0.20} \tag{11}$$

The results from this equation being employed for tails assays between 0.10% and 0.30% are presented in table 11. Table 12 is a further expansion of equation (11), where we multiply G_n with 27.000 which is the annual fuel consumption of a typical 1GW LWR (Marques, 2010, p. 3). The table thus determines the potential annual increased profit from switching to the optimal tails assays, when starting from various levels as of December 2022. This part of the research was conducted to show that although the profit differences are small per 1kg LEU, they become a significant motivator for each supplied reactor.

In our research question, we state three separate scenarios for demand, resulting in demand-shocks for which we calculate $\%\Delta P$. The scenarios were derived from the results of the phase 1 research combined with what we learned during the literature review. One of the key pieces of information needed to answer our research question was the magnitude of the demand shocks. As a concluding step of the phase 1 research, we determined the drivers of our demand shocks and the optimal tails assays level for each scenario. This served as the foundation for calculating the magnitudes of the demand shocks in phase 2.

The tails assays in scenarios 1 and 2 were chosen based on the results seen in figure 6. This figure demonstrated that during 2022 the profit maximizing operational tails assays had risen from 0.14% to 0.20%, and hence we chose this as our Scenario 1. We believe there are clear financial incentives for this scenario to occur.
Scenario 2 was based on the results in the same figure, however scenario 2 depicts tails assays increasing from the reference level to previous historical highs. Based on the data available to us, these have historically hovered around 0.24%. Scenario 2 would need prices for SWU or conversion, or a combination of both to rise relative to the price of U_3O_8. The literature review and background chapters did not reveal any on-going projects to expand SWU capacity. Because of this we believe this has a high likelihood of resulting in even higher SWU costs.

Our literature review determined that Russia controls a significant share of global enrichment capacity, and that geopolitical risk to the nuclear fuel cycle has increased. Scenario 3 is an approximation of how the uranium market could react, should geopolitical tensions cause Russian enrichment capacity to become partly or wholly unavailable to the global market. As a consequence, operational tails assays would need to increase well above historical highs. How high these would need to become in order for a smaller global capacity to produce enough LEU is uncertain. The required level would depend on the political decisions of each country currently dependent on russian LEU. We cannot predict these decisions, and therefore we simply chose a level for operational tails assays considerably higher than historical highs, at 0.30%.

6.3.2 Phase 2

In phase two we implemented the deductive research method by applying established theory in order to arrive at estimates regarding the predicted price responses for U_3O_8 in response to the demand shocks described in our research question. Based on our conclusions from phase one that increasing prices for SWU will cause rational market participants to shift to higher tails assays, we calculated the extent of the resulting shifts in demand for U_3O_8. We chose the Equilibrium Displacement Model because the model describes how endogenous variables respond to changes in exogenous variables(Bailey, 2008, p. 79).

From the theory chapter we have equation (5), which describes the Equilibrium Displacement Model. By solving for $\%\Delta P$ we can use the resulting equation, equation (12), to determine the price reactions to the demand-shocks that emerge from our three scenarios.

By solving for delta P we get:

$$\%\Delta P = \frac{S_D - S_s}{E_S - E_D} \tag{12}$$

In order to use equation (12) to calculate $\%\Delta P$ we applied the price-elasticities from table 4 of the literature review, and calculated demand shocks for each of the scenarios in our research question with equation (13).

Table 13 shows the demand shocks for U_3O_8 that result if enrichers change their operational tails assays from a reference level of 0.14%. Here, S_{D_n} is calculated using equation (13). In the equation, n represents the new tails assays after increasing or decreasing from the reference level. The demand shocks for U_3O_8 were calculated based on the quantities required to enrich 1kg of LEU at the various tails assays represented in the table. These quantities were found using the SWU Calculator from Urenco (Urenco, 2023, Sec. 1). We chose to use 0.14% as the reference tails assays because the results of our research show that this level has persisted as the optimal tails assays for most of the 5-year period starting in 2018. These results can be found in figure 6, showing the historical profit maximizing operational tails assays. The scenarios and their accompanying S_D are summarized in table 14.

$$S_{D_n} = \frac{kg\, UF_{6_n} - kg\, UF_{6_{0.14}}}{kg\, UF_{6_{0.14}}} \tag{13}$$

In addition to the demand shocks, we chose to model various levels of supply responses in our calculations. For each scenario we modeled these supply responses as 0, 1/3 and 2/3 of the demand shock. We chose to do this because the literature review determined that although the amounts are uncertain, there exists stockpiles of uranium that for years have covered the supply gap in the market. Mines that have been temporarily shut down, can also be a source of secondary supply. We determined that we could not definitively know the extent of likely supply responses from secondary supply to the $\%\Delta P$ changes, and therefore chose to model these as previously mentioned.

Now, that we had all the variables required we simply input these into equation (12) for the three scenarios. The calculated $\%\Delta P$ are represented by tables 15, 16 and 17. In our case, the exogenous variable is the surging prices for SWU and conversion, and that these prices affect the demand curve for U_3O_8.

6.3.3 Phase 3, part 1

In the final phase of the research we investigated the effects that other energy commodities have on demand for U_3O_8. This is the final key information necessary to answer our research question. During phases 1 and 2 we have solely researched relationships internally in the nuclear fuel cycle in isolation. The commodity market for Uranium is global, and we firmly believe that no energy commodity is unaffected by the availability and cost of other energy sources. The aim of this phase of our research was for this reason to determine weather price dynamics of other energy commodities support or contest our results from phases 1 and 2.

While conducting our literature review, we found that Kahouli had determined the crossprice-elasticity between U_3O_8 and coal both in the short- and long-run, and we used these to determine whether price changes for coal supported the demand shocks we had previously calculated for U_3O_8 as a result of increasing SWU prices.

Our literature review only produced one reliable measure for cross-price elasticitiy between energy commodities and U_3O_8. This commodity being coal, seen in table 9 which is the one we used for our calculations in phase 3. The other measures of cross-price elasticity we found were either statistically insignificant, or valid only for a specific country. We model the global market, and thus elected to omit this from our research.

Crossprice-elasticity of U_3O_8 to Coal		
	Short-run	Long-run
E_{UC}	1.025	3.439

Table 9: Crossrice-elasticitiy of U_3O_8 to Coal

In order to use this crossprice-elasticity we needed a measure of how much the price of thermal coal had risen. Our logic in choosing how to measure this was that a decision to build a nuclear fission plant is made based on long-term changes in price of the energy commodity that the plant is substituting. For this reason, we compare historical average coal prices to the average futures prices for 2026 and 2027. For the historical prices we limited the data collection to the preceding 5 years before the Russian invasion of Ukraine, which we collected from (investing.com, 2023a, sec. 1). The choice of limiting the future price data to 2026 and 2027 is due to the forward looking nature of the decision to build a plant, as well as 2027 being the furthest our source for the data published prices for at the time of data collection (CME Group, 2023, sec. 1). Both the historical and futures prices represent the monthly Argus/McCloskey's Coal Price Index, API2. The data used in this phase is accessible in the appendix chapter.

To be able to calculate the magnitude of the change in quantity demanded of U_3O_8 as a result of the change in price for Coal suggested by our data, we employ equation (8) and solve for $\%\Delta Q_D$, resulting in equation (14).

$$\%\Delta Q_D = E_{U,C} * \%\Delta P_B \tag{14}$$

The average Coal prices shown in table 18 were calculated by averaging the historical and futures prices for API2 Coal for the time periods in question. This data is shown in the appendix. We then calculate $\%\Delta P_B$ by dividing the average future API2 price by the average historical API2 price using equation (15), resulting in a measure of the expected future price increases that we can use to determine the expected change in quantity demanded of U_3O_8 with equation (14).

$$\%\Delta P_B = \frac{\overline{P_{Futures}}}{\overline{P_{Historical}}} \tag{15}$$

The results in table 19 show the expected changes in quantity demanded of U_3O_8. The results in this table was based on the cross-price elasticities determined by Kahouli, and the calculated $\%\Delta P_B$ for API2 Coal prices. We then inputted these into equation (14) to yield the results in the table. Additionally we also conducted a sensitivity analysis of the short- and long-run crosspriceelasticities which can be seen in the same table. We chose to do this due to the uncertainty of the elasticities, which result from few scientific papers having been published on the subject.

As previously stated, we could not find a measure of the cross-price elasticity of demand for U_3O_8 to Natural Gas. Even so, the price data for European natural gas prices were still useful to us. The demand reaction to large increases in the price for other energy commodities is highly relevant when discussing the last part of our research question, whether market fundamentals are supportive of our predicted price responses. We also believed researching the willingness to pay for energy security could help us in evaluating the magnitude of the price increases we modeled in phase 2. After collecting the price data from (investing.com, 2023b) we measured the $\%\Delta P$ from the lowest to the highest price in the time period we collected data for, which is shown in figure 7 in the results. We chose the time period of 2021 to 2022 because before 2021 prices had been hovering around the prices seen early in 2021. Furthermore, the Russian invasion of Ukraine happened during this period which tested European willingness to pay for natural gas both directly, and in its derived form of electricity.

Figure 8 is a representation of the price increases for Lithium Carbonate traded in China (investing.com, 2023c). This industrial chemical is used in Lithium Ion batteries, because of the high energy density it offers (SQM Lithium, 2023, Sec. 1). We chose to include this data in our research because Lithium Carbonate is an essential material for the production of Li-Ion batteries for electric vehicles, and because price increases for the material has important similarities with U_3O_8 that can help us in discussing the last part of our research question. Even if prices for Lithium Carbonate appreciates substantially, the transferred effect on the price of the battery as well as the electric vehicle is substantially lower. The price increases for Lithium Carbonate was measured in the same way as for the European Gas data. The time period for the Lithium Carbonate data was chosen, as this represents a period when very low prices coincided with a large increase in demand. The growth in demand in this case coming from the accelerating growth of electric vehicles world-wide.

6.3.4 Phase 3, part 2

To conclude phase 3, we also calculated the crossprice-elasticity of U_3O_8 to price changes for SWU. We did this by using equation (8) and inserting the increase in SWU prices collected from the price data from UxC LLC for $\%\Delta P_B$, and the demand shock from scenario 1 for $\%\Delta Q_D$. The demand shock from scenario 1 represents the change in demand that should occur, if enrichers change their operational tails assays in order to maximize their profits, given the market prices of December 2022.

As we have previously explained, the conversion cost is also a variable when minimizing costs for the production of LEU. However, the amount of conversion capacity required is linearly correlated to the quantity of U_3O_8 and is as such not a factor that affects the profit maximizing amounts of U_3O_8 and SWU. As a result of this, we isolated the price increase for SWU to be the only variable that affects demand for U_3O_8 in our calculations of LEU costs.
We note that this calculation uses a theoretically predicted, and not actually observed demand shock. Even so, we do believe the result to be reliable due to the fact that the demand shock has been calculated using economic theory as the profit maximizing change in quantity.

7 Results

In this chapter we present the results of our research. The research methodology was separated into separate phases, and as such so are the results. Generally, the results from phase 1 were important inputs in order to conduct phase 2.

7.1 Phase 1

During the previous five years spot prices for both SWU and Conversion services have been low, however during 2022 the prices for these services have appreciated significantly as can be seen in Figure 3.

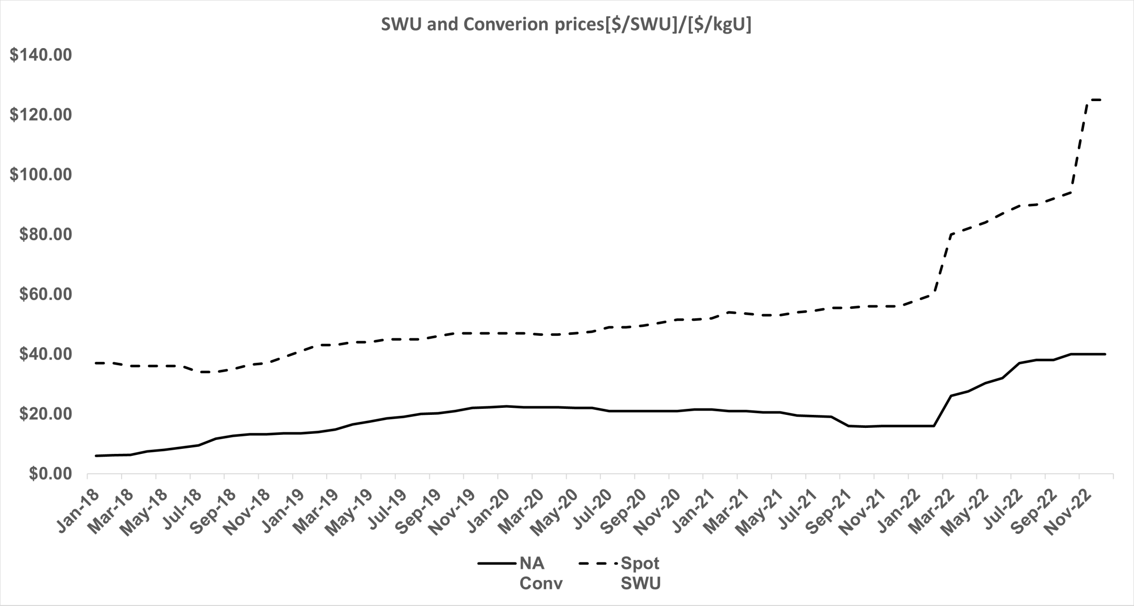

Figure 3: 5 Year Spot SWU[$/SWU] and Conversion cost[$/kgU]

Due to the fluctuating prices of U_3O_8, Conversion services and SWU, there will at each point in time be a profit maximizing operational tails assay level. The amounts in Table 10 represent the necessary amounts of the components needed to enrich 1 kg of LEU to a concentration of 4.4% ^{235}U, when using feed-stock with 0.711% ^{235}U, equal to that of naturally occurring U_3O_8 (Urenco, 2023, sec 1).

Components needed for 1kg LEU		
Operational Tails	kgU UF_6	SWU
0.10	7.038	10.159
0.11	7.138	9.770
0.12	7.242	9.419
0.13	7.349	9.101
0.14	7.416	8.809
0.15	7.576	8.542
0.16	7.695	8.294
0.17	7.819	8.064
0.18	7.947	7.849
0.19	8.081	7.649
0.20	8.219	7.460
0.21	8.363	7.282
0.22	8.513	7.115
0.23	8.669	6.956
0.24	8.832	6.805
0.25	9.002	6.662
0.26	9.180	6.526
0.27	9.365	6.396
0.28	9.559	6.272
0.29	9.762	6.153
0.30	9.976	6.039

Table 10: Components required for 1 kg LEU at various operational tails

For the majority of the time period, the LEU cost differences between the different operational tails assays have been low. As a result of the price developments for SWU during 2022, a significant gap has been developing which favor higher tails assays. This gap has been emerging because if enrichers are using lower tails assays, they would have to consume larger amounts of SWU capacity. Meanwhile, enriching at higher tails assays require larger quanitites of U_3O_8 which must be purchased and converted into UF_6. Thus, prices for the various materials and services can at times cause these profit gaps to emerge and evaporate.

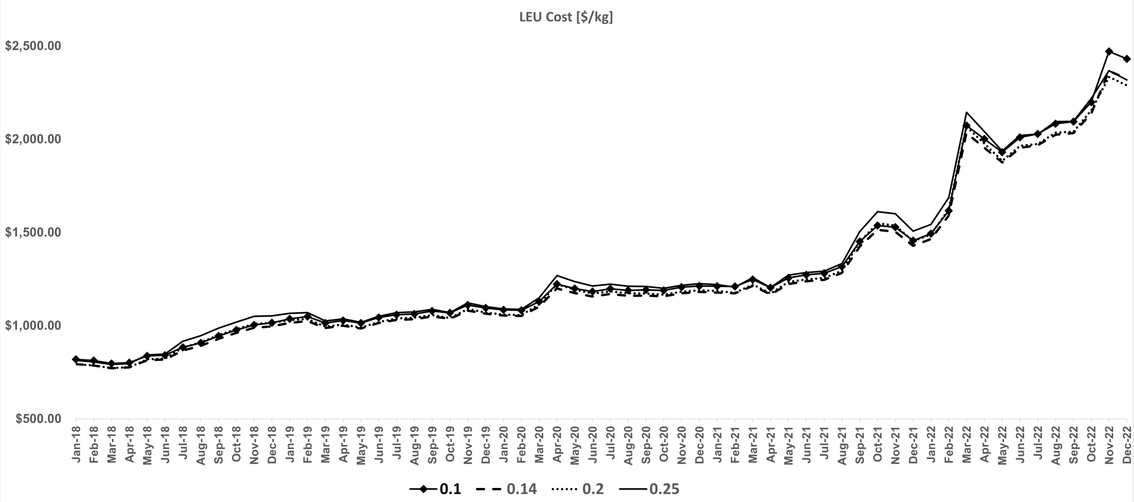

Figure 4: 5 Year Spot LEU cost

When examining the data for LEU cost for 2022, seen in Figure 5 we have determined that at the end of 2022, operational tails assays of 0.20% ^{235}U resulted in the lowest total LEU cost of the tails assays we examined. At this point in time, the extra profit to be gained when choosing operational tails of 0.20% ^{235}U instead of 0.14% was 36.13 US Dollars per kg of LEU, while when comparing operational tails of 0.10 and 0.2 the difference was 142.51 US Dollars per kg LEU. The corresponding dollar amounts per kg LEU is shown in table 11.

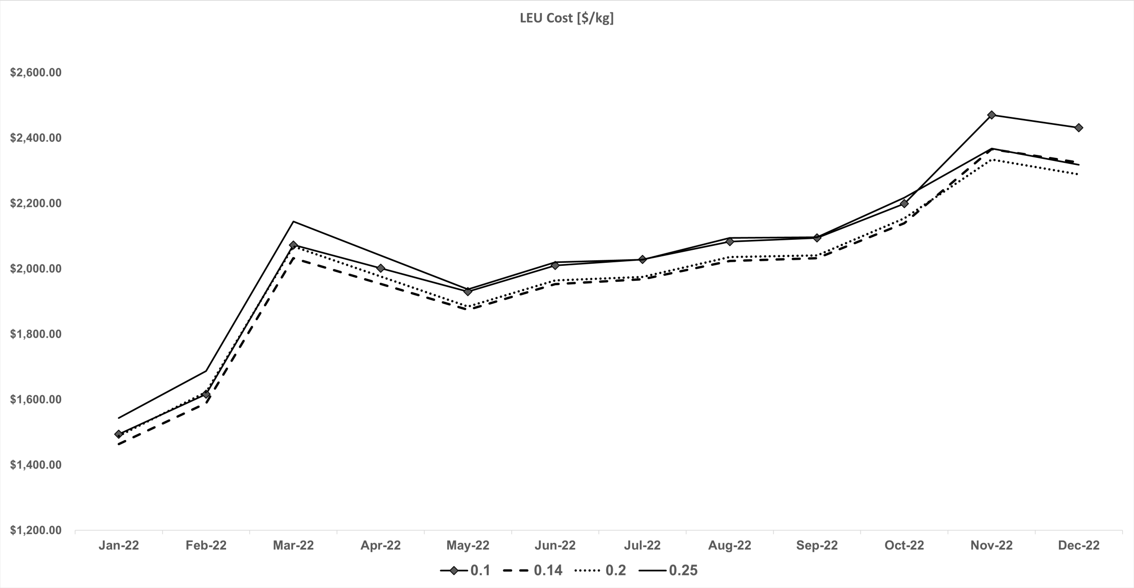

Figure 5: 1 Year Spot LEU cost

We calculated historical optimal operational tails assays using the information in Table 10, and the historical prices for the components, visualized in Figure 6.

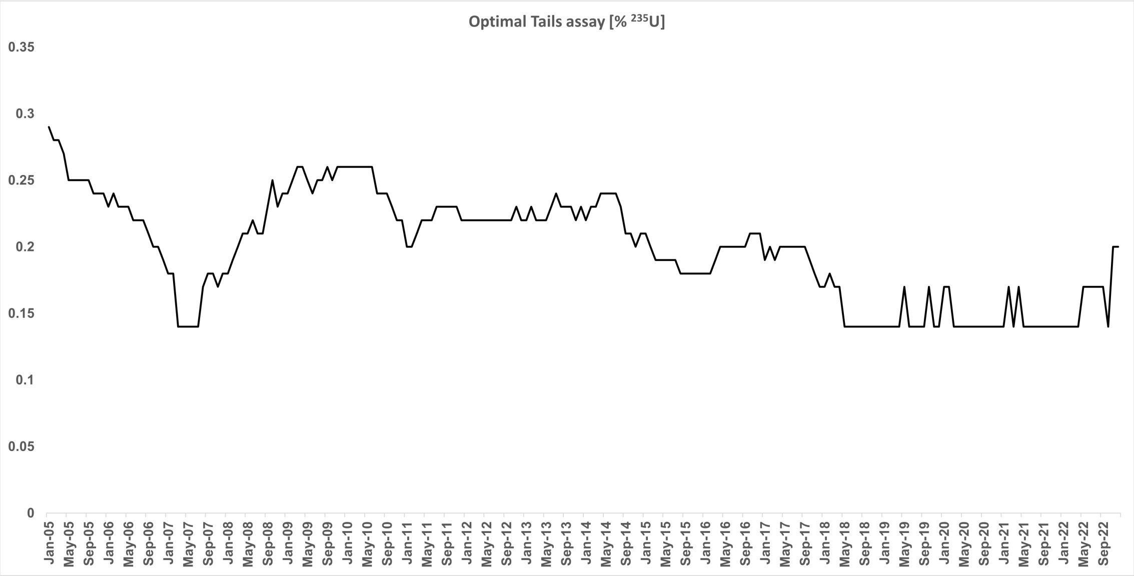

Figure 6: Historical Optimal Operational Tails Assays

December 2022		
Tails Assays	LEU Cost	LEU Cost - Optimal Tails
0.10	$2,431.15	$142.51
0.11	$2,399.02	$110.39
0.12	$2,372.31	$83.67
0.13	$2,350.21	$61.57
0.14	$2,324.77	$36.13
0.15	$2,317.79	$29.15
0.16	$2,306.43	$17.79
0.17	$2,298.14	$9.50
0.18	$2,292.38	$3.74
0.19	$2,289.49	$0.85
0.20	$2,288.64	$-
0.21	$2,290.15	$1.51
0.22	$2,294.02	$5.38
0.23	$2,299.89	$11.25
0.24	$2,307.91	$19.27
0.25	$2,318.08	$29.44
0.26	$2,330.45	$41.81
0.27	$2,344.73	$56.09
0.28	$2,361.24	$72.60
0.29	$2,379.86	$91.22
0.30	$2,400.92	$112.28

Table 11: Cost difference for 1 kg LEU at various tails assays

The price differences presents a significant opportunity for Enrichment companies, as nuclear reactors consume a large amount of LEU. This consumption is in fact 27 tonnes for a standard 1GW LWR. The dollar amounts in table 12 describe the additional profit gained for an enrichment company when transitioning from various operational tails assays, to the optimal operational tails assays. As of December 2022, enrichers switching from the previous optimal tails assays of 0.14% to the current of 0.20% could increase their profits by 975 510 USD for each 1GW LWR they supplied that year.

Profit differences of fuel requirements of a 1GW LWR	
December 2022	
Annual consumption [kg LEU]:	**27000**
Tails Assays	Profit, switching to optimal tails
0.10	$3,847,770.00
0.11	$2,980,395.00
0.12	$2,259,090.00
0.13	$1,662,525.00
0.14	$975,510.00
0.15	$787,185.00
0.16	$480,330.00
0.17	$256,500.00
0.18	$101,115.00
0.19	$23,085.00
0.20	$-
0.21	$40,770.00
0.22	$145,395.00
0.23	$303,750.00
0.24	$520,290.00
0.25	$795,015.00
0.26	$1,129,005.00
0.27	$1,514,430.00
0.28	$1,960,200.00
0.29	$2,462,940.00
0.30	$3,031,560.00

Table 12: Enrichment profit potential, 1 GW LWR

7.2 Phase 2

Table 13 shows the calculated demand shocks that occur should enrichers choose to either under- or overfeed from a reference operational tails assays of 0.14%. The reference level is equal to the level identified in figure 6, showing historical optimal tails assays. Based on these results, 0.14% is the level that most likely have been conducted by the enrichers for a significant time.

Reference Tails: 0.14			
Tails	kgU UF_6	SWU	S_D
0.1	7.038	10.159	-5.10%
0.11	7.138	9.77	-3.75%
0.12	7.242	9.419	-2.35%
0.13	7.349	9.101	-0.90%
0.14	7.416	8.809	0.00%
0.15	7.576	8.542	2.16%
0.16	7.695	8.294	3.76%
0.17	7.819	8.064	5.43%
0.18	7.947	7.849	7.16%
0.19	8.081	7.649	8.97%
0.2	8.219	7.46	10.83%
0.21	8.363	7.282	12.77%
0.22	8.513	7.115	14.79%
0.23	8.669	6.956	16.90%
0.24	8.832	6.805	19.09%
0.25	9.002	6.662	21.39%
0.26	9.18	6.526	23.79%
0.27	9.365	6.396	26.28%
0.28	9.559	6.272	28.90%
0.29	9.762	6.153	31.63%
0.3	9.976	6.039	34.52%

Table 13: Demand shocks resulting from various levels of under- and overfeeding

Table 14 summarizes the most important results from table 13 and connects each scenario to its corresponding, calculated demand shock.

Demand scenarios	
	S_D
Scenario 1	10.83%
Scenario 2	19.09%
Scenario 3	31.52%

Table 14: Demand scenarios

The following tables 15, 16 and 17 shows the associated $\%\Delta P$ responses that the Equilibrium Displacement Model suggest will occur as a response to the demand shocks, given the elasticities of supply and demand we identified during the literature review. The tables also model three different supply responses, S_S at 0, 1/3 and 2/3 of the amount of the demand shock in each scenario.

Scenario 1: $S_D = 10.83\%$		
S_S	$\%\Delta P$ Short-term	$\%\Delta P$ Long-term
$0 * S_D$	515.62%	124.46%
$1/3 * S_D$	343.74%	82.97%
$2/3 * S_D$	171.87%	41.49%

Table 15: EDM Suggested $\%\Delta P$ responses for Scenario 1

Scenario 2: $S_D = 19.09\%$		
S_S	$\%\Delta P$ Short-term	$\%\Delta P$ Long-term
$0 * S_D$	909.23%	219.74%
$1/3 * S_D$	606.15%	146.31%
$2/3 * S_D$	303.08%	73.16%

Table 16: EDM Suggested $\%\Delta P$ responses for Scenario 2

Scenario 3: $S_D = 34.52\%$		
S_S	$\%\Delta P$ Short-term	$\%\Delta P$ Long-term
$0 * S_D$	1643.81%	396.78%
$1/3 * S_D$	1096.87%	264.52%
$2/3 * S_D$	547.94%	132.26%

Table 17: EDM Suggested $\%\Delta P$ responses for Scenario 3

7.3 Phase 3

7.3.1 Part 1

To calculate the suggested demand shocks for U_3O_8 resulting from changes in the price of Coal, we first needed to determine the magnitude of the price change between the periods we determined to be relevant. As described in the methodology chapter, we determined this to be the difference between the 5-year average prior to the Russian invasion of Ukraine and the average futures price for 2026 and 2027.

Average API2 Prices	
Historical	Futures
86.46 $	115.96 $

Table 18: API2 Average prices

This price increase results in a change in Coal price, $\%\Delta P_B$ of 34.12%.

Table 19 shows the change in quantity demanded of U_3O_8, $\%\Delta Q_D$ resulting from the increase in Coal prices as suggested by the crossprice-elasticities determined by Kahouli. We note that the long-run changes in quantity demanded is vastly greater than even the highest demand shock suggested by our phase 2 results in table 13. The short-run changes in quantity demanded are more in line with the scenario 3 demand shock, but are still several times larger than the demand shock in scenario 1.

$\%\Delta Q_D$ **resulting from Coal prices**		
$E_{U,C}$	Short-run	Long-run
$0.9 * E_{U,C}$	31.48 %	105.60 %
$E_{U,C}$	37.47 %	117.34 %
$1.1 * E_{U,C}$	38.47 %	129.07 %

Table 19: $\%\Delta Q_D$ as suggested by cross-price elasticity

Figure 7 represents the Dutch TTF Gas price for the years 2021 to 2022 (investing.com, 2023b). In Europe, natural gas is used for amongst others, heating and electricity production. During the time period in question, the price increase from the lowest to the highest price were 2088.35%.

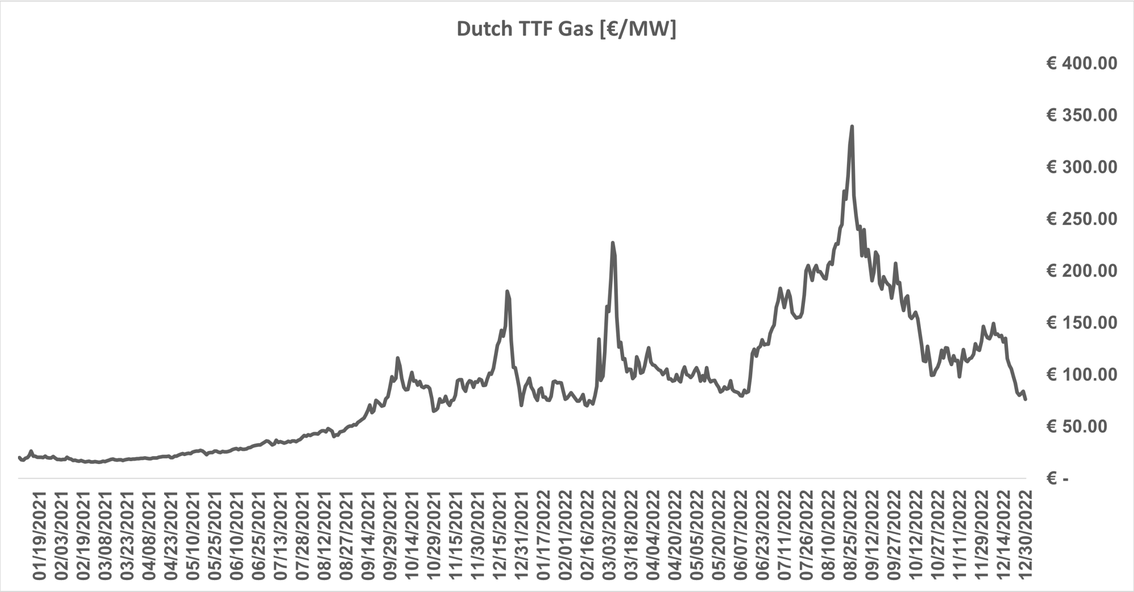

Figure 7: Dutch TTF Gas Prices

Price increases like these have also occurred for industrial minerals, shown in figure 8. This figure represents the prices for Lithium Carbonate of 99.5% purity sold in Chinese markets (investing.com, 2023c). Lithium Carbonate is a critical material in the production of Lithium-Ion batteries, of which China is a major producer. During the time period the figure represents, the price increase from the lowest to the highest price was 1458.44%.

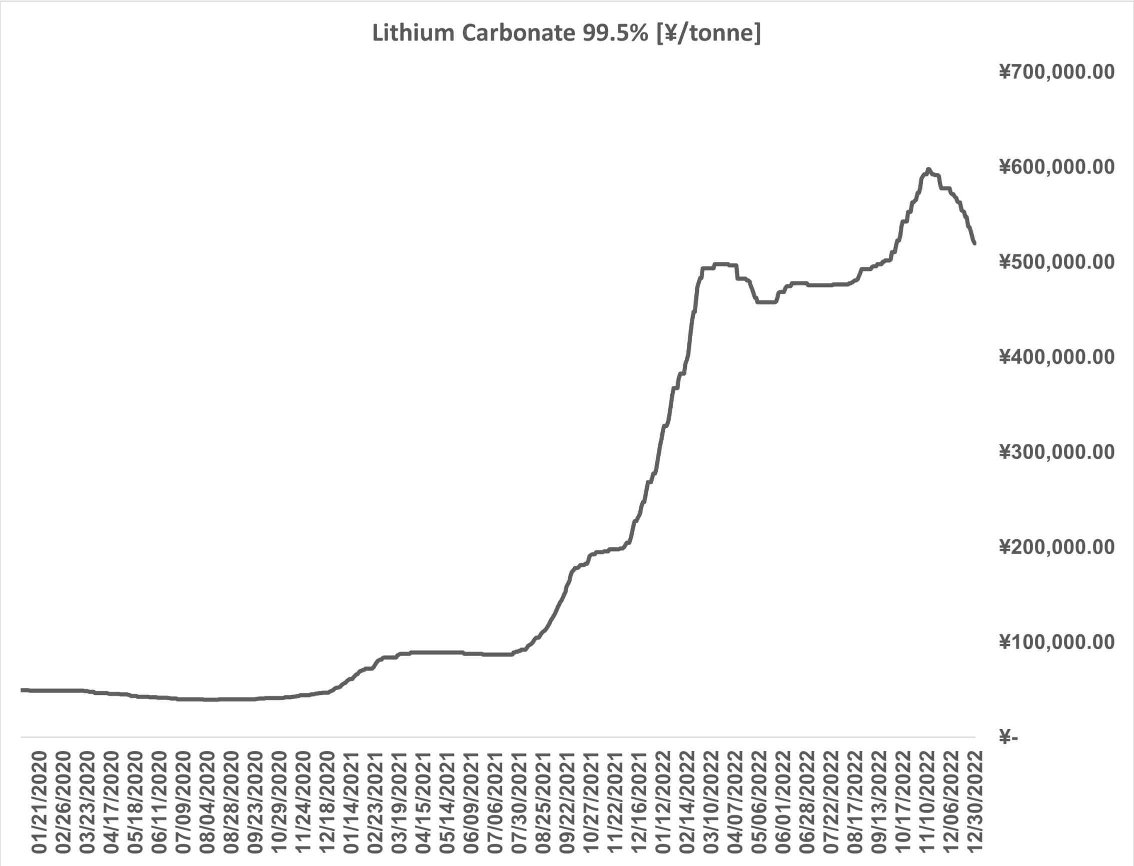

Figure 8: Chineese Lithium Carbonate Prices

7.3.2 Part 2

Additionally, in phase 3 we also calculated the crossprice-elasticity of U_3O_8 resulting from a price change in SWU. The UxC data shows that during 2022 Spot SWU prices increased 115.52 %, and our scenario 1 U_3O_8 demand shock was 10.83 %. This results in a crossprice-elasticity, $E_{U,S}$ of 0.094 which suggests that U_3O_8 and SWU are substitutes, although the substitution effect is small.

Cross-price elasticity u_{308}, SWU	
$E_{U,S}$	0.094

Table 20: Theoretical cross-price elasticity $E_{U,S}$

Figure 9 is simply the graphical representation of the cross-price elasticity of U_2O_8 to SWU, $E_{U,S}$. The x-axis determining the quantity demanded of U_3O_8 is scaled appropriately to the y-axis showing the price growth for SWU, however the x-axis is indexed. Thus, the two points in the graph differ in x-value equal to the demand shock from scenario 1. Figure 9 exemplifies that SWU and U_3O_8 are weak substitutes, as confirmed by the value of $E_{U,S}$.

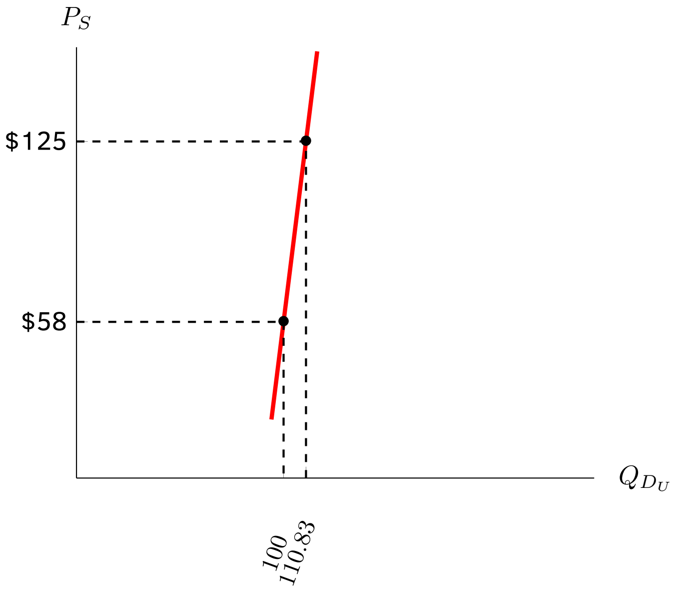

Figure 9: Graphical representation of $E_{U,S}$

8 Discussion

In this chapter we will discuss the results of our research which, in terms of the price responses we will do for each of the three scenarios our research question seeks to answer. First, we discuss the magnitude of the demand shocks we have identified before we discuss the predicted price reactions to these demand shocks. As an aid in this discussion, we use the information regarding market fundamentals and drivers identified during our literature review, and background chapters.

8.1 Demand shocks

The shocks to demand that we have identified during our research, all originate from decisions made regarding the level of operational tails assays at enrichment facilities. Figure 6 shows what the optimal operational tails assays have been since 2005, from a profit maximizing perspective. What it does not show, is what these levels have actually been during the same time period. The figure does however indicate that for an extended period of time, from 2018 to 2022 the profit maximizing operational tails assays have predominantly been 0.14%. This strengthens our belief that 0.14% was the operational tails assays in use in the beginning of 2022. Therefore we believe this level to provide a good point of reference for our calculations of the demand shocks in the three scenarios. We cannot confirm nor deny that 0.14% have actually been the average level for the market, but while assuming that enrichment companies seek to maximize their profits it is a reasonable assumption.

During the last two months of 2022 this profit maximizing level sharply rose to 0.20, and rational financial decisions suggest that enrichers thus will increase their operational tails assays to match this new elevated level, which gives us high confidence in our scenario 1 demand shock. Table 12 determined the yearly financial gain of doing this, in December 2022 to approximately total 1 Million $ per 1 GW reactor. If you account for the total amount of reactors in the global fleet, even though not all are 1 GW reactors, the financial incentives of scenario 1 seem evident. Even so, this change will likely not be instantaneous. Most likely there will be a gradual transition, one facility at a time. This is in part due to enrichers not being able to adjust the operational tails on the fly, but also due to the avaliability of UF_6, which just like SWU is a constrained resource.

The demand shock in scenario 2 is more hypothetical than scenario 1. Figure 6 clearly demonstrate that the profit maximizing operational tails assays that have persisted for the previous four years are significantly lower that they have been historically. In December 2022 where our data ends, there is no financial incentive to enrich at these elevated levels, above 0.20%. What we have seen though, are rising prices for separative work as seen in figures 2 and 3. Specifically the long term price for SWU has been elevated for a long time. Given the 345 million pound shortfall between contracted and spent U_3O_8 that Cameco referenced, it is likely that new enrichment contracts will need to specify high operational tails assays for the constrained global SWU capacity to be able to produce enough LEU. Thus, even though there is no clear financial incentive in our data for enrichment facilities to increase their operational tails assays to the levels required for scenario 2 to materialize, we believe that the fundamentals of the uranium market do allow for it to be possible.

Finally, scenario 3 attempts to model what the necessary increase in operational tails assays means for demand for U_3O_8, should Russian enrichment capacity become partly or wholly unavailable to global markets. From table 3 we know that Russia controls approximately 46% of the global capacity for enrichment. Today, LEU from Russia is used in reactors globally, and many reactors are in fact Russian built and require specially constructed fuel assemblies which makes utilities reliant on the state. Recently, proposed legislature in the US would seek to limit or ban the purchase of Russian Low Enriched Uranium. At the same time, Westinghouse, a western nuclear technology company has begun signing supply deals for fuel assemblies usable in the Russian built VVER reactors (Westinghouse Electric Company, 2023, sec. 1).

Scenarios 2 and 3 share two main similarities, neither are the most likely to occur based on the data and research we have conducted, yet at the same time, market fundamentals appear to allow for them given the occurrence of certain events. A limiting factor for both of them to materialize is the availability of conversion capacity. If the market cannot supply enrichers with sufficient UF_6, the overfeeding modeled in these two scenarios cannot occur. Russia, in the same way as for enrichment controls a significant amount of the global conversion capacity, however as we saw in the literature review, additional western capacity is going online in 2023. The new additions to western capacity are far from able to completely offset Russian capacity, but not insignificant either.

Phase 3 of our research also indicates that the magnitude of the demand shocks according to the cross-price elasticity of U_3O_8 in relation to coal prices, are reasonable. The results in table 18 are based on what the futures prices for coal were at the point of data collection, but we believe it is reasonable to expect that these types of calculations are made when planning to meet future energy demands.

We would like to yet again point out that our demand shocks are calculated with the assumption that enrichers as well as utilities seek to minimize the cost of LEU. This results in our calculated demand shocks being affected by the prices for U_3O_8, Conversion services and SWU and when any of these change, so will the resulting magnitudes of the demand shocks for U_3O_8. Due to this fact, we view the magnitudes of our calculated demand shocks to be reliable estimates of various states of the market, but not precise predictions. We have high confidence of the magnitude of the scenario 1 S_D, but the precise magnitudes of the demand shocks in scenarios 2 and 3 cannot be confidently determined unless the market enters these states. We do however, believe they are reasonable estimates.

8.2 Price responses

The results for the predicted price responses, $\%\Delta P$ to our three scenarios varied from 41.49% at the low end all the way up to 1643.81% at the highest. Granted, the low end is the long-term response where the supply response equals 2/3 of the demand shock in scenario 1 and the highest price response is in the short-run for the worst-case scenario with no supply response. Even so, this exemplifies that the results vary widely.

We modeled supply responses at 0, 1/3 and 2/3 of the demand shock in each scenario. Although these numbers may seem arbitrary we argue that modeling supply responses is essential due to the uncertainty of secondary supply. Predominantly this uncertainty results from the lack of information regarding global inventories, which our literature review failed to quantify. What the literature review did provide for us, with a reasonable degree of confidence is that supply will become available should the price of U_3O_8 reach levels where either secondary sources of supply become financially viable, or additional primary supply does. This, along with the uncertainty about the quantity of global inventories as well as how much of these inventories are mobile led us to decide that modeling the supply response in the way we did was just as good as any other. We did although note that secondary supply has filled the supply gap for many years, and thus we should model up to a 2/3 supply response to cover more of the possible supply reactions. Modeling a full supply response seemed unnecessary, as this would result in a $\%\Delta P$ of zero when using the EDM. In our scenarios, we like to think of the supply response in the short-term to model mobile inventory being brought to market, while in the long-term the modeled supply response would come from other sources like idled mines, or newly financially viable sources of supply being brought online.

8.2.1 Scenario 1

The scenario 1 results are, as we have mentioned earlier the price changes that the EDM suggest will occur if enrichers overfeed at the December 2022 optimal tails assays. Our calculations presume that they before this change were enriching at the previous profit maximizing level of 0.14%. The results found in table 15 show that in the short-term the price response to the a demand shock of 10.83% ranges from 515.62% to 171.87% when adjusting for varying magnitudes of supply response. In the long term the $\%\Delta P$ is significantly lower, ranging from 41.49% in the high response case, to 124.46% in the case where there is no supply response.

As for whether these price responses can materialize, we see several reasons for why they can. Firstly, based on the inflationary adjusted production costs of currently operating mines referenced in the literature review. Significant price increases are required to even incentivize continued operation of the high-cost mines. According to our literature review, currently operating mines have an average COGS of 55.50$ and a maximum cost of 114$. These are however not adjusted for the mining companies cost of capital, which in a high-inflation economy are already high before taking into account the risk premium a mining operation is likely to have. The December 2022 closing spot price for U_3O_8 was 47.75$. If we factor in a conservative 10% WACC, the highest cost currently operating mine would need a spot price of approximately 125$ just to break even, which would represent a 162.62% increase. Based on this calculation alone, we would argue that all of the long-term $\%\Delta P$ cases in scenario 1 are reasonable. This argument applies to all three of the scenarios, when looking at the long-term price responses.

Regarding the short-term price reactions predicted by the EDM, the numbers do seem rather high. One could argue that idled mines could be brought online to cover the increased demand or that open mines could see their output increased in the short-term. This definition of the short-term does however seem to be in a grey-area between the definitions for the short- and long-term presented in our theory chapter, and as such the WACC adjusted mining cost argument loses some of its appeal. The literature review did reveal a few facts to shed some light on the validity of the predicted short-term reactions. First, the LCOE for nuclear generated electricity is only slightly affected by price increases for U_3O_8, which indicates that although the EDM suggested price increases in the short-term are very high, the effect on the cost of electricity is substantially lower. Secondly, the price elasticity of demand for U_3O_8 determined by Kahouli does indicate that demand for U_3O_8 is rather insensitive to its own price, likely due to nuclear mostly serving base-load power demands where it is installed. These arguments for the short-term also do apply to all three scenarios, but at a certain point rising U_3O_8 costs would start to affect LCOE to a point where other energy sources would likely be preferred.

8.2.2 Scenario 2

For scenario 2, we saw the EDM predict short-term price responses ranging from 303.08% and 909.23%, while in the long-term the predictions ranged between 73.16% and 219.74%. This scenario, along with scenario 1 was based on optimal tails assays rising due to elevated costs for conversion and enrichment services. Should price reactions like those predicted by the EDM materialize, the very same calculations that created the demand responses would likely result in optimal tails assays changing, although only slightly. Even so, utilities may have already signed enrichment contracts at higher contractual assays resulting in the same amount of U_3O_8 being demanded as the contracts require utilities to supply material to the enrichers.

For the long-run price responses, the same WACC adjusted mining cost argument applies as for scenario 1. Furthermore, if we look at the historical prices for U_3O_8, the all-time highest price for U_3O_8 of 136$ represent a percentage change in price of 184.82% from the December 2022 closing price for U_3O_8. This increase is before adjusting the all-time-high for inflation since it happened in 2007. Hence, when comparing the long-term predicted $\%\Delta P$ in scenario 2 to mining costs and historical prices, they do appear to be realistic.

If we do adjust the 2007 ATH for inflation since 2007, it would equal a price for U_3O_8 of 306.35$ per pound, which would represent a 541.47% increase compared to the December 2022 closing spot price. We believe that adjusting this number for inflation makes for a reasonable argument, due to the high capital costs for both miners and utilities. For miners, almost all of their expenses have gotten more expensive since 2007 as they are a capital intensive industry with a need for skilled and hard-working labour. For utilities, most of their capital costs result from the investment into building the reactors which certainly have gotten more expensive, but they are also subject to the inflationary pressure from a highly skilled work-force. Hence, mining U_3O_8 have gotten more expensive since 2007, but at the same time the costs for utilities have also risen. The result is that even though production costs for U_3O_8 has risen due to inflation, this price relative to total costs of energy production remain relatively unchanged. Thus, costs for U_3O_8 still remain only a small fraction of total costs for utilities.

In the short-run the price responses are quite significant, and also a good example that the price responses suggested by the EDM in the various scenarios are linearly correlated to the supply response. Even though the price responses are substantial, due to the fact that fuel costs account only for a small part of total costs of electricity for a nuclear reactor, these increases would only slightly translate to electricity prices. Our price data and calculations show that in December 2022 at the optimal tails assays, U_3O_8 only accounted for 20.2% of fuel costs at current market prices. If we however factor in the predicted price reaction in the scenario 2 case with no supply response, the U_3O_8 share of the cost of LEU rises significantly. After the price reaction, while all other factors remaining equal the resulting price reaction from this scenario causes the cost of LEU to rise 407.73%. This would lead to a rise in LCOE, but according to the findings of Lorenczik et al. this number should still only rise approximately 65%. In fact, the affect on LCOE may actually be slightly lower as fuel costs in reality includes expenses for fabricating fuel assemblies using the LEU we have calculated prices for. It is however not specified in the paper if these expenses are included or not in their use of the term fuel costs.

For the cases with a low or no supply response, the model predicts price changes that would cause the price of U_3O_8 to reach record-setting levels, even when adjusted for inflation. Furthermore the implications for fuel costs could possibly cause an increase in quantity demanded of other energy sources while negatively affecting demand for nuclear energy due to reactors operating at lower output.

As our data statistics determined, the historical price data for Spot U_3O_8 has positive skewness and large excess kurtosis. The positive skewness implies many outliers at the right and the high excess kurtosis value implies fatter tails. Using these two summary statistics together we infer that the distribution of historical price data for U_3O_8 exhibits many outliers to the far right of the mean, representing very high prices. We firmly believe that what drives the price of U_3O_8 is enrichment economics, fundamentals and own-price elasticity of demand and that there is no causal relationship between historical and current prices. The summary statistics do however show that the historical tendency of outliers towards higher prices exists.

8.2.3 Scenario 3

When reading the results from the EDM regarding the price reactions in scenario 3, we were initially tempted to discount the results due to the magnitudes of the price responses. In the long-run the predicted $\%\Delta P$ ranges between 132.26% and 396.78% while in the short-run this range is between 547.94% and 1643.81%.

When looking at the long-run numbers for price change, the high supply-response case where S_S equal 2/3 of S_D would bring the price of U_3O_8 to levels that would make currently operating high-cost mines financially viable and would likely incentivize the development of new mines even for high-cost deposits. The low supply response case, along with the case with no supply response both result in a price for U_3O_8 below the inflation-adjusted ATH. Both of these cases would bring the price of U_3O_8 to levels that could make currently operating high-cost mines very profitable, and should result in new mine developments being started at large scales. The $\%\Delta P$ that results from the case with no supply response, even though below the inflation-adjusted ATH still approaches it and it is questionable whether this large of an increase in price is necessary to incentivize new capacity. As was seen in the previous up-cycle in the late 2000s, prices of these magnitudes rather caused a delayed overcapacity in the market causing prices to plummet. Based on the predicted price response to the case where S_S equals 1/3 of S_D, this seems to also apply for this case as the predicted price response is large. Any such delayed oversupply would likely cause prices to plummet, however this price response would not be a result of the shocks modeled in this scenario but rather another one.

In the short-run, many of our arguments as to why the predicted $\%\Delta P$ can occur still seem to apply for the cases with a supply response of 1/3 and 2/3 of S_D in scenario 3. These two cases would cause fuel costs to rise by 737.14% and 491.87%, representing a 117.94% and 78.7% increase in LCOE which are substantially lower than the increases in European electricity prices in the 2020-2022 period (tradingeconomics.com, 2023). This would significantly impact the attractiveness of nuclear power, but also serves as example that the price of U_3O_8 does not significantly affect the total cost of electricity generated from nuclear fission reactors. Price increases like those predicted for these two cases would likely cause a supply-reaction from numerous sources. All of these sources of supply would be highly profitable at these prices, but apart from mobile inventory and perhaps extraction from seawater few of these are readily available on short notice. The initial price response to the demand shock is because of this only affected by the sources of supply that are able to be brought to market at the same time as the demand surfaces. Thus, for the initial price response, mobile inventories and those sources able to react as quickly are the only variable limiting the magnitude of the price response. Furthermore, the price reactions in all of the supply response cases in this scenario, along with the no supply response case in scenario 2 seem extreme, these magnitudes are not unheard of. If we examine Dutch TTF Gas prices in the period 2021-2022 we find a 2088.35% price increase from the lowest to the peak following the energy crisis of 2022(investing.com, 2023b, sec 1). Similarly, Lithium Carbonate, a critical material for the production of Li-ion batteries saw prices rise 1053.85% from the lowest to the highest, during the period 2021-2022 and and 1458.44% when extending the time period to 2020-2022 (investing.com, 2023c, sec 1). Additionally, these examples also serve to demonstrate that price changes caused by shocks often result in partial equilibria, instead of general ones.

A factor affecting the predicted $\%\Delta P$ responses in all scenarios is our choice of the EDM. The model attempts to determine price responses based on elasticities of supply and demand in reaction to shocks to a combination of supply and demand. As we have stated earlier, the commodity market for U_3O_8 is a slow-moving one. During our research, we have calculated what the EDM predicts should be the price reactions to sudden shocks, which may not appear all at once in the real world. This may have caused the predicted price reactions to be larger than we can expect to see in the real world. We believe this applies to the short-run cases, as the short-run elasticity of supply and demand represent the initial response to a change in price and the basis for the demand shocks in our scenarios may be gradual. In the long-run we believe that this is less the case, due to the elasticities of supply and demand represent the readjustment to a new equilibrium, which intuitively correlates better with the slow-moving uranium market.

8.3 Cross-price elasticity

According to our results, U_3O_8 and SWU are weak substitutes. This implies that when the consumption of one of the goods increases, demand for the other should decrease. This effect is evident due to the physics of enrichment, but we also find valid justification for our results through the logic of profit maximization.
We calculated the cross-price elasticity of demand between U_3O_8 and SWU on the basis of the demand shock from scenario 1. This demand shock, originates from the profit maximizing quantity of U_3O_8 rising as a result of increasing prises for SWU, but the cost of conversion is also a part of the equation.

In the enrichment process, SWU is the factor driving the quantity of U_3O_8 that is needed, not conversion. Conversion capacity is necessary to transform U_3O_8 into gaseous UF_6, but the quantity of conversion required is linearly correlated with the quantity of U_3O_8. The physics of enrichment allow for either the amount of SWU, or the amount of Uranium in the centrifuges to be varied. The need for conversion services though, is directly correlated to the amount of Uranium that is being fed into the centrifuges. When SWU prices are high, it may be preferential to feed greater amounts of Uranium into the centrifuges. When SWU prices are low, the opposite occurs. If the quantity of U_3O_8 demanded changes, so does the demand for conversion services.

Therefore, even though the price of conversion is a variable affecting the profit maximizing quantity of U_3O_8, we argue that any cross-price elasticity effects are isolated to SWU. The fact that the price of conversion is a variable in our calculations of the demand shock, may negatively affect the precision of $E_{U,S}$. However, we still believe that any cross-price elasticity affecting demand for U_3O_8 is a result of price changes for SWU. In fact, not only does the price of conversion services not affect the cross-price elasticity of demand for U_3O_8 in relation to SWU prices. The cross-price elasticity for U_3O_8 and for conversion can be said to be the same thing.

A factor that may temporarily affect the cross-price elasticity, is inventories. If, for example an enricher has been underfeeding for an extended period of time, if not sold on the spot market they will have varying quantities of Uranium in either U_3O_8 of UF_6 form. This can result in a rise in SWU prices not affecting quantity demanded of U_3O_8 or conversion services, as it is not necessary to purchase these in the market. This affect is temporary, and over an extended period of time the demand will have to resurface once these inventories are spent.

9 Conclusion

Before delivering our conclusions we restate our research question and the three demand scenarios we have modeled.

Research question:

> ***Which changes does the Equilibrium Displacement Model suggest will occur in the price of U_3O_8 in response to the identified demand shocks, and are market fundamentals supportive of these price changes?***

While working on this thesis, we have identified several potential shocks to demand that may occur:

- The resulting demand shock should enrichers choose to overfeed at the December 2022 optimal tails assays. The resulting S_D of 10.83% is due to operational tails assays increasing from 0.14 to 0.20
- The resulting demand shock should enrichers choose to overfeed at historical high optimal tails assays. The resulting S_D of 19.09% is due to operational tails assays increasing from 0.14 to 0.24
- A loss of Russian enrichment capacity, forcing operational tails assays up due to constrained SWU supply. The resulting S_D of 34.52% is due to operational tails assays increasing from 0.14 to 0.30

During our research, we have arrived at results for all three of the potential shocks to demand described in our research question, both in the short- and long-term. Each of the potential shocks are described in, and arises from separate future market sates, which we have called our scenarios. The scenarios themselves are different both in how they affect the magnitude of the demand shock, but also in regards to what drives them. For this reason, we will answer the research question separately for each of them.

9.1 Scenario 1

Our results, and the discussion regarding the market fundamentals convince us that these are supportive of the suggested price changes for scenario 1 both in the short- and long-term. Focusing on the long-term price changes, we also conclude that the price responses are absolutely necessary, while in the short-term we conclude that the suggested price changes for all supply-response cases are supported by the fundamentals of the market.

9.2 Scenario 2

Our results, and the discussion regarding the market fundamentals convince us that these are supportive of the suggested price changes for scenario 2 both in the short- and long-term. In the short term, the price increases are still possible, however we conclude that the two lowest supply-response cases in the short-term cannot possibly remain a driver of the price for long, as they would increasingly incentivize further supply to reach the market. Effectively creating partial equilibria that drive price in the short term, but also cause supply responses that lead to a general equilibrium in the future. Additional supply responses than those modeled in this scenario are likely to materialize, but they would on the other hand not be associated with the price changes predicted by the model. Instead these would represent new supply-shocks that would cause price reactions from another starting point after the initial demand shock has been reacted to. Therefore, we conclude that market fundamentals are supportive for the price responses in the short-term. In the long-term, the price changes still appear to be necessary for the market to respond to the increase in demand, based on the fundamental factors in the long-term.

9.3 Scenario 3

In the long-term, we find that the price reactions predicted by the EDM range from necessary to possible, based on the arguments made in the discussion chapter, and that market fundamentals are supportive of the predicted price changes. The short-run price reactions, although extreme still appear to be supported by the relative low share of total costs that U_3O_8 represent. In conclusion, we believe that these characteristics and the fundamentals of the market allow for extreme price reactions for U_3O_8 but we do note that the equilibrium-prices predicted by the model in the short-term should be partial, and not general equilibria.

9.4 Recommendations

The Uranium market is not one which academic research has focused on. Based on our literature review which shows increasing demand for nuclear power, and abundant news-flow regarding renewed nuclear programs globally and a turn of public opinion we believe this will change in the future. Furthermore, our literature review and phase 1 research also determined that the shocks likely to result from this as well as other factors are shocks to demand, and for this reason we recommend that these are the focus of any further research.

In our research, we decided to employ the Equilibrium Displacement Model to calculate price responses to possible future shocks to demand for U_3O_8, and as we have alluded to earlier this may not necessarily be the best model for the Uranium market. Should further research be conducted on our subject of price reactions to demand shocks in this market, we recommend to employ another model to calculate the magnitude of the price responses. Calculating the price responses using other models would in our view contribute to a nuanced discussion regarding the validity of our results.

In addition to these recommendations regarding further research, and regardless of whether or not our predictions materialize, it is evident to us that the price of U_3O_8 must rise in order to secure sufficient supply for the increase in global reactor capacity. To this end, we recommend that utilities broadly sign long-term contracts with mining companies, at prices that are financially profitable for the marginal production required to supply future reactor requirements. From the utilities perspective, giving mining companies predictable demand at profitable prices will ensure that utilities have security of supply without having to first pay record breaking prices for an extended period of time. If they do not, we believe that the cycle in the Uranium market will repeat and that volatility will return to previous levels. Along with this volatility, we believe that prices can reach record-setting levels as a result of the slow-moving nature of the mining industry.

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Appendix

API2 Historical Monthly Prices						
Date	Price	Open	High	Low	Volume	Change
1/2/2022	$254.65	$254.65	$254.65	$254.65	0.11K	42.86%
1/1/2022	$178.25	$178.25	$178.25	$178.25	0.51K	30.35%
1/12/2021	$136.75	$121.00	$121.00	$121.00	0.13K	22.37%
1/11/2021	$111.75	$111.00	$111.00	$111.00	0.42K	-51.70%
1/10/2021	$231.35	$231.35	$231.35	$231.35	0.61K	6.08%
1/9/2021	$218.10	$218.10	$218.10	$218.10	1.57K	41.07%
1/8/2021	$154.60	$154.60	$154.60	$154.60	1.08K	16.42%
1/7/2021	$132.80	$122.30	$122.30	$122.30	0.50K	9.98%
1/6/2021	$120.75	$95.90	$95.90	$95.90	0.30K	40.24%
1/5/2021	$86.10	$81.70	$81.70	$81.70	0.14K	20.00%
1/4/2021	$71.75	$70.25	$70.25	$70.25	0.07K	2.35%
1/3/2021	$70.10	$65.50	$65.50	$65.50	0.39K	6.37%
1/2/2021	$65.90	$67.75	$67.75	$63.55	0.10K	-2.80%
1/1/2021	$67.80	$69.35	$69.35	$69.35	0.64K	2.39%
1/12/2020	$66.22	$63.50	$63.50	$63.50	0.11K	8.56%
1/11/2020	$61.00	$50.70	$50.70	$50.70	0.04K	8.25%
1/10/2020	$56.35	$57.25	$57.25	$57.25	0.36K	-1.57%
1/9/2020	$57.25	$52.60	$52.60	$52.60	0.34K	9.78%
1/8/2020	$52.15	$51.70	$51.70	$51.70	0.22K	4.51%
1/7/2020	$49.90	$50.25	$50.25	$50.25	0.38K	0.50%
1/6/2020	$49.65	$44.70	$44.70	$44.70	0.37K	28.63%
1/5/2020	$38.60	$39.75	$39.75	$39.75	0.22K	-3.38%
1/4/2020	$39.95	$48.00	$48.00	$48.00	0.95K	-19.29%
1/3/2020	$49.50	$47.00	$47.00	$47.00	0.22K	2.48%
1/2/2020	$48.30	$49.00	$49.00	$48.90	0.41K	-4.17%
1/1/2020	$50.40	$50.40	$50.40	$50.40	0.83K	-5.17%
1/12/2019	$53.15	$53.15	$53.15	$53.15	0.59K	-5.17%
1/11/2019	$56.05	$56.05	$56.05	$56.05	0.19K	-0.80%
1/10/2019	$56.50	$56.50	$56.50	$56.50	0.69K	-5.12%
1/9/2019	$59.55	$59.55	$59.55	$59.55	1.03K	9.77%
1/8/2019	$54.25	$54.25	$54.25	$54.25	0.30K	-6.30%
1/7/2019	$57.90	$55.15	$55.15	$55.15	1.11K	18.40%
1/6/2019	$48.90	$48.90	$48.90	$48.90	0.58K	-13.37%
1/5/2019	$56.45	$56.45	$56.45	$56.45	0.68K	-4.32%
1/4/2019	$59.00	$59.00	$59.00	$59.00	0.83K	-15.17%
1/3/2019	$69.55	$69.55	$69.55	$69.55	0.26K	-7.27%
1/2/2019	$75.00	$75.00	$75.00	$75.00	0.45K	-5.24%
1/1/2019	$79.15	$79.15	$79.15	$79.15	1.31K	-8.66%
1/12/2018	$86.65	$86.65	$86.65	$86.65	0.20K	-2.09%
1/11/2018	$88.50	$88.50	$88.50	$88.50	0.29K	-9.18%
1/10/2018	$97.45	$97.45	$97.45	$97.45	0.50K	-2.99%
1/9/2018	$100.45	$100.45	$100.45	$100.45	0.28K	2.87%
1/8/2018	$97.65	$97.65	$97.65	$97.65	0.77K	2.68%
1/7/2018	$95.10	$95.10	$95.10	$95.10	0.81K	-1.40%
1/6/2018	$96.45	$96.45	$96.45	$96.45	0.38K	1.53%
1/5/2018	$95.00	$95.00	$95.00	$95.00	0.41K	11.44%
1/4/2018	$85.25	$85.25	$85.25	$85.25	0.44K	7.30%
1/3/2018	$79.45	$79.45	$79.45	$79.45	0.73K	-2.58%
1/2/2018	$81.55	$81.55	$81.55	$81.55	0.81K	-8.98%
1/1/2018	$89.60	$89.60	$89.60	$89.60	0.67K	-5.19%
1/12/2017	$94.50	$94.50	$94.50	$94.50	0.59K	1.89%
1/11/2017	$92.75	$92.75	$92.75	$92.75	0.58K	-2.16%
1/10/2017	$94.80	$94.80	$94.80	$94.80	1.43K	3.78%
1/9/2017	$91.35	$91.35	$91.35	$91.35	0.38K	4.04%
1/8/2017	$87.80	$87.80	$87.80	$87.80	1.40K	5.40%
1/7/2017	$83.30	$83.30	$83.30	$83.30	1.64K	5.24%
1/6/2017	$79.15	$79.15	$79.15	$79.15	0.48K	3.06%
1/5/2017	$76.80	$76.80	$76.80	$76.80	0.66K	1.79%
1/4/2017	$75.45	$75.45	$75.45	$75.45	0.76K	2.86%
1/3/2017	$73.35	$73.35	$73.35	$73.35	0.44K	-5.78%

Table 21: API2 Historical Coal Prices

API2 Futures Contracts			
Term	Price	Vol	Updated
Jan-26	$121.10	0	13:00:01 CT
MTFF6			12-Apr-23
Feb-26	$120.65	0	13:00:01 CT
MTFG6			12-Apr-23
Mar-26	$120.20	0	13:00:01 CT
MTFH6			12-Apr-23
Apr-26	$119.75	0	13:00:01 CT
MTFJ6			12-Apr-23
May-26	$119.30	0	13:00:01 CT
MTFK6			12-Apr-23
Jun-26	$118.90	0	13:00:01 CT
MTFM6			12-Apr-23
Jul-26	$118.40	0	13:00:01 CT
MTFN6			12-Apr-23
Aug-26	$117.95	0	13:00:01 CT
MTFQ6			12-Apr-23
Sep-26	$117.50	0	13:00:01 CT
MTFU6			12-Apr-23
Oct-26	$117.05	0	13:00:01 CT
MTFV6			12-Apr-23
Nov-26	$116.60	0	13:00:01 CT
MTFX6			12-Apr-23
Dec-26	$116.15	0	13:00:01 CT
MTFZ6			12-Apr-23
Jan-27	$115.70	0	13:00:01 CT
MTFF7			12-Apr-23
Feb-27	$115.25	0	13:00:01 CT
MTFG7			12-Apr-23
Mar-27	$114.80	0	13:00:01 CT
MTFH7			12-Apr-23
Apr-27	$114.40	0	13:00:01 CT
MTFJ7			12-Apr-23
May-27	$113.95	0	13:00:01 CT
MTFK7			12-Apr-23
Jun-27	$113.50	0	13:00:01 CT
MTFM7			12-Apr-23
Jul-27	$113.05	0	13:00:01 CT
MTFN7			12-Apr-23
Aug-27	$112.65	0	13:00:01 CT
MTFQ7			12-Apr-23
Sep-27	$112.20	0	13:00:01 CT
MTFU7			12-Apr-23
Oct-27	$111.75	0	13:00:01 CT
MTFV7			12-Apr-23
Nov-27	$111.35	0	13:00:01 CT
MTFX7			12-Apr-23
Dec-27	$110.90	0	13:00:01 CT
MTFZ7			12-Apr-23

Table 22: API2 Futures Prices

API2 Averages	
Type	Price
Historical	$86.46
Futures	$115.96

Table 23: API2 Average Prices