Small modular nuclear reactors as a cost-effective source of clean baseload electricity

A cost-benefit approach to cost-effectiveness analysis

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Preface

This thesis is a part of my master´s degree in Economics at the University of Bergen.
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Abstract

The world needs stable and sustainable, low-carbon energy sources to address the pressing challenges of climate change and energy security. Unlike non-renewable sources of electricity, many renewable sources are intermittent. This intermittency poses a challenge in ensuring a reliable and steady supply of electricity to meet the baseload demand. Nuclear energy offers the advantage of being virtually carbon-free and capable of providing a consistent power output, to meet baseload demand. Small modular nuclear reactors also known as SMRs, present potential improvements over traditional large-scale nuclear reactors, making SMRs a potentially feasible contributing solution to the security of supply issue posed by renewables. On this basis my thesis proposes the question:

Can small modular nuclear reactors be a cost-effective solution to the security of supply issue in achieving carbon-neutral power grids?

Through using a cost-benefit analysis framework for financial net present value estimation while exploring the relevant economic literature, I model the financial returns of small modular nuclear reactors, SMRs, and large-scale reactors. I proceed to use the financial estimates from the cost-benefit analysis framework to model the cost-effectiveness measures of SMRs and large-scale reactors, and perform cost-effectiveness analysis comparing SMRs to large-scale reactors and an all-renewable battery-based solution for benchmarking.

My results imply the needed retail market electricity price for the return on the nuclear power plant to be worthwhile for investors, ranges between $147 and $213 per MWh, for SMRs. Meanwhile, that of the large-scale reactors ranges between $101 and $2806 per MWh, and combining lead-acid batteries with intermittent wind and solar under ideal conditions, might require a retail electricity price of $575 per MWh. As I estimate the historical real average retail price for electricity over the last few years to be $140, it seems that neither SMRs nor large-scale reactors are competitive in wholesale electricity markets without policy intervention. However, my results suggest SMRs require a lower retail price of electricity for the investment to be attractive, compared to large-scale reactors and the benchmarking alternative. This led to the conclusion that small modular nuclear reactors can be a cost-effective solution to the security of supply issue in achieving carbon-neutral power grids. I recommend that policy intervention should be used to incentivize investments in SMRs and other carbon-neutral solutions, as long as the financial and social costs of these interventions are lower than the benefit of achieving carbon-neutral power grids.

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Abbreviations and acronyms

Descriptions here are credited to Rothwell (2015) if no other citation is stated.

ABWR	advanced boiling water reactor
AEO	US EIA’s Annual Energy Outlook
ALWR	advanced light water reactor
AP1000	Westinghouse’s 1 117 MW advanced passive pressurized water reactor
BWR	boiling water reactor
CBA	cost-benefit analysis (Boardman et al., 2018)
CEA	cost-effectiveness analysis (Boardman et al., 2018)
FOAK	first-of-a-kind reactor
kW	kilowatt electric
LCOE	levelized cost of electricity or energy
LMR	liquid metal reactor also known as a fast reactor
LWR	light water reactor
MIT	Massachusetts Institute of Technology
MW	megawatt electric also known as MWe
MWh	megawatt-hour
NOAK	nth-of-a-kind reactor
NPP	nuclear power plant
NPV	net present value
OCC	overnight construction costs
OL3	the Finnish Olkiluoto 3 1600 MW nuclear reactor (Rogers, 2023)
PRIS	IAEA’s Power Reactor Information System
PWR	pressurized water reactor
SMR	small modular reactor
TVA	Tennessee Valley Authority
TVO	OL3’s owner and operator, Teollisuuden Voima (Rogers, 2023)
U-235	uranium isotope 235
U-238	uranium isotope 238
WACC	real weighted average cost of capital
WWER/VVER	water-moderated water-cooled electricity reactor

Parameters and variables

All parameters and variables using $ values are in 2023 USD in the modeling analysis. Inflation is accounted for through r.

AD	aggregated debt after construction
CF	average capacity factor also known as average load factor
DC_{LWR}	yearly decommissioning costs of an LWR, during decommission
DC_{MW}	overnight decommissioning costs per MW
DC_{NPV}	net present value of total decommissioning costs
DC_{SMR}	yearly decommissioning costs of SMRs, during decommission
E	average MWhs produced annually
FC_{LWR}	yearly financing costs of an LWR, during downpayment
FC_{NPV}	net present value of total financing costs
FC_{SMR}	yearly financing costs of SMRs, during downpayment
F_{MWh}	fuel expenditures per MWh
G	average percentage of the retail price of electricity awarded to power generation
KC_{LWR}	yearly construction costs of an LWR, during construction
KC_{MW}	overnight construction costs per MW
KC_{SMR}	yearly construction costs of SMRs, during construction
L	average annual power plant employment during operation
l	percentage of electricity supply lost in transmission
M	miscellaneous operational costs i.e., cost of maintenance materials, replacement of depreciating physical capital, supplies, operating fees, property taxes, and insurance premiums not covered by PIN
MW	power plant net megawatt electric capacity
NPV	net present value
NPV_{LWR}	net present value of building an LWR
$NPV_{LWR-OL3}$	net present value of building the OL3 reactor
NPV_{SMR}	net present value of building SMRs
$\bar{n}$	construction period in years
$\dot{n}$	downpayment period in years

$\tilde{n}$	decommission period in years
OM_{MWh}	operation and maintenance costs per MWh
PIN	insurance premium for off-site damages from accidents including major nuclear accidents
P_L	the average wage of power plant employees during operation
p_{MWh}	average retail price of electricity per MWh
$p_{MWh}^{NPV \geq 0}$	minimum retail price of electricity per MWh needed for $NPV \geq 0$
R_{LWR}	yearly operational revenue of a LWR, during operation
R_{NPV}	net present value of the total revenue stream
R_{SMR}	yearly operational revenue of SMRs, during operation
r	real discount and interest rate, real WACC
T	operational period in years
t	years ahead from the present
VC_{LWR}	yearly operational variable costs of a LWR, during operation
VC_{MW}	operational variable costs per MWh
VC_{NPV}	net present value of total variable operational costs
VC_{SMR}	yearly operational variable costs of SMRs, during operation
$\%NPV_{FC}$	percentage of net present value of costs stemming from financing costs
$\%NPV_{VC}$	percentage of net present value of costs stemming from operational variable costs

1. Introduction

In our increasingly energy-dependent world, the rising demand for energy is largely met through the combustion of fossil fuels, thereby exacerbating the warming of our planet (IEA, 2021). Over the last few years, the combination of a full-scale Russian invasion of Ukraine, COVID-19, and political pushback on globalism, has pushed established supply chains to their limits and further challenged our dependence upon fossil fuels. The world needs stable and sustainable, low-carbon energy sources to address the pressing challenges of climate change and energy security (Equinor ASA., 2022). Among the options available, nuclear power has emerged as a prominent contender due to its potential to provide reliable baseload electricity while generating minimal greenhouse gas emissions (Donovan & Kolasinski, 2020). However, nuclear power certainly faces challenges of its own. Concerns regarding safety, proliferation of nuclear weapons, handling of nuclear waste, and high capital costs, have soured the reputation of nuclear power among the public (Office of Nuclear Energy, 2021; Funk et al., 2020; Leppert, 2022).

In recent years, there has been a growing interest in the potential of Small Modular Reactors, SMRs, to ease these concerns. SMRs promise several advantages over traditional large-scale nuclear reactors, such as reduced land usage, enhanced safety features, and flexibility in deployment (Liou, J., 2023). As a result, SMRs have gained significant attention from policymakers, industry stakeholders, and researchers worldwide. My thesis aims to critically assess the current state of SMR technologies and to evaluate, from an economic point of view, their feasibility and potential in different energy market scenarios. I seek to examine the cost considerations, market dynamics, and financial aspects associated with nuclear energy, and to propose whether the promises of SMRs sufficiently increase the viability of new investments in nuclear energy. By exploring the economic viability and competitiveness of nuclear power today, my research will contribute to the broader understanding of its role in a sustainable and economically efficient energy landscape.

The significance of my thesis lies in the continuous need to evaluate the economic feasibility of potential long-term solutions, in this case nuclear power, to the challenges of climate change and energy security, in a constantly changing world. Understanding the cost dynamics, potential risks, and benefits associated with nuclear power today is vital for policymakers, energy companies, and society at large. As countries strive to transition to a low-carbon future and meet their climate targets, it is essential to assess whether nuclear power can effectively contribute to decarbonization efforts while ensuring economic stability and affordability. To achieve the objectives of my thesis, I will conduct a comprehensive analysis of existing literature, empirical studies, and case studies. My research will encompass a range of factors, including capital costs, operational expenses, fuel supply and waste management, regulatory frameworks, electricity market dynamics, and externalities associated with nuclear power. By synthesizing and critically evaluating these factors, I aim to provide a nuanced understanding of the economic dimensions of modern nuclear energy. Finally, this thesis aims to address the question: *Can small modular nuclear reactors be a cost-effective solution to the security of supply issue in achieving carbon-neutral power grids?*

My findings will inform policymakers, investors, and stakeholders involved in energy planning and decision-making processes. By shedding light on the economic viability of SMRs, this thesis seeks to contribute to evidence-based discussions and policy formulation regarding the future of nuclear energy, its role in sustainable development, and its potential implications for energy systems and markets in the pursuit of a low-carbon future.

1.1 Methodology

In answering my research question, I will conduct a cost-effectiveness analysis comparing expenses associated with utilizing SMRs or site-based light water reactors, for supporting renewable energy production. My goal is to benchmark these costs against an all-renewable battery-based alternative. In uncovering the cost and revenue dynamics of nuclear power, I will use a cost-benefit analysis framework using factor estimates from economic theory and empirical evidence to model new investments in constructing a conventional site-based light water reactor, which I will often refer to as the LWR, and constructing SMRs. For the LWR model, there is more available research and empirical data as there are many operational large-scale nuclear reactors in the world today. For the SMR model, I am not as fortunate as there are very few SMRs in commercial operation (Liou, 2023). Therefore, factor estimates for SMRs will have to be based on the predicted differences between them and traditional large-scale nuclear reactors, upon what is predicted by economic theory, the relevant literature, and reporting from the industry. I will compare the resulting estimates to each other and the benchmark. I will assess whether SMRs have the potential to be more cost-effective than established large-scale nuclear reactors. Finally, I will conclude whether SMRs can be a cost-effective solution to the security of supply issue in achieving carbon-neutral power grids.

2. Background

2.1 Carbon-neutral power grids & the security of supply issue

Carbon-neutral power grids refer to the establishment of electricity networks that produce net zero carbon emissions over their operational lifetime. According to Equinor ASA. (2022), "Net zero, sometimes called carbon neutrality, refers to the equilibrium between the number of anthropogenic greenhouse gases released into the atmosphere and the amount removed and stored by carbon sinks". Carbon sinks refer to storing captured carbon dioxide emissions, CO_2, underground (Equinor ASA., 2023). Achieving carbon neutrality involves a shift away from fossil fuel-based power generation, which releases significant amounts of greenhouse gases like CO_2, the primary greenhouse gas contributing to climate change. This shift requires the usage of renewable energy sources such as solar, wind, hydroelectric, and geothermal power, which do not produce CO_2 emissions during electricity generation. By minimizing carbon emissions from power generation, carbon-neutral energy grids play a vital role in mitigating climate change and promoting a sustainable energy future (UN, 2023; EPA, 2022). This forms the basis of my central objective, as our power grids are currently not carbon neutral, and to become carbon neutral we need to reduce and capture carbon emissions.

Why not just replace fossil fuels with renewables? The price of renewable energy, especially wind and solar, trended downward for a long time until COVID-19 spread worldwide in 2020. In most countries today, solar photovoltaics and onshore wind are the cheapest options for expanding electricity production capacity (IEA, 2023a). It appears increasingly likely that renewable sources will eventually replace fossil fuels as our primary source of electricity. However, this transition is not without its challenges, particularly when it comes to meeting the demand for baseload electricity. Baseload electricity refers to the constant and consistent supply of electricity that is required to meet the minimum energy needs of a region or country. Unlike non-renewable sources like coal or natural gas power plants, which can provide continuous baseload power, many renewable sources are intermittent, meaning they rely on factors such as sunlight or wind availability. This intermittency poses a challenge in ensuring a reliable and steady supply of electricity to meet the baseload demand (Arango-Aramburo et al., 2021; Gawell & Matek, 2015). Addressing the security of supply problem is crucial to maximizing the potential of renewable energy and facilitating the transition to a sustainable low-carbon future. A common argument for entirely renewable power grids is that this supply challenge can be met by using advanced battery technology and improving our power grids to become better at evening out supply and demand over great distances. Gawell & Matek (2015) argue to the contrary, “Intermittent sources alone cannot cost-effectively generate electricity for a balanced grid.”. They argue that baseload renewables like hydroelectric power and geothermic power should be in focus when combatting the problems posed by intermittency and overgeneration. However, hydroelectric, and geothermal power have limitations of their own that restrict their deployment and raise doubts about the notion that they can effectively solve this problem alone (IEA, 2023b; EIA, 2022a). Finally, combining fossil fuels with carbon capture and storage technology might be economically viable, but a large percentile of emissions stemming from the fossil fuel electricity production value chain, cannot currently be efficiently captured. The key takeaway is that betting on any one technology alone for electricity supply is unwise, as we need a broad portfolio of electricity sources for a stable and sustainable power grid (EIA, 2022b; Baylin-Stern & Berghout, 2021).

2.2 Nuclear power

Nuclear power harnesses the energy released through a process called nuclear fission. Typically, in a nuclear power plant, the fuel, usually uranium or plutonium, undergoes controlled chain reactions. These reactions cause the fuel atoms to split, releasing an enormous amount of energy in the form of heat. This heat is usually used to generate steam, which drives a turbine connected to a generator, producing electricity. Unlike conventional power plants that burn fossil fuels, nuclear power plants emit close to no greenhouse gases except water vapor during operation, making them a low-carbon or even carbon-free energy source. The energy density of nuclear fuel is exceptionally high, allowing for a small amount of fuel to generate significant amounts of electricity over a long period (Nuttal, 2022). While nuclear energy is a non-renewable source of power, it offers the advantage of being virtually carbon-free and capable of providing a consistent power output to meet baseload demand. SMRs present potential improvements over traditional large-scale nuclear reactors, making SMRs a potentially feasible contributing solution to the security of supply issue posed by renewables (Donovan & Kolasinski, 2020).

For my analysis, I will be modeling based on assumptions specifically for light water reactor designs, LWRs, for both SMRs and large-scale reactors. Note that when I refer to LWRs in other chapters I am referring to large-scale LWRs only, not SMRs. Light water reactor is an umbrella term for multiple technological designs of nuclear fission reactors, these are PWRs, WWERs/VVERs, BWRs, and ABWRs (see abbreviations and acronyms). Most nuclear fission reactors undergoing construction, operation, or decommissioning, are LWRs. The reason to make this distinction is that there are other nuclear reactor designs such as liquid metal reactors that have different qualities, are not as established, and which would further complicate the analysis (Rothwell, 2015).

2.3 Cost-effectiveness

What does it mean for SMRs to be cost-effective in achieving carbon-neutral power grids? Perman et al. (2011) defines cost-effective pollution abatement instruments as follows:

> Suppose a list is available of all instruments which are capable of achieving some predetermined pollution abatement target. If one particular instrument can attain that target at a lower real cost than any other can then that instrument is cost-effective.

Boardman et al. (2018) describes cost-effectiveness analysis, CEA, as usually used in situations with two key characteristics. First, the decision being evaluated has a single major benefit that is hard to monetize. Here, this is facilitating carbon-neutral power grids and global warming mitigation through supplying low-carbon baseload electricity, where the costs of not doing anything are hard for us to measure and agree upon. Second, the only costs being measured are the financial costs of the decision. Here, these are the financial returns of costs and revenues of investing in SMRs reflected in the cost per unit of electricity produced required for the investment to be covered. To measure the cost-effectiveness there also needs to be a relative quantified non-monetized measure of benefit, and I have chosen to consider every clean MWh added to the baseload electricity supply as a unit of benefit. For SMRs to be cost-effective in this respect the costs per MWh need to be lower than that of the alternative methods to ensure carbon-neutral power grids. However, as I cannot reasonably know the costs of every proposed alternative solution to this problem, I am using a benchmark for comparison. As a benchmark, I am using an estimate from Elkadeem et al. (2021) of the minimum cost of energy in a completely renewable energy system utilizing a combination of wind, solar, and lead-acid batteries in Saudi Arabia, where conditions for wind and solar are near optimum. This benchmark is a cost of energy production of about $345 per MWh.

3. Economic theory

3.1 Cost-benefit analysis

As mentioned, I am performing a cost-effectiveness analysis to answer my research question. However, to estimate the financial costs and revenues I need to make this assessment and to improve upon the more barebones structure of CEAs, I have chosen to adapt a cost-benefit analysis framework to suit my needs. As stated by Boardman et al. (2018): “Cost-benefit analysis, CBA, is a policy assessment method that quantifies in monetary terms the value of all consequences of a policy to all members of society”. Cost-benefit analysis is primarily used for policy assessments of public programs and projects, where various policy options are compared to each other through their present discounted real values, or net present values, NPVs. The NPV of a policy option is determined by aggregating the discounted real benefits and subtracting the discounted real costs associated with that policy. Net present values discount cash flows to account for the time value of costs and benefits i.e., you would rather be rewarded today than tomorrow so you can enjoy the reward immediately or, if possible, invest it in financial assets. We also tend to account for inflation to obtain the real costs and benefits for the NPV. CBA is a comparative analysis where there are at least two options; applying a new policy or sticking to the status quo. Numerous options may be considered. However, when making a recommendation, the primary decisive factor is which option has the highest NPV. There are ten major steps in conducting CBA (Boardman et al., 2018):

1. Explain the purpose of the CBA
2. Specify the set of alternative projects
3. Decide whose benefits and costs count
4. Identify the impact categories, catalogue them, and select metrics
5. Predict the impacts quantitatively over the life of the project
6. Monetize all impacts
7. Discount benefits and costs to obtain present values
8. Compute the net present value of each alternative
9. Perform sensitivity analysis
10. Make a recommendation

Step 1; The purpose of the CBA, was introduced in the introduction. To reiterate, I want to know whether SMRs can be cost-effective as a contributing solution to the security of supply in achieving carbon-neutral power grids. Step 2; the set of alternative projects, was explained in the methodology chapter, but the options might still not be inherently obvious. The options forming the CBA are investing in a large-scale LWR or investing in SMRs. However, these options are both compared to the Elkadeem et al. (2021) all-renewable battery-based cost-effectiveness benchmark of $345 per MWh.

Step 3; Whose benefits and costs count? Social costs and benefits are difficult to estimate for any source of energy, and as a result, we cannot fully internalize the externalities of nuclear power or any other source of power. Some externalities, like the cost of handling nuclear waste and the risk of nuclear accidents, are already partially internalized in financial costs through strict regulation in most countries. Regulation intended to avoid accidents is by far the biggest driver of the financial costs of nuclear power. Although it is not easy to accurately estimate financial costs and revenues, it is more feasible than estimating all the social costs and benefits of nuclear power (Lévêque, 2015). For these reasons and as other social costs and benefits are usually left out when performing the cost-effectiveness analysis, I have opted to focus on the financial costs and benefits of these investments. I will exclude any social costs or benefits that are not already internalized in the costs of production or the effective non-monetized benefit of clean MWhs. I leave estimating further social costs and benefits to follow-up research within the field. Following my assumptions, the CBA framework is like a NPV analysis. NPV analysis also known as NPV modeling is a project assessment method that uses discounted financial cashflows to assess the value of a project (Hopkinson, 2016). After disregarding most social costs and benefits in the CBA framework the methodologies are practically the same, so I've opted to still refer to my approach as a CBA.

Step 4; Identify, catalogue, and select metrics for the impact categories. Rothwell (2015) describes NPV analysis for nuclear power plants as follows:

> The net present value (NPV) incorporates electricity price information. The NPV is equal to the present discounted value of revenues minus costs over periods of construction (for example five years), operation (for example 50 years), and decommissioning (for example ten years). In NPV analysis, the costs and benefits (primarily revenues) are discounted to the present at the decision maker's opportunity cost of capital.

I catalogue the impact categories in my CBA as Rothwell does here. These impact categories are the fixed costs associated with financing construction, the variable costs associated with operation, the fixed costs associated with decommissioning, and the revenue resulting from electricity sales, R, of the power plants. All categories are measured in USD where possible. Steps 5 through 7 are performed throughout the theoretical chapter of my thesis, while steps 8 through 10 are performed through the analysis, discussion, and conclusion chapters of my thesis. For the last steps, in contrast to a typical CBA, the value of the resulting NPV is not the only value of interest for my recommendation. A positive NPV would imply that the technology is competitive under my modeling assumptions, that investing in it is profitable by itself, and that no policy intervention should be needed for the technology to be adopted. However, the cost per MWh is what determines the cost-effectiveness of the technology.

3.1.1 Cost-benefit analysis vs. LCOE based analysis for nuclear power

When comparing investments in electric utilities it is standard practice within energy economics to use the levelized cost of electricity methodology, LCOE, as many consider it as the gold standard metric for decision-making. LCOE is calculated as the real average cost of electricity, accounting for all electricity produced by the plant during its lifetime, and all foreseeable costs including construction, financing, decommissioning, and operational costs. Compounding all this into a single metric, the LCOE makes for easy comparison between electric utilities. However, the LCOE method clouds the dynamics that form the costs of supply and does not consider electricity demand at all. Furthermore, disparities between LCOE estimates are significantly greater than the disparities between the estimated construction costs themselves, which are large. These are significant downsides to the LCOE methodology when considering investments in nuclear power, as the upfront capital investment for constructing and financing a nuclear power plant can be very high and carry a lot of risk. Even though the LCOE might be lower for nuclear power than a given alternative, building a nuclear power plant is likely to cost billions of dollars, it takes many years to complete construction and start production, and construction costs are prone to go over budget. Using CBA through calculating NPVs incorporates electricity demand in the model to estimate the flow of revenue generated and allows us to better deconstruct cost flows into their source of origin (Rothwell, 2015; Lévêque, 2015). The LCOE might appear as the perfect option to estimate financial costs when determining cost-effectiveness. However, I have chosen to use a CBA framework instead as the LCOE leaves us with less information for analysis, it is less flexible for tweaking assumptions, and it does not model the dynamics of nuclear power in as much of a transparent and intuitively understandable fashion.

3.2 Economics of LWRs

For my NPV models, I define the following variables to represent periods in time: $\bar{n}$ is the construction time for nuclear reactors in years, T is the operational lifetime in years, $\dot{n}$ is the number of years between $\bar{n}$ and the maturity date of the aggregated debt from financing construction, and $\tilde{n}$ is the number of years required to decommission the reactor. All categories of costs or revenues are assumed to be constant each year they are actively being incurred or enjoyed respectively. For example, annual variable costs have the same positive value each year of the plant's operative lifetime, but before and after the operative lifetime they are equal to zero. The costs associated with financing construction, FC_{LWR}, are incurred through annual downpayments of the aggregated debt after construction is finished, AD. Downpayments are assumed to be annuity term downpayments. The first downpayment is one year after construction is finished $\bar{n}+1$, and they go on through the rest of the $\dot{n}$ years until it has been $\bar{n}+\dot{n}$ years since the investment when the last downpayment is made. The costs associated with decommissioning the power plant, DC_{LWR}, are first incurred the year following the end of the power plant's lifetime, namely the year $\bar{n}+T+1$. The last costs of decommissioning are incurred the year decommissioning is finished, namely $\bar{n}+T+\tilde{n}$. Revenue from the sale of electricity, R_{LWR}, and variable costs associated with operation, VC_{LWR}, are incurred /enjoyed during the operational lifetime of the plant i.e. from the first year following finalization of construction $\bar{n}+1$, to the end of the operational lifetime of the powerplant at $\bar{n}+T$. By discounting these cashflows for the present, we get the expression for the net present value of investing in a new LWR, NPV_{LWR}:

$$NPV_{LWR} = \sum_{t=\bar{n}+1}^{\bar{n}+T} \frac{R_{LWR}}{(1+r)^t} - \sum_{t=\bar{n}+1}^{\bar{n}+T} \frac{VC_{LWR}}{(1+r)^t} - \sum_{t=\bar{n}+1}^{\bar{n}+\dot{n}} \frac{FC_{LWR}}{(1+r)^t} - \sum_{t=\bar{n}+T+1}^{\bar{n}+T+\tilde{n}} \frac{DC_{LWR}}{(1+r)^t}$$

3.2.1 Financing & construction costs of LWRs

The costs of financing construction are by far the biggest financial hurdle for nuclear power. Regarding the high costs of financing construction Lévêque (2015) states: "If no spell is found to lift the curse of escalating costs, nuclear power will be gradually sidelined". There are three primary economic aspects of nuclear power plants, NPPs, construction costs that are of interest. The first two are how we do not seem to observe any significant learning effects or economies of scale benefits for NPP construction, while the last aspect of interest is how regulation increases the costs of construction over time. The first two are fascinating qualities from the economist's point of view, as they contrast our theories of supply-side dynamics in most industries, where costs tend to fall because of economies of scale and learning effects. Real costs of constructing NPPs are higher now than when constructing the world's first reactors as costs have steadily risen over time, primarily caused by regulation. Lévêque (2015) refers to this phenomenon as "the diseconomies of scale". Both the overnight construction costs, OCCs, i.e., the estimated costs of construction without accounting for time, and the timewise length of construction, have been continuously on the rise in most countries over the last decades (Lévêque, 2015).

An important reason why we do not observe benefits from economies of scale or learning effects is the lack of standardization and continuous change of designs. It seems that the lack of economies of scale benefits in terms of the size of individual NPPs is mainly caused by larger complex designs needing more complex safety features. However, the cost reducing benefits of mass constructing new reactors might exist, it just seems they never get the chance to materialize. NPP designs are very diverse, few reactors are ever constructed per design, they are built and operated over long timespans, and expertise deteriorates over time. Because of this, learning effects and economies of scale benefits for most reactor designs never get the chance to reduce costs meaningfully (Lévêque, 2015).

As regulatory frameworks are very different in-between countries, and as the costs caused by increased regulation seem to be the primary driver of NPP's costs, we cannot generalize construction costs into a single number. There is also limited data on the construction costs of nuclear power. There are some available data from the US, France, and a couple of others like Finland, but there is limited publicly available and reliable data from either the former Soviet Union, Japan, India, South Korea, or the People's Republic of China (Lévêque, 2015). Therefore, I will limit myself to a three-country estimate approach for construction costs, based on the scientific literature and observed data. I will be considering the construction costs of building in France, the US, and the specific cost of one of the most recently finished European large-scale reactors, the 1600 MW electric capacity Olkiluoto 3 reactor in Finland also known as OL3 (Rogers, 2023). As these estimates and cases have significant implications for my analysis, they will be scrutinized thoroughly in this chapter. The metric usually used when discussing OCCs is USD per kW electric capacity, I will be using USD per MW electric capacity. This is equivalent to USD per kW electric capacity multiplied by one thousand and is referred to as just "per MW". Realistically, construction costs are not incurred over a single night. I will assume that construction costs per year are equal fractions of the OCCs, expressed as KC_{LWR}. I express the OCCs per MW as KC_{MW}. By multiplying KC_{MW} by the MW electric capacity and dividing by the construction time $\bar{n}$, I get the expression for KC_{LWR}:

$$KC_{LWR} = \frac{KC_{MW} \times MW}{\bar{n}}$$

The recent case of the OL3 reactor seems like a worst-case scenario. The final costs of the project, first estimated to be €3 billion or €1 850 000 per MW, were later estimated to be €6,6 billion or €4 125 000 per MW. The construction time estimates, first estimated to be 4,5 years were later estimated to be 10 years. A similar type of reactor is being constructed at Flamanville in France which had a similar cost estimate at the start of construction. This estimate was later revalued to €8,5 billion. Two similar reactors being considered for construction in the UK in 2013 were projected to cost almost €10 billion each (Lévêque, 2015). Today we know that the OL3 reactor took eighteen years to construct and had a total financing cost of €11 billion or €6 875 000 per MW, equated to $12,4 billion or $7 750 000 per MW. These numbers are roughly around four times as large as the original estimates for both the financial costs and the construction period. The total costs of $12,4 billion came to light after the Finnish operator TVO and the main construction contractor Areva sued each other, and investment losses had to be disclosed from both sides before a settlement could be reached. These proceedings happened around 2018, but these are the estimated costs both parties would incur by the completion of the OL3 reactor. The OL3 started commercial operation the 16th of April 2023 (Rogers, 2023; World Nuclear Industry Status Report, 2019; Forsell & Rosendahl, 2018). Even though years have passed since 2018, the $12,4 billion in 2023 USD is likely to still be the best OL3 financial cost estimate and is what I will use when considering this reactor.

Even though the Flamanville reactor could end up costing much more than the initial expectation, construction costs have historically grown far less in France than in the US. Some US economists estimated as high as a 25% annual increase in nuclear power financing costs from regulation alone. Lévêque (2015) states that the more reasonable estimates are that the OCCs in the US have risen at an annual rate of 9,2%, while the OCCs in France have risen at an annual rate of 1,7%. Still, if this is the true growth rates of costs then the US costs of construction would be very high today. An annual growth rate of 9,2% would imply costs approximately double every eight years. The OCCs of natural gas and coal fired power plants also rose steeply during the 2000s. The difference is that OCCs of fossil fuels can be estimated relatively accurately and are more predictable, while the accuracy of estimated NPP construction costs has historically been very poor (Lévêque, 2015). NPP financial and construction costs are recognized simply as an uncertainty. Uncertainty in this context meaning that we might not know the underlying probability distribution of total construction costs. Rothwell (2015) describes this uncertainty as potentially caused by so-called "unknown unknowns".

This uncertainty has not stopped analysts from trying to estimate costs, and as one might imagine estimates vary wildly. Rothwell (2015) compares three different American OCC estimates from 2010 for building AP1000 model ABWRs and adjusts them to 2013 USD. These estimates consider 6 reactors considered separately for construction in pairs by three different companies; The Georgia Power Company, South Carolina Electric and Gas, and Progress Energy. They were respectively $4 500 000, $3 900 000, and $4 800 000, with a mean of $4 400 000, per MW in 2013 USD. Both Rothwell (2015) and Lévêque (2015) refer to a 2009 MIT study which estimated the OCC to be $4 000 000 per MW in 2007 USD, which Rothwell adjusts for inflation to get $4 550 000 per MW in 2013 USD.

The US Energy Information Administration presents estimated assumptions of OCCs yearly in its Annual Energy Outlook reports, the AEOs. The AEO assumed OCCs in 1997 to be about $2 534 000 per MW in 1995 USD, in 2014 to be about $5 555 000 per MW in 2013 USD, and in 2023 be about $7 191 000 per MW in 2022 USD (Rothwell, 2015; EIA, 2023a). Rothwell (2015) compares the 2010 AEO assumptions with the 2005 findings from the Tennessee Valley Authority, TVA. He critiques the AEO for calculating what he claims to be unrealistically high so-called indirect costs and owner's costs in comparison with what is observed. Rothwell proceeds to use the percentile distribution of cost categories from the TVA's findings to correct AEO's findings, which approximately reduces the assumed costs by 20%. If we assume this to be systematically consistent then we can correct the 2014 AEO estimate to be around $4 444 000 per MW in 2013 USD, which is in line with the other estimates (Rothwell, 2015). If I do the same to the 2023 AEO estimate and adjust for inflation, we get a 2023 estimate of about $5 924 000 per MW in 2023 USD, which I will use as the lower bound OCCs estimate for the US in my analysis.

The growth of the AEO assumptions is not anywhere near Lévêque's (2015) proposed annual increase of 9,2% for the US. If the 1997 AEO assumption grew at that rate it would be more than $25 000 000 per MW in 2023 USD, by 2023 while ignoring inflation. The 2009 MIT study followed up a study they published in 2003 and their OCC findings doubled over those

6 years, implying that the growth in costs could be very steep (Lévêque, 2015). Adjusting the 2009 MIT findings for inflation and applying the growth rate of 9,2% over 14 years while assuming it does not include inflation, I get an OCC of about $20 000 000 per MW in 2023 USD. This is far more than the total financing costs of the OL3 reactor, still we cannot reject this as a possibility. Therefore, I will use this for the US higher bound OCC in my analysis.

The difference between the lower bound and upper bound estimates for building in the US is concerningly large, but it might reflect an extraordinary circumstance. Lovering et al. (2016) is a study of historical construction costs. It covers 153 LWRs from the US, France, Japan, South Korea, West Germany, Canada, and India. The data shows that the US is an outlier in terms of construction cost growth, and that the trend of rising overnight costs of construction might be misleading for the rest of the world. In many other countries the growth is stable and low. Since 1972 South Korea had a negative growth in construction costs. The reasonings given for this contrast were that the US and France suffered first-mover disadvantages of deploying an evolving technology, stemming from them being pioneers in the field. For the US the extraordinary growth in costs seems to have largely stemmed from the costs of retrofitting power plants undergoing construction to higher safety standards after the Three Mile Island partial meltdown incident in 1979. In contrast the Chernobyl meltdown incident of 1986 seems to have had only a small impact on costs in France. The youngest US LWR started construction the year before the Three Mile Island incident, and it seems that the extra cost of retrofitting the 51 reactors that were under construction at the time was extraordinarily high. Such an anomaly might skew our entire image of the growth of costs in the US (Lovering et al., 2016). As stated by Lovering et al. (2016) "…drawing any strong conclusions about future nuclear power costs based on one country's experience – especially the US experience in the 1970s and 1980s – would be ill-advised.".

For France it seems that growth in wages being higher than inflation was an important cause of raised construction costs. The countries who managed to keep low or even a negative growth of costs seem to have achieved this through focus on standardization. To fairly assess the lower bound OCCs in France, I am applying the possibility of static cost growth from Lovering et al. (2016) on the OCCs of the last four completed French nuclear reactors. These were about €1 442 000 per MW in 2010 EUR and started construction between 1984 and 1991. Converting to June 2010 USD and adjusting for inflation this equals about $2 463 000 per MW in 2023 USD (Statista, 2023). For the French higher bound estimate, I am adjusting the lower bound with Lévêque's French 1,7% annual growth of construction costs over the 32 years since the last completed French nuclear reactor started construction in 1991 (Lovering et al., 2016; Lévêque, 2015). The higher bound estimate I will use for France becomes about $4 224 000 per MW in 2023 USD. As shown in Table 1, between mid-2009 and mid-2019 63 reactors were completed in nine countries with a world mean construction time of 9,8 years. The US construction time is once again an outlier compared to the mean, but as China opened over 58% of these reactors China skews the mean towards their industry. The relative difference between the shortest and the longest construction times over these ten years is bigger than the relative difference between my French lower bound, and US upper bound, OCC estimates. To model the implications of this inconsistency I will use the world mean, minimum and maximum construction times from Table 1 in my analysis.

Table 1: "Construction Times of 63 Reactor Units Started up 2009-7/2019"

		Construction Time (in years)		
Country	**Units**	**Mean Time**	**Minimum**	**Maximum**
China	37	6	4,1	11,2
Russia	8	22,2	8,1	35
South Korea	6	6	4,1	9,6
India	5	9,8	7,2	14,2
Pakistan	3	5,4	5,2	5,6
Argentina	1	33	33	33
Iran	1	36,3	36,3	36,3
Japan	1	5,1	5,1	5,1
USA	1	43,5	43,5	43,5
World	**63**	**9,8**	**4,1**	**43,5**

(World Nuclear Industry Status Report, 2019)

For the Finnish OL3 reactor we already know the construction time, and as we have a figure of $12,4 billion for total financing cost, I will use this as the aggregated debt of financing construction, AD, for the OL3. After exploring the economic literature and the available data on the biggest financial hurdle for nuclear power I am left with a wide range of estimates as shown on the next page in Table 2.

Table 2: Construction cost and construction time for French and American LWRs in 2023

Country	OCC	$\overline{n}$ est.	KC_{MW}	$\overline{n}$
USA	High	Max.	$20 000 000	43,5
USA	High	Mean	$20 000 000	9,8
USA	High	Min.	$20 000 000	4,1
USA	Low	Max.	$5 924 000	43,5
USA	Low	Mean	$5 924 000	9,8
USA	Low	Min.	$5 924 000	4,1
France	High	Max.	$4 224 000	43,5
France	High	Mean	$4 224 000	9,8
France	High	Min.	$4 224 000	4,1
France	Low	Max.	$2 463 000	43,5
France	Low	Mean	$2 463 000	9,8
France	Low	Min.	$2 463 000	4,1
Country	**Reactor**		AD	$\overline{n}$
Finland	OL3		$12 400 000 000	18

3.2.2 Variable costs of LWRs

The OCC typically accounts for roughly 55% of the costs of producing nuclear power, while interest from financing typically accounts for roughly another 15%, meaning financing construction typically accounts for roughly 70% of costs. Operation and maintenance, decommissioning, fuel production and spent fuel storage typically accounts for the remaining roughly 30%. Decommissioning costs are usually the least impactful and make up the minority of these 30% as they are incurred far in the future and are heavily discounted in the present. However, the other non-financing costs are incurred during electricity production. If the plant's revenue is not significantly larger than these costs, then it cannot hope to repay the financial investment (Lovering et al., 2016; Rothwell, 2015; Lévêque, 2015).

These variable costs, the VC_{LWR}, consist of the costs dependent on the MWhs produced by the power plant. My model separates variable costs into operational costs and maintenance per MWh, OM_{MWh}, and fuel expenditures per MWh, F_{MWh}, as Rothwell (2015) does when calculating the LCOE. E, is the MWhs produced over a year. It is defined by the MW electric capacity of the plant, MW, multiplied by the plant's capacity factor, CF, and the average number of hours over a year which is evened out to be 8 766 hours, by averaging out leap years over four years. The capacity factor also known as load factor, CF, refers to the average percentage level of the MW electric capacity the plant operates at (Rothwell, 2015; IAEA, 2023a). The VC_{LWR} and E are expressed as follows:

$$VC_{LWR} = (OM_{MWh} + F_{MWh}) \times E$$

$$E = 8\,766 \times MW \times CF$$

As VC_{LWR} is assumed to be constant over the operative lifetime of the plant, the same applies for OM_{MWh}, F_{MWh} and E. MW is locked in by the reactor design when constructing the reactor, therefore as E is constant CF must be a constant average over the operative lifetime as well. I will borrow estimates for F_{MWh} and OM_{MWh}, and not estimate them myself as endogenous variables. However, I will briefly explain how these values are determined. F_{MWh} is dependent on the cost of fuel rods in relation to the burnup rate and thermal efficiency of the fuel. The cost of fuel rods is dependent on the price of natural uranium, the enrichment level required for the fuel, the price of enrichment services and that of final fuel rod fabrication, and how long these processes take. F_{MWh} is also dependent on the costs of short-, and long-term storage of spent nuclear fuel, so the whole fuel cycle is cowered by F_{MWh}. OM_{MWh} is dependent upon the number of employees used to run the plant over a year, L, multiplied by the annual average burdened labor rate including benefits for plant employes, p_L, miscellaneous costs, M, and an insurance premium for off-site damages from accidents including major nuclear accidents, PIN. Finally, both F_{MWh} and OM_{MWh} is determined by dividing by E so they are per MWh (Rothwell, 2015). OM_{MWh} is expressed as follows:

$$OM_{MWh} = \frac{(P_L \times L) + M + PIN}{E}$$

M includes costs of maintenance materials, replacement of depreciating physical capital, supplies, operating fees, property taxes and insurance premiums not covered by PIN. M can by calculated by estimating it as a percentage of $P_L \times L$. Rothwell (2015) does this to find M being 65% of the size of $P_L \times L$ after certain insurance premiums were increased in the wake of the Three Mile Island accident. PIN is a controversial figure, as both the probability of and the damage caused by major nuclear accidents are disputed figures. However, PIN is unlikely to be large enough to have any big implications for the costs of nuclear power. Rothwell (2015) sets PIN/E to be about $1 per MWh in 2013 USD. Around the same time Lévêque

(2015) sets PIN/E to be about €1 per MWh after assuming damages to be €1 trillion, 2,5 times the damage cost estimated by a Swedish study of the Chernobyl disaster, and assuming 100 times the accident probability Areva claims for the reactor design used by the OL3. In many countries the power plant would only be liable for a fraction of the actual damages if an accident were to occur. However, I chose to accept Rothwell's estimate as part of the overall VC_{LWR} estimate, as the difference between it and Lévêque's is minimal. Abiding by it covers much of the uncertainty regarding both the probability and the possible damage of a major accident, while having very little impact on my analysis (Rothwell, 2015; Lévêque, 2015).

When estimating F_{MWh} and OM_{MWh} we must make some assumptions regarding how the LWR is designed and operated. These assumptions are based on what is the most common traits of LWRs. As mentioned, the enrichment level required of the fuel rods and the price of enrichment services is an important driver of VC_{LWR}. Mined natural uranium, often referred to as yellowcake uranium, is normally 99,275% U-238 and 0,711% U-235. Yellowcake tends to not be sufficiently fissile to use as fuel. Enriching uranium refers to increasing the concentration of U-235, which can be done through different methods, among these using diffusion, centrifuges, or lasers. We assume to be considering a LWR reactor using 4,5% enriched uranium, this is in line with the assessments of Rothwell (2015) for an ordinary NPP, and similar to what is suggested by Sovacool & Valentine (2012). It is complicated to calculate an exact price for nuclear reactor fuel as it varies by reactor technology and market circumstances for the price of uranium and enrichment services. I have chosen to use the Rothwell's (2015) estimates for F_{MWh} at $8 in 2013 USD, which after accounting for inflation becomes about $10,5 in 2023 USD. Rothwell estimates fuel expenditures to be about $6,6 per MWh in 2013 USD without fuel disposal and interim storage. This is more than the estimates of $4,6 per MWh from the World Nuclear Association (2022) even without accounting for inflation. Rothwell (2015) implies that about 170 metric tons of yellowcake is needed to feed a 1000 MW NPP for a year at 4% enrichment, leaving about 11% of the tonnage as fuel. Meanwhile, Sovacool and Valentine (2012) implies that about 200 metric tons of natural uranium is needed to be processed to feed a standard 1000 MW NPP for a year using at least 3,5% enrichment, leaving about 15% of the tonnage as fuel. However, these differences are likely caused by differences in the approximations and the different enrichment levels considered. These small differences in operating costs are relatively negligible (Rothwell, 2015; Sovacool & Valentine, 2012; World Nuclear Association, 2022).

OM_{MWh} is harder to calculate than F_{MWh}, as there is very little publicly available data on operation and maintenance costs. We have already discussed estimating PIN, and that M can be estimated as a fraction of $P_L \times L$. Rothwell (2015) estimates P_L and L to get appropriate figures for $P_L \times L$ and to estimate M as a fraction of $P_L \times L$. By using semi-log regression, the regression method deemed most appropriate for NPP labor staffing he is able to estimate L for two 1 117 MW ALWRs to be 1 356 and assumes P_L to be \$80 000 in 2013 USD. With this information Rothwell predicts OM_{MWh} to be in the range between \$8,31 and \$12,61, in 2013 USD (Rothwell, 2015). Adjusted for inflation the OM_{MWh} range becomes between about \$11 and \$16,5, in 2023 USD. I do not deem it necessary to use two different estimates for OM_{MWh} as the \$5,5 difference will just separate the required revenues per MWh to break even by \$5,5 per MWh, which instead will just be noted for the analysis. I choose to use the mean between these estimates of OM_{MWh} and round up to whole USD, meaning I set OM_{MWh} as \$14. By adding up OM_{MWh} and F_{MWh} I get the following expression for VC_{LWR}:

$$VC_{LWR} = \$24{,}5 \times 8\,766 \times MW \times CF = \$214\,767 \times MW \times CF$$

Both OM_{MWh} and F_{MWh} are estimated under American circumstances and there could be some differences to conditions seen in France and Finland. F_{MWh} should largely be similar in the west as fuel mining and production is largely an international effort. For example, the uranium used could be mined in Australia. Fuel disposal and interim storage is handled somewhat differently, but France, Finland, and the US prices in these costs in a similar manner as fuel expenses. Expenses of OM_{MWh} could vary more because of differences in regulation and the cost of labor. However, the difference is not too meaningful when compared to the impact of differences in OCC and demand for electricity between France, Finland, and the US. Therefore, I assume the same basis of variable costs in between these western countries. To complete estimations of variable costs and construction costs I have to assume an MW and an achievable CF. The OL3 has an MW of 1600, while the Flamanville-3 reactor under construction in France has an MW of 1630, and many of the newer reactors are expected to be built at an MW around 1600-1650. Therefore, for simplification I will assume that all LWRs in my analysis has an MW of 1600. The CF is impactful as it does not change the construction costs much, and not at all in my model, but it has a big impact on the size of both VC_{LWR} and R_{LWR}. Lévêque (2015) illustrates that improving CF from 75% to 85% can cut the total cost per MWh by 10%. The US had a CF of around 90% over the last decades, while the IAEA's (2023a) PRIS database shows that the worldwide CF could be expected to be closer to 80%. I choose to use the IAEA data and assume a CF of 80% (Rothwell, 2015; Lévêque, 2015; IAEA, 2023b). I also need to assume an operational lifetime of the plant, T, for the analysis. Rothwell (2015) suggests 50-60 years, Lévêque (2015) suggests 60 years, and the World Nuclear Industry Status Report (2019) assumes a 40-year lifetime as the industry average. According to the Office of Nuclear Energy (2022) some reactors might operate for as much as 80 years, but extending the lifecycle tends to be dependent on meeting new regulatory requirements and market conditions, so this does not apply to all reactors. There is no one correct answer to this question. I choose to assume a 60-year operational lifetime for LWRs, T. Following these assumptions, I am left with 13 cases for analysis:

Table 3: OCC, construction time, and variable costs for France, USA, and Finland in 2023

Country	**OCC**	$\bar{n}$ **est.**	$KC_{MW} \times MW$	$\bar{n}$	VC_{LWR}
USA	High	Max	\$32 000 000 000	43,5	\$274 901 760
USA	High	Mean	\$32 000 000 000	9,8	\$274 901 760
USA	High	Min	\$32 000 000 000	4,1	\$274 901 760
USA	Low	Max	\$9 478 400 000	43,5	\$274 901 760
USA	Low	Mean	\$9 478 400 000	9,8	\$274 901 760
USA	Low	Min	\$9 478 400 000	4,1	\$274 901 760
France	High	Max	\$6 758 400 000	43,5	\$274 901 760
France	High	Mean	\$6 758 400 000	9,8	\$274 901 760
France	High	Min	\$6 758 400 000	4,1	\$274 901 760
France	Low	Max	\$3 940 800 000	43,5	\$274 901 760
France	Low	Mean	\$3 940 800 000	9,8	\$274 901 760
France	Low	Min	\$3 940 800 000	4,1	\$274 901 760
Country	**Reactor**		AD	$\bar{n}$	VC_{LWR}
Finland	OL3		\$12 400 000 000	18	\$274 901 760

3.2.3 Decommissioning costs of LWRs

At the end of a nuclear power plant's operational lifetime, it enters decommissioning. Sovacool & Valentine (2012) describe decommissioning as:

> Decommissioning is a long, costly, and arduous task of safely disposing of the physical features of a nuclear plant and restoring the facility and surrounding land to a

safe enough level to be entrusted to other uses. The process includes all of the administrative, operational, and technical procedures associated with ceasing operations, removing spent or unused fuel, reprocessing or storing radioactive liquids and wastes, deconstructing and decontaminating structures and equipment, shipping contaminated equipment offsite, and remediating the land, air, and water around the reactor site.

Rothwell (2015) states that an NPP should be dismantled within 10-20 years after ceasing operation to take advantage of the plant operating personnel expertise. However, this statement comes forth as more normative than descriptive. According to Sovacool & Valentine (2012), decommissioning usually takes at least 60 years and can cost anything between $300 million and $5,6 billion. Sovacool & Valentine (2012) cite the World Nuclear Association for these figures. Lévêque (2015) points out that by the time he wrote his book no French reactors had been completely decommissioned, and worldwide less than 20 reactors had been completely decommissioned. Lévêque (2015) states that the first French dismantling of any reactor was scheduled to be completed in 2019, after 28 years of decommissioning. By the time of writing, this reactor, the Chooz A 300MW PWR, is yet to have finished decommissioning (World Nuclear News, 2022).

However, decommissioning costs are a relatively small problem from an investor's point of view. These costs are incurred decades in the future, and even in my shortest scenarios, this is first after more than 64 years have passed since the start of construction. As these costs are discounted, they become relatively small in the present. Lévêque (2015) illustrates this point: "…at an annual rate of 8 percent, €1 million would only be worth €455 in a century.". There does not seem to be any agreed-upon decommissioning cost or timeframe, but I will just assume the upper value from Germany of €1 000 000 Euros for decommissioning stated by Lévêque (2015). I assume that these are in 2010 EUR as Lévêque uses 2010 EUR in other instances, and nothing else is specified. Converting to 2010 USD and adjusting for inflation, I get a decommissioning cost per MW, DC_{MW}, of roughly $1 700 000 per MW in 2023 USD (Statista, 2023). This DC_{MW} for a 1600 MW reactor is somewhere in the middle of the cost range presented by Sovacool & Valentine (2012) earlier. Furthermore, I will use the minimum of 60 years for the decommissioning time, $\tilde{n}$. DC_{LWR}, can then be calculated by multiplying $DC_{MW} \times MW$, and dividing by $\tilde{n}$:

$$DC_{LWR} = \frac{DC_{MW} \times MW}{\tilde{n}} = \frac{\$1\ 700\ 000 \times 1600}{60} \approx \$45\ 333\ 000$$

3.2.4 Revenue from LWRs

The revenue of an LWR comes primarily from the sale of electricity (Rothwell, 2015; Lévêque, 2015). Calculating revenue accurately is very complicated as electricity market structures are complicated and differ around the world. It is normal for nuclear power plants to sell electricity to retailers through local wholesale markets, while retailers sell electricity to consumers. Retailers take a markup for their service which increases the retail market price. In 2022 about 60% of the average electricity price in the US went to electricity generation, according to EIA (2023b). Furthermore, some of the electricity supply is lost in transmission and distribution which should be accounted for, the percentage lost varies between countries and even American states. I choose to use Wirfs-Brock's (2015) stated 6% average loss of supply, and I denote this effect as $l = 0{,}06$ (World Nuclear Industry Status Report, 2019; EIA, 2023b).

It can be hard to scale up or down large-scale nuclear power plant's electricity production. This is one of the areas where SMRs have a big potential to improve over traditional large-scale reactors, as SMRs are more flexible in terms of geographical deployment and in terms of adjusting electricity output. NPPs do downscale production to flexibly meet demand to some degree, and this is part of the reason why $CF \neq 1$, as planning for downtime and reduced output of reactors is done to meet demand meaning power plants do not run at full capacity all the time (Office of Nuclear Energy, 2020). More flexibility could mean that NPPs could optimize production to meet demand when demand is the highest. However, as large-scale nuclear power is not that flexible, I choose to assume that demand is reflected by the annual average price of electricity in retail markets, p_{MWh}. I also assume that nuclear power plants only earn roughly 60% of p_{MWh} per MWh, as observed for the US in EIA (2023b), and I assume that this applies for France and Finland as well. Finally, I assume that the 60% cut of p_{MWh} is after both taxation and power grid rent have already been accounted for. The US real average residential retail electricity price between 2000 and 2022 equates to roughly \$140 per MWh, 60% of \$140 is \$84 (EIA, 2022c). Ewen (2023) presents a large dataset of European wholesale electricity prices between 2015 and 2023. By adjusting these prices for inflation, I have calculated the real average of wholesale electricity prices in Europe to be roughly €87,78. Comparing \$84 to €87,78, I am comfortable with assuming a p_{MWh} of \$140 for Finland, France, and the US, given how hard it is to predict electricity prices in the far future. The expression for annual revenue, R_{LWR}, consists of the average price of electricity per

MWh, p_{MWh}, multiplied by the cut of sales going to generation, G, multiplied by the annually produced supply of electricity, E, except the portion lost to transmission and distribution, l:

$$R_{LWR} = p_{MWh} \times G \times (1 - l) \times E$$

$$R_{LWR} = \$140 \times 0{,}564 \times E \approx \$885\,969\,140$$

3.3 Economics of SMRs

The NPV for the SMR investment is almost identical to that of the NPV for the LWR investment. It uses the same variables only concerning SMRs instead of the LWR:

$$NPV_{SMR} = \sum_{t=\bar{n}+1}^{\bar{n}+T} \frac{R_{SMR}}{(1+r)^t} - \sum_{t=\bar{n}+1}^{\bar{n}+T} \frac{VC_{SMR}}{(1+r)^t} - \sum_{t=\bar{n}+1}^{\bar{n}+\dot{n}} \frac{FC_{SMR}}{(1+r)^t} - \sum_{t=\bar{n}+T+1}^{\bar{n}+T+\tilde{n}} \frac{DC_{SMR}}{(1+r)^t}$$

3.3.1 Financing & construction costs of SMRs

One of the key differences between traditional LWRs and SMRs is that LWRs are constructed on-site, while SMRs are partially or entirely constructed by modules that are fabricated off-site. SMRs hold promise for potentially reducing costs through factory-based manufacturing, standardized designs, and passive safety features. However, the actual cost savings and advantages have yet to come to fruition. The big question is whether there could be significant economies of scale benefits for mass production of SMRs and whether there is a significant loss from economies of scale benefits for reactor size. As discussed earlier in the thesis these are contentious questions, and we will probably not know the answer unless mass production of SMRs occurs (Rothwell, 2015; World Nuclear Industry Status Report, 2022; Liou, 2023).

When discussing the mass production benefits for SMRs the literature tends to refer to the FOAK; first-of-a-kind reactor, and the NOAK; nth-of-a-kind reactor, where n is a large number. Rothwell (2015) supposes that a FOAK SMR of 180MW could cost $1,5 billion to construct in OCC, while that of the NOAK to have fallen to $1 billion, both in 2013 USD. Adjusting for inflation, this equates to a FOAK OCC of about $10 889 000 per MW and a NOAK OCC of about $7 260 000 per MW, both in 2023 USD. Rothwell internalizes economies of scale losses and gains for SMRs in comparison to LWRs in his estimates. He uses a scale factor that implies for every doubling in reactor size costs decline 10%, and to get the effect of mass production he reduces this effect itself by 10% on top of removing certain costs specific to building a FOAK and reducing contingency costs. Rothwell's (2015) NOAK estimate is about 33% cheaper than the FOAK estimate. Once again, economies of scale benefits for reactor size are contentious, so Rothwell's estimates here could be seen as pessimistic. Rothwell himself admits economies of scale benefits stemming from reactor size have not been observed for reactors larger than 600 MW. The cost difference between SMRs and traditional reactors can also be attributed to their safety features. SMRs incorporate advanced passive safety systems that can mitigate the risk of severe accidents. These safety features may reduce the need for complex emergency response mechanisms and expensive containment structures, potentially leading to cost savings in construction (Liou, 2023; ANSTO, 2020; Rothwell, 2015).

There is some correlation between OCC and construction time. However, the literature does not agree on how strong this correlation is. If mass production of SMRs can reduce construction times significantly then costs may be reduced significantly just from reduced discounting and financing costs alone. The NuScale 57MW SMRs are designed to be very modular with each reactor unit being the size of about 23 by 4,6 meters. The module reactors each have a total shipping weight of 700 tons and would be shipped in 3 parts each. NuScale claims that when production gets going, they will be able to produce a 12-reactor power plant over less than 3 years. NuScale points to Black et al.'s (2019) estimates for their NuScale 12-reactor "VOYGR" power plants, which estimate an OCC of $3 466 000 per MW in 2015 USD, this is equivalent to about $4 432 000 per MW in 2023 USD. NuScale has been met with heavy criticism by industry watchers as their pilot reactors have been plagued by cost overruns and construction delays. The criticism I have observed tends to be rooted in fears of repeating the nuclear industry's history of ever-rising costs and construction times, and fears of its competitiveness next to the alternatives (Black et al., 2019; Rothwell, 2015; Liou, 2023; Crownhart, 2023; Schlissel & Wamsted, 2022; Schlissel, 2022; NuScale, 2023).

SMRs come in a range of sizes. While the NuScale reactors are on the smaller side at 57 MW, Rolls-Royce is planning on building 470 MW SMR power stations, pushing the limits of the definition of an SMR, but they are still much smaller than the 1600 MW LWRs. Rolls-Royce claims that by the time they have completed their fifth reactor, OCC should be at £1,8 billion in 2021 GBP. Converted to 2021 USD and adjusted for inflation this is equivalent to about $2,781 billion or about $5 917 000 per MW, in 2023 USD. They also claim to be able to construct these SMRs over 5,5 years each (Associated Press, 2022; Rolls-Royce, 2023; Rolls-Royce, 2021; Exchange Rates UK 2023).

The fundamentals that separate SMRs from traditional nuclear reactors suggest that SMRs should be cheaper and quicker to build. Standardization, mass production, flexibility in deployment, and passive safety, are all traits of SMRs that are missing in most large-scale LWRs. Their absence all contributes to either the high financing costs of LWRs or LWRs' unsuitability to meet demand in many instances (Black et al., 2019; Liou, 2023; MIT Energy Initiative, 2018). The prominent argument for preferring large-scale LWRs is economies of scale stemming from reactor size, which the literature tells us is highly questionable. I will examine the NOAK OCC projections of Rothwell, Rolls-Royce, and NuScale, of respectively $7 260 000 per MW, $5 917 000 per MW, and $4 432 000 per MW. For construction times I will use a lower estimate of NuScale’s 3 years and a higher estimate of Rolls-Royce’s 5,5 years, which is a similar range to what is expected by many researchers in the field (ANSTO, 2020). The approximate overnight construction costs case samples of Rothwell, Rolls-Royce, and NuScale, over 3 and 5,5 years are collected in Table 4. Yearly construction costs during construction of SMRs are calculated in the same manner as those of LWRs. They are calculated by multiplying the per MW OCC, KC_{MW}, with the net capacity, MW, and divided by construction time, $\bar{n}$:

$$KC_{SMR} = \frac{KC_{MW} \times MW}{\bar{n}}$$

Table 4: Construction costs and times reported for SMRs, in 2023 USD

Model	$\bar{n}$ **est.**	KC_{MW}	$\bar{n}$	MW	$KC_{MW} \times MW$	KC_{SMR}
Rothwell	High	$7 260 000	5,5	180	$1 306 800 000	$237 600 000
Rothwell	Low	$7 260 000	3	180	$1 306 800 000	$435 600 000
Rolls-Royce	High	$5 917 000	5,5	470	$2 780 990 000	$505 600 000
Rolls-Royce	Low	$5 917 000	3	470	$2 780 990 000	$927 000 000
NuScale	High	$4 432 000	5,5	684	$3 031 488 000	$551 200 000
NuScale	Low	$4 432 000	3	684	$3 031 488 000	$1 010 500 000

3.3.2 Variable costs of SMRs

Rothwell (2015) uses the same model to calculate fuel costs, and operational and maintenance costs, as with large-scale LWRs. I will be using the same formula as with LWRs as well:

$$VC_{SMR} = (OM_{MWh} + F_{MWh}) \times E$$

Rothwell (2015) calculates higher F_{MWh} and OM_{MWh} for SMRs than that of LWRs. He estimates F_{MWh} to be \$12 per MWh in 2013 USD, roughly \$15,7 per MWh in 2023 USD after adjusting for inflation. The main reason given for the higher F_{MWh} is that SMRs typically need a slightly higher enrichment than that of LWRs, of right under 5%. Rothwell (2015) uses 4,95% for the SMR estimate and both the Rolls-Royce and Nuscale SMRs use 4,95% enrichment as well (Nuscale, 2023; Rolls-Royce, 2023). Rothwell (2015) also lists lower burnup rate, lower efficiency, and more expensive fuel fabrication caused by lack of experience in SMR fuel fabrication, as reasonings for the higher F_{MWh}.

Rothwell estimates OM_{MWh} to be in the range between \$13,19 to \$17,72 per MWh in 2013 USD, roughly \$17,24 to \$23,15 per MWh in 2023 USD after adjusting for inflation. The main reason given for the higher OM_{MWh} is in this case that Rothwell's modeling implies a base annual employment required to run any reactor of 250. As Rothwell calculates estimates for a reactor with twin SMRs of 180 MW each, requiring an annual employment of 350, which implies an increase in annual employment of 50 per 50 MW added. This implies relatively high staffing costs for SMRs in comparison to large-scale LWRs. Furthermore, as M is calculated as a percentage of staffing costs, M rises as well. Rothwell assumes the PIN per MWh to be the same as with LWRs, which is not very impactful, but this combined with the staffing assumptions might make this estimate slightly less accurate. Two of the most important improvements SMRs promise over large-scale LWRs are improved safety features with a lower need for human intervention. However, as we know from LWRs OM_{MWh} estimates suffer from a lot of uncertainty, they are dependent on regulatory frameworks to some degree, and OM_{MWh} for SMRs especially tend to get little attention in research (Rothwell, 2015; Liou, 2023; Vegel & Quinn, 2017). I will use the same assumption as when dealing with LWR OM_{MWh}, and take the mean between the ends of the range. The mean is about \$20,2 per MWh, and as the SMR F_{MWh} is roughly \$15,7, I assume an SMR OM_{MWh} of \$20,3, to round up $F_{MWh} + OM_{MWh}$ to a whole number, which becomes \$36 per MWh.

In terms of the operational lifetime of SMRs, both NuScale and Rolls-Royce claim an operational lifetime of 60 years, so I will assume an operational lifetime, T, of 60 years in my analysis. Both Nuscale and Rolls-Royce claim a capacity factor, CF, of 95% as well, so I will use a CF of 95% for my SMR estimates. Given the modular design of these reactors with lower downtime, this seems realistic if deployed under the right circumstances where SMRs support relatively stable renewables (Nuscale, 2023; Rolls-Royce, 2023). I can now use these common estimates between SMRs to get VC_{SMR} as a function of MW:

$$VC_{SMR} = \$36 \times 8\,766 \times MW \times 0{,}95 \cong \$299\,797 \times MW \approx \$300\,000 \times MW$$

3.3.3 Decommissioning costs of SMRs

Yearly decommissioning costs for SMRs, DC_{SMR}, are likely to be like those of LWRs. I see no significant reason why it would be any different. There might be some increase in costs from the higher fuel enrichment or some decrease from streamlining the decommissioning of SMRs as they should not be as diverse in design per reactor as large-scale LWRs. However, some of the earlier LWRs like the Chooz A 300 MW PWR, which is still in decommissioning after over 30 years, were of a comparable MW size to the proposed SMR power plants (World Nuclear News, 2022). As the impact of this estimate is small following the long operational lifetime of the plant, I will use the same estimates for DC_{SMR} as for DC_{LWR}, where the decommissioning period, $\tilde{n}$, is 60 years and the decommissioning cost per MW, DC_{MW}, is \$1 700 000:

$$DC_{SMR} = \frac{DC_{MW} \times MW}{\tilde{n}}$$

$$DC_{SMR} = \frac{\$1\,700\,000}{60} \times MW \approx \$28\,333 \times MW$$

3.3.4 Revenue from SMRs

The revenue stream from SMRs is also very similar to that of LWRs. As SMR's modules are intended to be built in a factory and deployed with more flexibility than LWRs, and since the distinction between operators and constructors should be larger than that of LWRs, there could be some differences in the actual business structure. For example, does the constructor lease out or sell SMRs? Is the constructor needed to play an active service part in plant operation, or does he sell the completed reactor like a goods product? It really depends on the approach of how these deals are made, it appears very case-specific, and I do not intend to speculate how constructors design their business models. Regardless, approximately the same calculation applies, the operator or SMR customer needs to pay the constructor for the reactor, and the operator needs to earn a large enough share of the retail electricity price to cover costs for its generation. Therefore, I will use the same expression for the yearly operational revenue of SMRs, R_{SMR}, as that of LWRs, R_{LWR}:

$$R_{SMR} = p_{MWh} \times G \times (1 - l) \times E$$

I cannot imagine many reasons why the cut going to generation, G, would be any different from the assumptions I made for LWRs as about 0,6 is the general G for all power generation in the US in 2022 (EIA, 2023b). Maybe the increased flexibility in deployment implies a lower or higher G, but this effect is not obvious. I leave it to future research to determine the effect on wholesale market contracts for SMRs and how they impact G. There could be somewhat less of a loss to heat during transmission of energy, l, if reactors are more flexibly deployed and therefore closer to the destination consumer. However, according to Wirfs-Brock (2015), only 2 percentage points of energy is lost to transmission, so we are unlikely to reduce this substantially. I choose to use a G of 0,6 and a l of 0,06 for SMRs as with LWRs and assume that any effect of increased flexibility in deployment is observed in being able to keep a CF of 0,95, 0,15 more than that of my assumptions for LWRs. I also assume a p_{MWh} of \$140, as with LWRs. Annual operational revenue of SMRs, R_{SMR}, becomes a function of the MW net electric capacity, MW, and the retail price of electricity, p_{MWh}:

$$R_{SMR} = p_{MWh} \times G \times (1 - l) \times E$$

$$R_{SMR} = \$140 \times 0{,}564 \times 8\,766 \times MW \times 0{,}95 \approx \$657\,580 \times MW$$

3.4 Financial mathematics

A central assumption of my model is that the discount rate and the real cost of capital are the same value, r. This assumption has big implications as investing in nuclear can mean no return on the investment for decades and there could still be costs to pay over 100 years after construction is finished. The real cost of capital is also very impactful as the majority of costs are financial costs from construction. The larger, r, is the harder it is for investments in large

LWRs or in SMRs to be worthwhile, as a high discount rate and interest rate suggest there are better alternatives for our capital. However, as we have seen investing in nuclear energy is risky as there are a lot of uncertainties and risks involved and these are big investments whether it is LWRs or SMRs. There are several approaches to choosing interest rates and discount rates (Rothwell, 2015; Lévêque, 2015).

Lévêque (2015) discusses which discount rate should be chosen for nuclear power when including the general preference for the present, the product of the marginal utility of consumption today versus tomorrow, and the growth rate per capita. He points out that there is little agreement on what discount rate to use, and points to literature using anything from 3% to 6%, and even declining discount rates that can start at 3% and end at 1% after 100 years. Lévêque's (2015) discount rates incorporate the social costs and benefits to a large degree, which might be a little inappropriate with my CBA as it is focused on the financial investment. Rothwell (2015) uses risk-adjusted interest rates in the form of weighted average cost of capital, or WACC. WACC is more appropriate for both the interest rate and the discount rate in my model as it is commonly used in NPV project analysis to account for the alternative cost of the investment. The WACC is calculated by adding the products of equity market value times equity market value growth and debt market value times debt market value growth and dividing by the sum of equity market value and debt market value. This rate covers the opportunity cost of capital as Hopkinson (2016) explains:

> In principle, proceeding with a project is a good decision provided that it has a rate of return that exceeds the opportunity cost of capital. This opportunity cost is the rate of return that investors expect from other opportunities with an equivalent level of risk. If the project does not meet or exceed this hurdle, investors should decline it. This principle is called the Rate of Return Rule. If the discount rate used for Net Present Value (NPV) modelling reflects the cost of capital, the Rate of Return and Net Present Value Rules are equivalent.

As I have assumed the financial costs of constructing the large-scale LWR and the SMRs are annuity downpayments on aggregate debt, there is no equity financing internalized in my models. However, this should not make the model too different as equity investors incur the alternative cost of not investing their money elsewhere as well, but it is still a simplification of reality. Rothwell (2015) estimates a real weighted average cost of capital of about 7,5% for both traditional large-scale reactors and SMRs when there is a large percentage of debt financing. Around the time Rothwell (2015) was published, inflation rates for the US, Finland, and France had been steadily low since the 1990s, but as of 2022 inflation rates of all three countries were at levels not seen since the 1980s (The World Bank, 2023). By the time of writing the policy rate of the US is 5,5% while that of France and Finland is 4,25%, which might imply a higher WACC in the short run (Trading Economics, 2023). However, my thesis does not attempt to forecast inflation or policy rates, as that would require a thesis of itself, and I will assume that in the long run inflation and policy rates even out and are reflected as part of the interest/discount rate I use. As social costs and benefits are not the primary concern of the investor, I opt for assuming Rothwell's (2015) WACC of 7,5% as an appropriate interest/discount rate, but I will conduct some of my sensitivity analysis by changing this rate.

3.4.1 Simplifying the NPV & financing construction

My NPV equations for SMR and LWR investments share the same basic structure and can be simplified similarly. I will use NPV_{LWR} in this and the next chapter, but the simplifications would be the same for NPV_{SMR}. First, as the stream of revenue and variable costs are discounted over the same period, we can combine their cashflows in the model:

$$NPV_{LWR} = \sum_{t=\bar{n}+1}^{\bar{n}+T} \frac{R_{LWR} - VC_{LWR}}{(1+r)^t} - \sum_{t=\bar{n}+1}^{\bar{n}+\dot{n}} \frac{FC_{LWR}}{(1+r)^t} - \sum_{t=\bar{n}+T+1}^{\bar{n}+T+\tilde{n}} \frac{DC_{LWR}}{(1+r)^t}$$

Next, we can use the sum of a geometric series formula to simplify these expressions:

$$NPV_{LWR} = (R_{LWR} - VC_{LWR}) \frac{1-(1+r)^{-T}}{r(1+r)^{\bar{n}}} - FC_{LWR} \frac{1-(1+r)^{-\dot{n}}}{r(1+r)^{\bar{n}}} - DC_{LWR} \frac{1-(1+r)^{-\tilde{n}}}{r(1+r)^{\bar{n}+T}}$$

Yearly financing costs, FC_{LWR}, is the term downpayment on the aggregated debt of construction costs, AD. Downpayments start at the end of the year following finalization of construction, after $t = \bar{n}$, and end by the loan maturity date at $t = \dot{n}$. Because the discount rate and the interest rate are the same under my assumptions, the loan maturity date is irrelevant to the NPV. This is the case in my model as over the downpayment period the interest paid for delaying payment to the next year is counteracted by the discount rate. Using a formula for term downpayment of annuity debt I form the following equation for FC_{LWR}:

$$FC_{LWR} = \frac{AD \times r}{1-(1+r)^{-\dot{n}}}$$

I assume that debt is incremented yearly during construction to pay off the yearly costs of construction, KC_{LWR}. Aggregate debt, AD, is the debt including accrued interest, accumulated by the time construction is finished and the power plant starts operation:

$$AD = KC_{LWR}(1+r)\frac{(1+r)^{\bar{n}}-1}{r}$$

By rearranging FC_{LWR} and AD into NPV_{LWR}, I get the following expression for NPV_{LWR}:

$$NPV_{LWR} = (R_{LWR} - VC_{LWR})\frac{1-(1+r)^{-T}}{r(1+r)^{\bar{n}}} - KC_{LWR}\frac{(1+r)^{\bar{n}+1}-(1+r)}{r(1+r)^{\bar{n}}} - DC_{LWR}\frac{1-(1+r)^{-\tilde{n}}}{r(1+r)^{\bar{n}+T}}$$

The expressions for R_{LWR}, VC_{LWR}, KC_{LWR} & DC_{LWR} can now be inserted into the expression:

$$NPV_{LWR} = (0{,}564p_{MWh} - OM_{MWh} - F_{MWh}) \times 8\,766 \times MW \times CF \times \frac{1-(1+r)^{-T}}{r(1+r)^{\bar{n}}} - \frac{KC_{MW} \times MW}{\bar{n}} \times \frac{(1+r)^{\bar{n}+1}-(1+r)}{r(1+r)^{\bar{n}}} - \frac{DC_{MW} \times MW}{\tilde{n}} \times \frac{1-(1+r)^{-\tilde{n}}}{r(1+r)^{\bar{n}+T}}$$

From this point, the SMR and LWR investments diverge and by inserting the rest of the unique estimates defined in the previous chapters, except r and p_{MWh}, for each of them we get the full expressions for NPV_{LWR} and NPV_{SMR} that will be used in the analysis:

$$NPV_{LWR} = (0{,}564p_{MWh} - \$24{,}5) \times 11\,220\,480 \times \frac{1-(1+r)^{-60}}{r(1+r)^{\bar{n}}} - \frac{KC_{MW} \times 1600}{\bar{n}} \times \frac{(1+r)^{\bar{n}+1}-(1+r)}{r(1+r)^{\bar{n}}} - \$45\,333\,000 \times \frac{1-(1+r)^{-60}}{r(1+r)^{\bar{n}+60}}$$

$$NPV_{SMR} = (0{,}564p_{MWh} - \$36) \times 8\,328 \times MW \times \frac{1-(1+r)^{-60}}{r(1+r)^{\bar{n}}} - \frac{KC_{MW} \times MW}{\bar{n}} \times \frac{(1+r)^{\bar{n}+1}-(1+r)}{r(1+r)^{\bar{n}}} - \$28\,333 \times MW \times \frac{1-(1+r)^{-60}}{r(1+r)^{\bar{n}+60}}$$

As we do not know the KC_{MW} for the OL3 reactor we have the following expression for $NPV_{LWR-OL3}$, where $AD = \$12\,400\,000\,000$ and $\bar{n} = 18$:

$$NPV_{LWR-OL3} = (0{,}564p_{MWh} - \$24{,}5) \times 11\,220\,480 \times \frac{1-(1+r)^{-60}}{r(1+r)^{18}} - \$12\,400\,000\,000 \times \frac{1}{(1+r)^{18}} - \$45\,333\,000 \times \frac{1-(1+r)^{-60}}{r(1+r)^{78}}$$

4. Modeling & analysis

4.1 Modeling results

After estimating costs, revenues, and the corresponding relevant variables and parameters, the resulting NPVs are calculated in Table 5 on the next page. Also, included in the far-right column of Table 5 is the minimum retail price of electricity per MWh, p_{MWh}, needed for the return on the nuclear power investment to beat the real WACC of 7,5%, meaning $NPV \geq 0$. I refer to this measure as $p_{MWh}^{NPV\geq0}$ in Table 5 and in the text onwards. The lower this measure is the more cost-effective an outcome is. The first column assigns a case index to each set of estimates to make them easier to reference in the text. The next columns "Country/Est.", "OCC" and "$\bar{n}$" categorize the differences in assumptions for the 19 different case scenarios covering LWRs and SMRs. The total NPV is shown in the following column, followed by the total NPVs of financing costs and variable operating costs, FC_{NPV} and VC_{NPV} respectively, and their corresponding percentages of the total NPV of all costs, $\%NPV_{FC}$ and $\%NPV_{VC}$ respectively. Finally, the right side of the column is comprised of the total NPV of decommissioning costs and of revenues, DC_{NPV} and R_{NPV} respectively, and the $p_{MWh}^{NPV\geq0}$.

The NPV tells me that only 2 of the 19 cases are worthwhile for any investors under my assumptions, these are cases 11 and 12, namely the ones using France's lower bound OCC estimate for constructing an LWR over 4,1 or 9,8 years. Cases 11 and 12 are worthwhile for the investor as their NPVs are positive, meaning the investment returns beats the alternative cost of not getting returns from investing in other assets, represented by the real WACC. The severity of present value losses varies widely between other cases, but the numerical differences in the NPV column does not paint a complete picture of the differences between cases. For example, it would be misleading to describe the US cases with a NPV loss of more than \$2 billion, as automatically less cost-effective than the other cases. Even though the US cases are predicted to be big losses, the most optimistic US case, case 6, has a lower $p_{MWh}^{NPV\geq0}$ than that of the Finnish OL3, half the SMR estimates, and two of the French estimates.

Both the NPV and the $p_{MWh}^{NPV\geq0}$ are important, as if a case is not worthwhile for investors, they will not invest without policy intervention regardless of how little they would lose if they invested. Policymakers need to know which policy options require the least amount of intervention to incentivize investment in the transition to carbon-neutral power grids, and the $p_{MWh}^{NPV\geq0}$ tells us the required retail market conditions for nuclear to be competitive. The

Table 5: Thesis modeling results. (NPVs and $p_{MWh}^{NPV\geq 0}$s under $T = 60$, $\tilde{n} = 60$, $G = 0{,}6$, $l = 0{,}06$, $r = 7{,}5\%$ and $p_{MWh} = \$140$)

Case	**Producer**	**OCC**	$\bar{n}$	NPV	FC_{NPV}	$\%NPV_{FC}$	VC_{NPV}	$\%NPV_{VC}$	DC_{NPV}	R_{NPV}	$p_{MWh}^{NPV\geq 0}$
1	USA	High	43,5	-$9,7 B.	$10,0 B.	*98,5 %*	$0,2 B.	*1,5 %*	$0,3 M.	$0,5 B.	$2 860
2	USA	High	9,8	-$19,8 B.	$23,8 B.	*93,0 %*	$1,8 B.	*7,0 %*	$3,8 M.	$5,7 B.	$623
3	USA	High	4,1	-$22,7 B.	$28,7 B.	*91,4 %*	$2,7 B.	*8,6 %*	$5,8 M.	$8,7 B.	$507
4	USA	Low	43,5	-$2,6 B.	$3,0 B.	*95,0 %*	$0,2 B.	*4,9 %*	$0,3 M.	$0,5 B.	$871
5	USA	Low	9,8	-$3,0 B.	$7,0 B.	*79,8 %*	$1,8 B.	*20,2 %*	$3,8 M.	$5,7 B.	$215
6	USA	Low	4,1	-$2,5 B.	$8,5 B.	*75,9 %*	$2,7 B.	*24,0 %*	$5,8 M.	$8,7 B.	$181
7	France	High	43,5	-$1,8 B.	$2,1 B.	*93,2 %*	$0,2 B.	*6,8 %*	$0,3 M.	$0,5 B.	$638
8	France	High	9,8	-$1,0 B.	$5,0 B.	*73,8 %*	$1,8 B.	*26,2 %*	$3,8 M.	$5,7 B.	$166
9	France	High	4,1	-$0,1 B.	$6,1 B.	*69,2 %*	$2,7 B.	*30,7 %*	$5,8 M.	$8,7 B.	$141
10	France	Low	43,5	-$0,9 B.	$1,2 B.	*88,8 %*	$0,2 B.	*11,1 %*	$0,3 M.	$0,5 B.	$390
11	France	Low	9,8	$1,0 B.	$2,9 B.	*62,1 %*	$1,8 B.	*37,8 %*	$3,8 M.	$5,7 B.	$115
12	France	Low	4,1	$2,4 B.	$3,5 B.	*56,7 %*	$2,7 B.	*43,2 %*	$5,8 M.	$8,7 B.	$101
13	Finland	OL3	18	-$1,2 B.	$3,4 B.	*77,4 %*	$1,0 B.	*22,6 %*	$2,1 M.	$3,2 B.	$192
14	Rothwell	SMR	5,5	-$0,5 B.	$1,1 B.	*70,1 %*	$0,5 B.	*29,9 %*	$0,6 M.	$1,0 B.	$213
15	Rothwell	SMR	3	-$0,5 B.	$1,2 B.	*68,0 %*	$0,6 B.	*31,9 %*	$0,7 M.	$1,3 B.	$200
16	Rolls-Royce	SMR	5,5	-$0.9 B.	$2,4 B.	*65,6 %*	$1,2 B.	*34,4 %*	$1,5 M.	$2,7 B.	$186
17	Rolls-Royce	SMR	3	-$0,8 B.	$2,6 B.	*63,4 %*	$1,5 B.	*36,5 %*	$1,8 M.	$3,3 B.	$174
18	NuScale	SMR	5,5	-$0,4 B.	$2,6 B.	*58,8 %*	$1,8 B.	*41,1 %*	$2,2 M.	$4,0 B.	$155
19	NuScale	SMR	3	-$0,2 B.	$2,8 B.	*56,5 %*	$2,2 B.	*43,4 %*	$2,7 M.	$4,8 B.	$147

Notes: The first column from the left "Case" refers to the identifying index of the total NPV estimate for an investment in an LWR or in SMRs "Producer" refers to the circumstances of each estimate, whether the estimate is specific to a country, a company, or Rothwell. "OCC" refers to the characteristics of the overnight construction cost estimates. If the OCC is "High" it is the higher bound estimate for France or the US, and if it is "Low" it is the lower bound estimate for France or the US. If the OCC is "OL3" it refers to the specific cost circumstances of the Finnish OL3 reactor, while if it is "SMR" then the estimate is for an SMR, and the OCC is categorized by the "Producer" estimate. "$\bar{n}$" is the number of construction years for each estimate. "NPV" refers to the total net present value of each investment case estimate. "FC_{NPV}" refers to the net present value of financing costs. "$\%NPV_{FC}$" refers to the FC_{NPV} percentage of the total net present value of the costs of each investment case estimate. "VC_{NPV}" refers to the total net present value of variable operating costs. "$\%NPV_{VC}$" refers to the VC_{NPV} percentage of the total net present value of the costs of each investment case estimate. "DC_{NPV}" refers to the total net present value of decommissioning costs. "R_{NPV}" refers to the total net present value of revenue streams. "$p_{MWh}^{NPV\geq 0}$" refers to the minimum retail price of electricity per MWh needed for $NPV \geq 0$. B. Billion, M. Million

$p_{MWh}^{NPV\geq 0}$ is also important when considering the impact of deviations from the assumed p_{MWh} of $140 on estimation results, as the likelihood of wrongfully dismissing the financial returns of nuclear power based on price assumptions declines the larger the deviation would need to be.

The NPV and $p_{MWh}^{NPV\geq 0}$ paints a grim picture for the current financial returns of both LWRs and SMRs. It is readily apparent that the worst circumstances are seen for LWRs in the US, especially with the higher bound OCC estimates of cases 1, 2 and 3. My worst-case scenario is case 1 which has a predicted NPV loss of $9,7 billion for the investor and a $p_{MWh}^{NPV\geq 0}$ of $2 860, which is just absurdly high. The predicted NPV losses of cases 2 and 3 are higher, but it is questionable that constructing a reactor over 9,8 or 4,1 years has as high of an OCC as that of a reactor constructed over 43,5 years. This characteristic is a simplification of reality I have assumed to simplify the modeling, and as mentioned before the literature describes some correlation between the OCC and $\bar{n}$. The estimated costs of NPPs in the model can become smaller while construction time becomes longer if the total OCC does not grow in pace with the number of construction years and if the OCC gets large enough. This would imply that reducing costs per MWh is possible just by having a longer construction time, which is a misleading metric. This fallacy is more avoidable using the CBA framework than with the LCOE as the LCOE does not consider demand and the $p_{MWh}^{NPV\geq 0}$, which reveal that case 2 and 3 has a $p_{MWh}^{NPV\geq 0}$ of $623 and $507, respectively, compared to case 1's much higher $2 860 $p_{MWh}^{NPV\geq 0}$. The other standouts are the remaining estimates with 43,5-year construction times, namely cases 4, 7, and 10. While their NPV losses do not stand out all that much, the $p_{MWh}^{NPV\geq 0}$ for each of them are $871, $638, and $390, respectively.

The cases I have discussed thus far are all among the best- and worst-case estimates for LWRs with either the highest or lowest OCC estimates, or the highest construction times. While these cases should not be dismissed as they are predicted possibilities from the theoretical and empirical literature, they should not be taken as given outcomes either. The worst-case estimates share a common factor separating them from the rest of the estimates, financing costs make up between 88,8% to 98,5% of the net present value of costs, underlining the fact that underestimating construction time and financing of construction can be disastrous for the investor. Meanwhile, financing costs make up between 56,7% to 62,1% for the best-case estimates. This is not radically different from that of the remaining estimates for LWRs and SMRs, not discussed this far, which range from 56,5% to 79,8%. As expected, the majority of costs are variable operational costs or financing costs, while decommissioning costs are negligible in the bigger picture making up less than 0,1% of the net present value of total costs in every scenario.

The remaining cases for LWRs, cases 5, 6, 8, 9, and 13, have NPV losses between $3 billion and $0,1 billion, and a $p_{MWh}^{NPV\geq 0}$ between $141 and $215. These include the US lower bound and French upper bound OCC estimates with the mean and low construction times of 9,8 and 4,1 years, respectively. Also included is the OL3 reactor which I earlier described as seeming like a worst-case scenario with a construction time of 18 years. This no longer seems like an apt description after seeing how much worse the literature suggests financing costs can be. Keeping in mind how the Three Mile Island incident affected the historical data for US OCCs, and how the OL3 was finished this year with the AD and $\bar{n}$ taken directly from this case, these estimates appear as more likely outcomes for most new LWR investments than that of the others discussed for LWRs. However, I cannot claim that any outcome is more likely than others as because of the previously discussed "unknown unknowns", I do not know the underlying probability distribution of OCCs. Therefore, I choose to assume every outcome is as likely as any other outcome.

The SMR cases, case 14 through 19, have a NPV loss of between $0,9 billion and $0,2 billion, and a $p_{MWh}^{NPV\geq 0}$ between $147 and $213, which is quite similar to that of LWR cases 5, 6, 8, 9 and 13. Except for the Rothwell estimates, these SMR results are based on the targeted costs and construction times for NOAK reactors by NuScale and Rolls-Royce themselves. It is concerning for the competitiveness of SMRs that the NPVs of these are negative when they are based on the projections of the proponents of SMRs. From my findings, it appears most likely that both LWRs and SMRs will struggle to compete with fossil fuels in electricity markets without policy intervention. My modeling suggests that the promises of SMRs are hampered by high costs of financing, just as with LWRs. However, the higher variable costs of SMRs compared to LWRs raise the $p_{MWh}^{NPV\geq 0}$ for the SMR cases by about $20, as every $1 increase in VC_{MWh} increase the $p_{MWh}^{NPV\geq 0}$ by roughly $1,77. I discussed earlier how this increase in variable cost might not be all that accurate, as SMRs promise passive safety features with less human intervention. Furthermore, even though some of the higher flexibility in ability to adjust output when meeting demand is captured by the higher CF of SMRs, the flexibility in deployment is not represented in the model. Because of the origin of the OCC estimates, the counterintuitive nature of the variable costs, and the promising aspects left out of the model, there is reason to believe that SMRs could be either more or less costly than what is presented by my results. Even so, I have to assume that the available information is somewhat reliable.

The LWRs have a higher mean and median $p_{MWh}^{NPV\geq 0}$ than that of SMRs overall. The LWRs' overall mean and median $p_{MWh}^{NPV\geq 0}$ are roughly \$322 and \$215, respectively, while the mean and median $p_{MWh}^{NPV\geq 0}$ for LWR cases 5, 6, 8, 9, and 13 are roughly \$177 and \$181, respectively. The SMRs' mean and median $p_{MWh}^{NPV\geq 0}$ are roughly \$178 and \$180, respectively. If only cases 5, 6, 8, 9, and 13 were to be considered for LWRs, then determining which technology is most cost-effective would be a very close call. If the positive NPV cases 11 and 12 were to be added to this group as well, then LWRs would have an apparent win in cost-effectiveness. However, as discussed, I would not deem the worst-cases for LWRs as dismissible and I assume every case outcome is as likely as any other. Therefore, the SMRs' $p_{MWh}^{NPV\geq 0}$ has both a lower mean and median than that of LWRs, implying SMRs are more cost-effective than LWRs.

The Saudi-Arabian all-renewable battery-based benchmark for electricity costs of \$345 per MWh from Elkadeem et al. (2021), is not in comparable terms to the $p_{MWh}^{NPV\geq 0}$, as p_{MWh} is the retail price of electricity, while the all-renewable battery-based benchmark is in the form of electricity production cost. Without even considering the transmission loss, the benchmark should at least be adjusted by dividing by G to get a comparable $p_{MWh}^{NPV\geq 0}$ of \$575 per MWh, assuming the benchmark can generate revenue with no construction time. However, this is not even needed as every SMR $p_{MWh}^{NPV\geq 0}$, and more often than not the LWR $p_{MWh}^{NPV\geq 0}$ as well, is lower than the \$345 per MWh benchmark electricity costs themselves. Therefore, under my modeling assumptions, SMRs are more cost-effective than both LWRs and the all-renewable battery-based solutions. Therefore, SMRs can be a cost-effective solution to the security of supply issue of carbon-neutral power grids.

4.2 Sensitivity analysis

There are certain relationships in my models that I want to further scrutinize. I want to see how sensitive the NPVs and the $p_{MWh}^{NPV\geq 0}$s are to OCC per MW changes, KC_{MW}, and to real interest and discount rate changes, r. Furthermore, I want to know how sensitive the $p_{MWh}^{NPV\geq 0}$s are to construction time changes, $\bar{n}$, and how sensitive the NPVs are to retail electricity market demand changes, p_{MWh}. Note, I am not including the OL3 in my sensitivity analysis.

4.2.1 Sensitivity to overnight construction costs

In Figure 1 the $p_{MWh}^{NPV\geq0}$ is modeled as a function of the KC_{MW} for LWRs under the mean $\bar{n}$ of 9,8 years, and for SMRs under the upper $\bar{n}$ of 5,5 years. When modeling the $p_{MWh}^{NPV\geq0}$ here, the only variables separating the individual LWR cases, and the individual SMR cases, are the $\bar{n}$ and KC_{MW}. The LWRs and the SMRs are separated from each other by the SMRs' higher variable operational costs and capacity factor, and their lower construction times. From Figure 1 it is apparent that under my other assumptions, SMRs are still systematically more cost-efficient than LWRs as long as the KC_{MW} is roughly \$2,43 million or higher. For their $NPVs$ to be positive in the model, the LWRs cannot have a KC_{MW} higher than roughly \$3,33 million, while the SMRs cannot have a KC_{MW} higher than roughly \$3,7 million.

In Figure 2 on the next page, the NPV is modeled as a function of the KC_{MW} in the same fashion as with the $p_{MWh}^{NPV\geq0}$ in Figure 1. However, as the SMR estimates have different MW and the MW is part of what determines the NPV, SMRs are separated into three graphs by their MW. In figure 2 the p_{MWh} is set at \$140. From Figure 2 it is apparent that the potential returns and the potential losses for a 1600 MW LWR are both higher than those of the SMRs. This is partly because of the difference in the level of MW between LWRs and SMRs. However, you can notice that the per MW returns and losses are higher for SMRs than for LWRs. This is largely because the SMRs have much higher variable operational costs in my model. Figures 1 and 2 do not change my assessment of SMRs superior cost-effectiveness.

Figure 1: $p_{MWh}^{NPV\geq0}$ sensitivity to overnight construction costs per MW, KC_{MW}

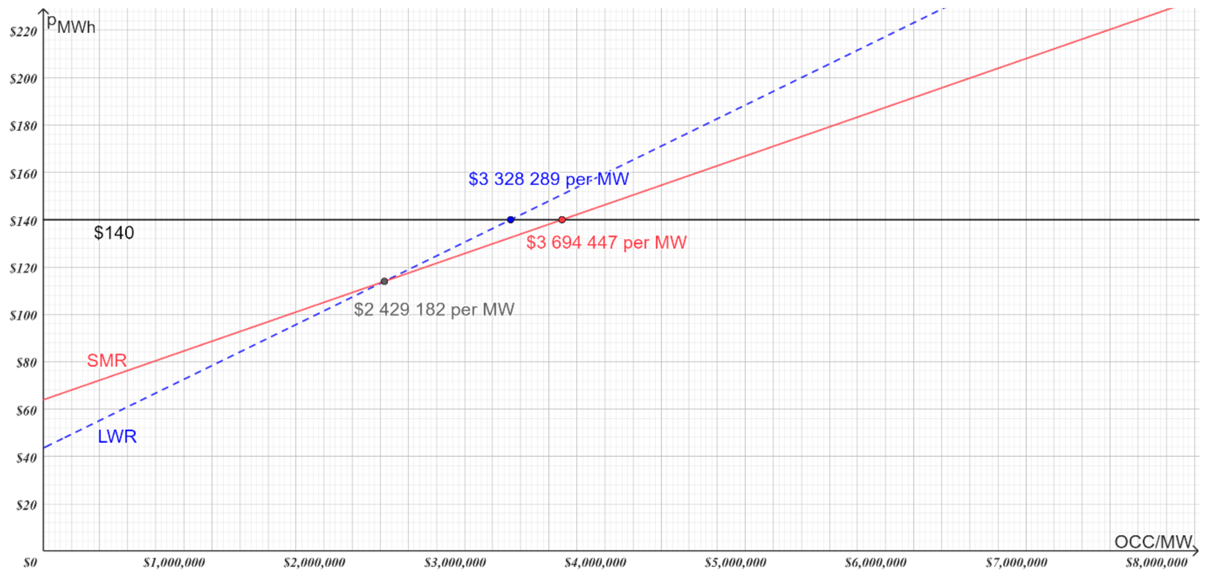
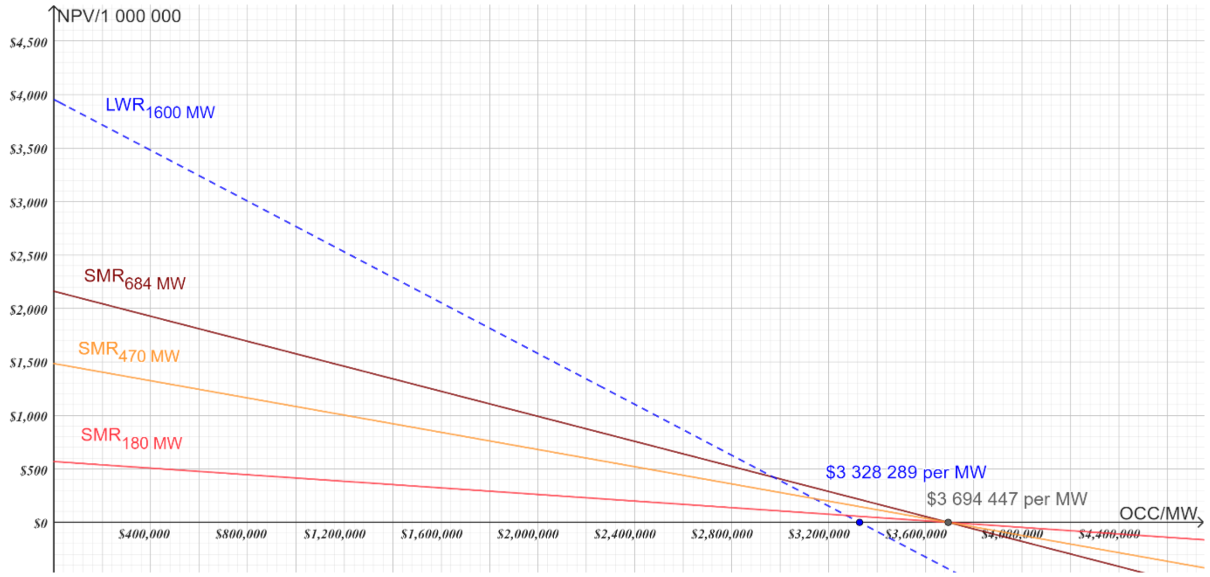


Figure 2: NPV sensitivity to overnight construction costs per MW, KC_{MW}



4.2.2 Sensitivity to the real interest and discount rate

In Figure 3 the NPV is modeled as a function of r for the LWR cases under the mean $\bar{n}$ of 9,8 years, and for the SMR cases under the upper $\bar{n}$ of 5,5 years. p_{MWh} is set at \$140. In Figure 4 the $p_{MWh}^{NPV\geq 0}$ is modeled as a function of the r in the same fashion as with the NPV in Figure 3. One can immediately infer from Figures 3 and 4 that the US higher bound OCC estimate is simply too expensive to be a worthwhile investment, as the r and the p_{MWh} would have to be at least 3% and \$260, respectively to beat the alternative cost. Observe in Figure 3 that the LWRs' NPVs are more sensitive to changes in r than that of the SMR cases, most of the time. As expected, the higher the OCC and $\bar{n}$ are the lower r must be for investors to want to bet on nuclear energy. In Figure 3 only the NuScale estimate can have a worthwhile return for investors at a higher r than the French LWR higher bound OCC estimate. Meanwhile, the Rothwell SMR estimates need a lower r than all the LWR estimates except the US higher bound OCC estimate. The Rolls-Royce SMR can handle a higher r than that of the US lower bound estimate, but only barely.

Figure 4 reveals how close the comparison between SMRs and LWRs is. The shaded area of Figure 4 shows where r is at $7{,}5\% \pm 1\%$. The only interesting change within the shaded area is if the real interest and discount rate was 1% lower, as the US lower bound LWR OCC would beat the Rothwell SMR in cost-effectiveness. Outside the shaded area, it appears that the higher the r the more cost-effective SMRs are in comparison to LWRs, and vice versa. An

Figure 3: NPV sensitivity to real interest and discount rate changes, r

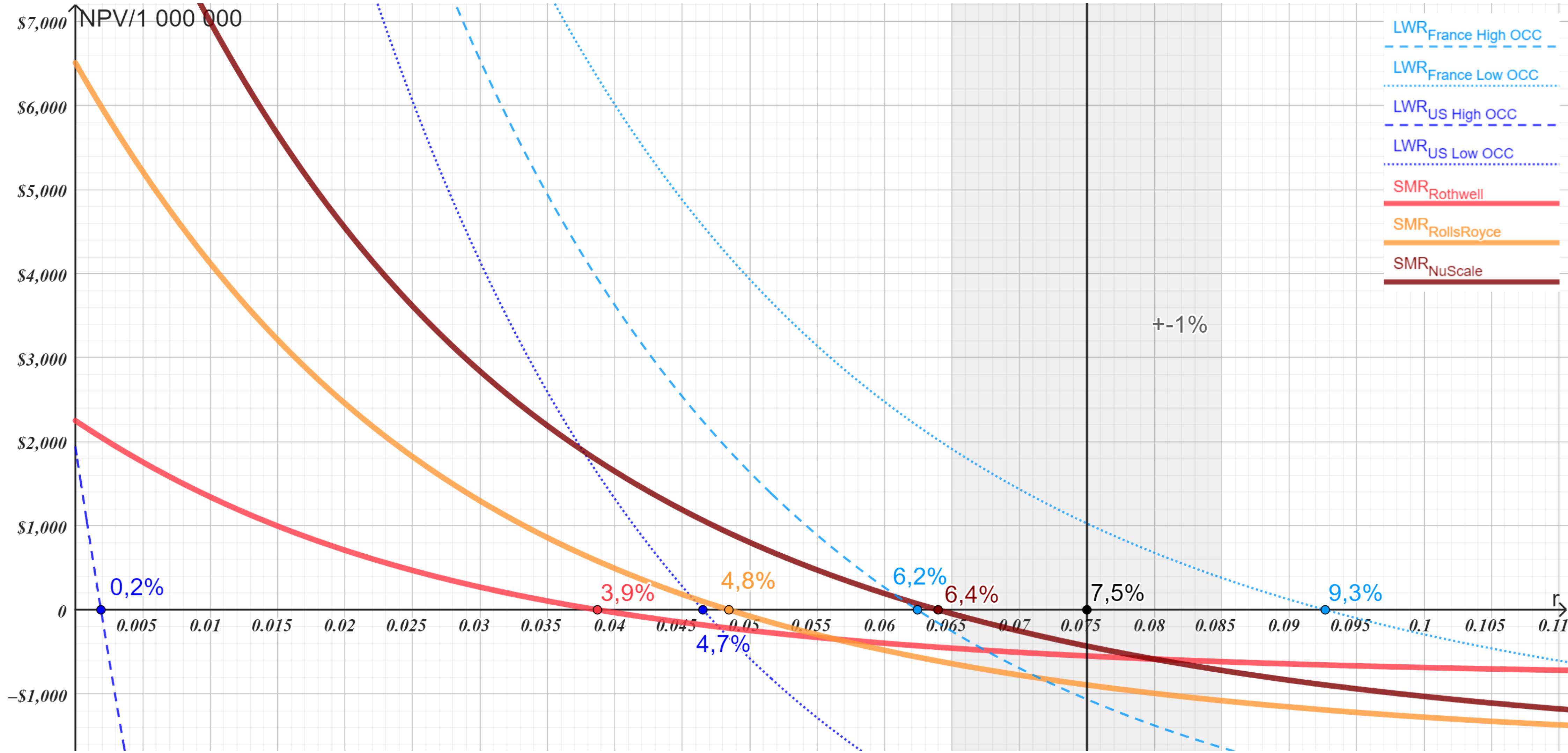
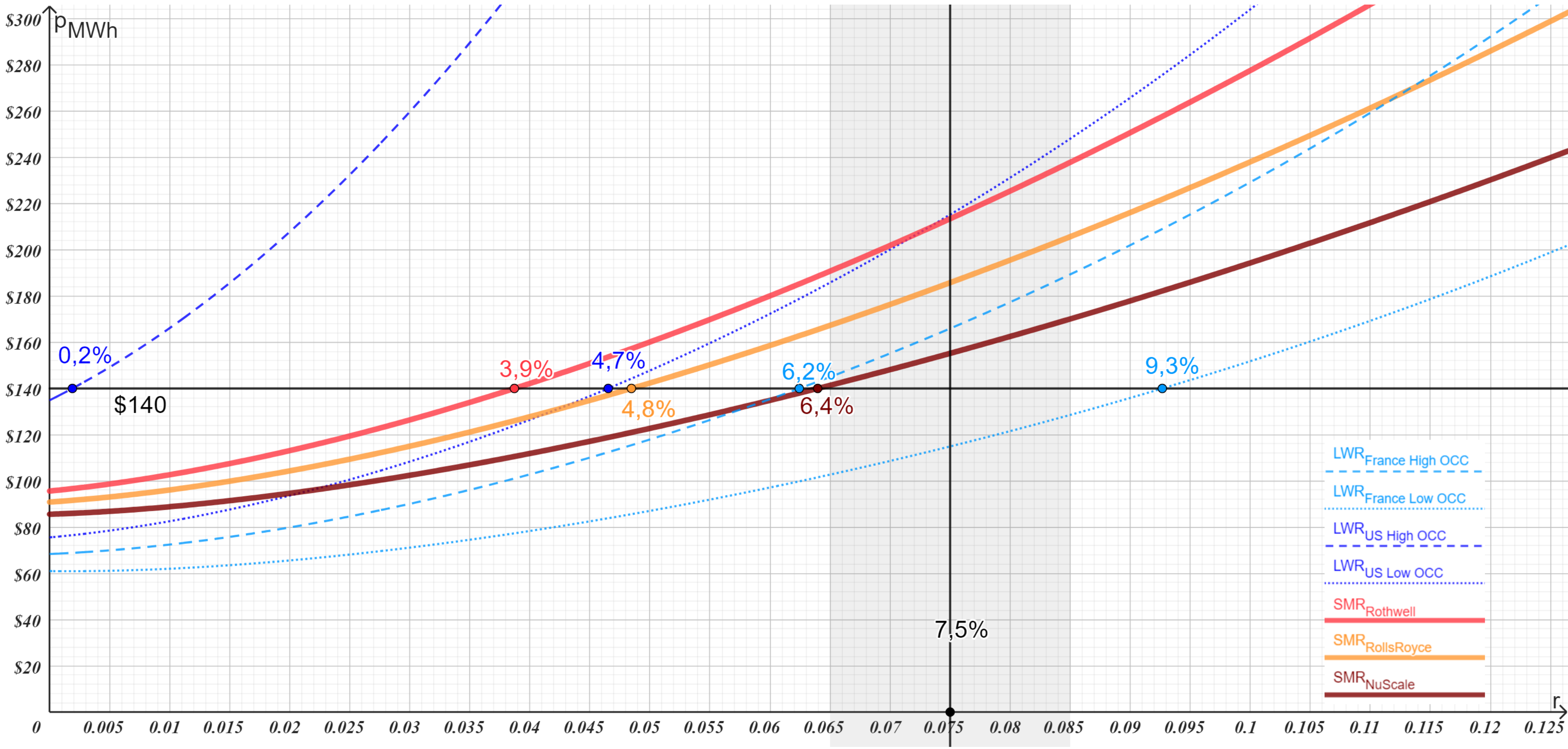


Figure 4: $p_{MWh}^{NPV\geq 0}$ sensitivity to real interest and discount rate changes, r



important reason for this is that the LWRs have historically had longer construction times than the SMRs are predicted to have, leading to LWRs being more sensitive to changing the real discount and interest rate. Both the interest rate and the discount rate separately should have the same overall effect outside of my model as well, but they could be at different levels, more realistically. The key takeaway from these figures is that the real interest and discount rates used when determining both the financial returns and the cost-effectiveness of SMRs compared to established nuclear technologies, are decisive in determining which technology comes out on top. However, I can only state this as applicable when my other assumptions hold, and I leave finding the general impact of real interest and discount rates on the cost-effectiveness and financial returns of LWRs and SMRs to future research.

4.2.3 Sensitivity to construction time

In Figure 5 the $p_{MWh}^{NPV\geq 0}$ is modeled as a function of the $\bar{n}$ for the LWR and SMR cases. The US upper bound OCC estimate gets such large $p_{MWh}^{NPV\geq 0}$s in Figures 5 and 6 that they are outside the limits of the figures I have used. The slopes of the graphs in Figure 5 show how r increasingly reduces the present value of future revenues and costs, with the growth of $\bar{n}$. Every $p_{MWh}^{NPV\geq 0}$ estimate grows at a rate compounding for every increase in $\bar{n}$. As the SMRs have higher variable operational costs and higher CFs, their $p_{MWh}^{NPV\geq 0}$s grows at a slower rate than those of the LWRs. If anything, this shows that my SMR estimates might be skewed in a pessimistic direction by the variable operational costs being too high. If the French LWRs had the same construction times as SMRs they could be more cost-effective than SMRs. However, as discussed, we have mostly seen a tendency for longer construction times for LWRs in North America and Europe, and it is hard to see how this could change in the foreseeable future. For western nations like France, the US, and Finland at least, this is not a likely outcome for any LWR investment without drastic changes in construction efficiency like what has been observed in China and South Korea. As discussed, the NuScale SMRs have seen construction delays, but for the later NOAK reactors the modular design of SMRs is intended to shorten construction times to predictable short periods of time. Unless SMRs end being built as slowly as LWRs, the impact of construction times is a relative benefit for SMRs. However, if SMRs fail at shortening construction times compared to LWRs, it could be that we are just as well off with building LWRs or prioritizing other solutions.

4.2.4 Sensitivity to demand

In Figure 6 the NPV is modeled as a function of the p_{MWh} for the LWR cases under the mean $\bar{n}$ of 9,8 years, and for the SMR cases under the upper $\bar{n}$ of 5,5 years. The slopes of the graphs are linear and dependent upon the $\bar{n}$ and the MW. Each graph can be shifted primarily by changing the OCC or the variable costs. The LWR graphs all have the same increase rate, as they all have the same $\bar{n}$ and MW, while the SMR graphs differ because they have different MWs. The key insight from Figure 6 is that the potential gains and losses are bigger for LWRs when the p_{MWh} deviates from expectations, as building larger scale and less modular reactors requires an all-or-nothing approach. Either the constructor stays invested in the project until construction is complete, or they lose out on any opportunity for revenue, while SMRs have the advantage of offering a more incremental deployment. However, as factories need to be built by SMR constructors to manufacture the modules needed for assembly, the business model might have a comparable all-or-nothing aspect for the constructors of SMRs.

4.2.5 Analysis summary

My initial results implied that SMRs are more cost-effective than LWRs and all-renewable battery-based solutions. After isolating and scrutinizing certain variables and parameters, it seems that this notion holds under small deviations of these variables and parameters. It holds as long as overnight construction costs for LWRs are higher than about \$2,5 million per MW, r does not deviate much more than 1% from the 7,5% used in my modeling, and construction times become shorter for SMRs than for LWRs. The construction time, and the real interest and discount rate, appear to be the most impactful variables in determining whether SMRs are more cost-effective than LWRs. A variable I have not scrutinized in this chapter, which receives some attention in the literature, for example Lévêque (2015), is the capacity factor, CF. In the model I have assumed it to be 0,95 for SMRs, 0,15 more than for LWRs, but there are reasons not inherently apparent in my model, why it could be lower for both LWRs and SMRs in a carbon-neutral power grid. As the CF seems unlikely to change enough to have implications for the comparison between LWRs, SMRs, and the benchmark, I have chosen to briefly discuss it in the discussion part of my thesis and not here. I will also note that I have only scrutinized changes in isolated variables, and if multiple variables were to significantly differ in reality, then the results and their implications may change. However, as it stands, my interpretation of SMRs likely being the most cost-effective solution has not changed.

Figure 5: $p_{MWh}^{NPV\geq 0}$ sensitivity to construction time, $\bar{n}$

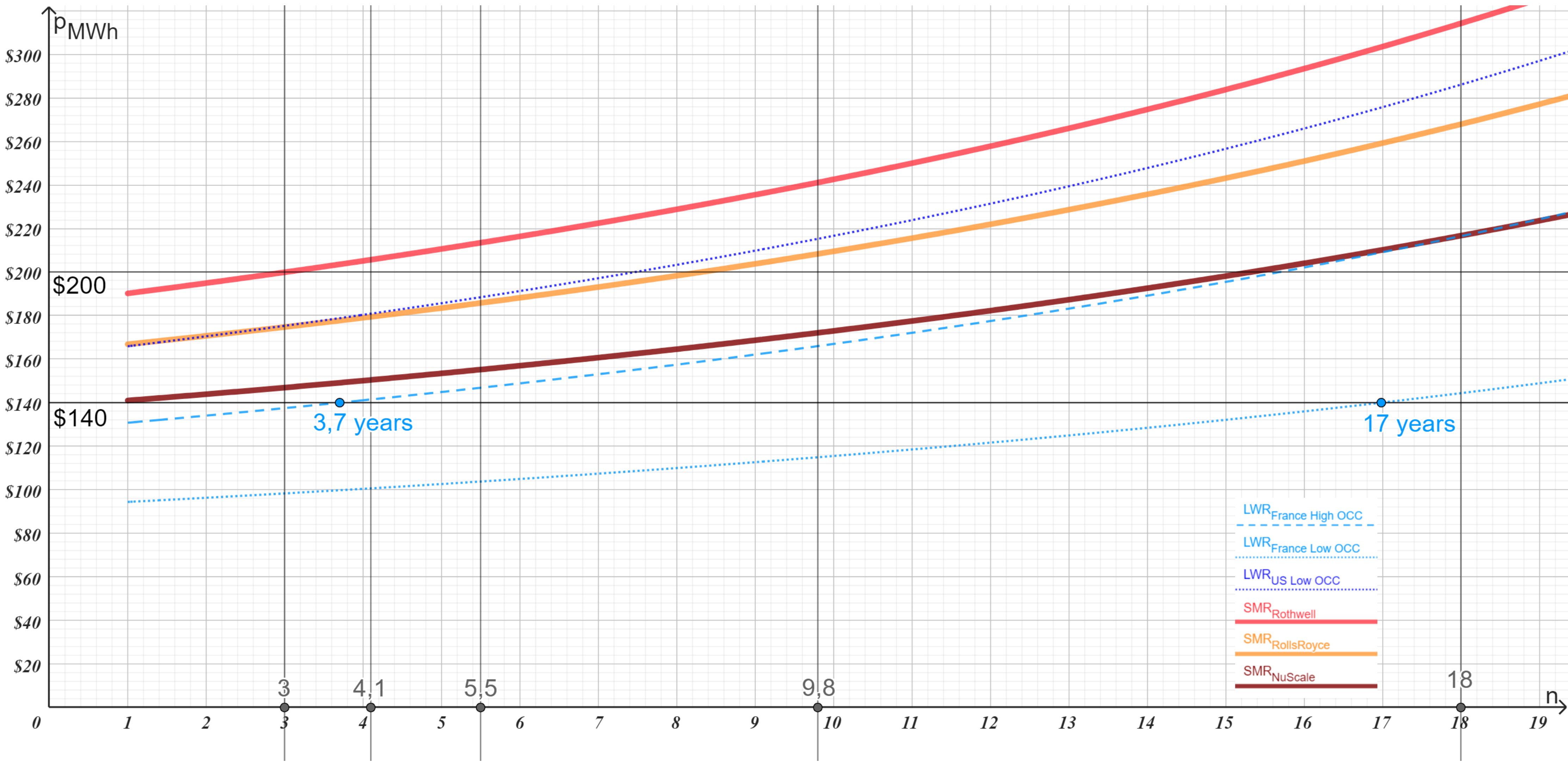
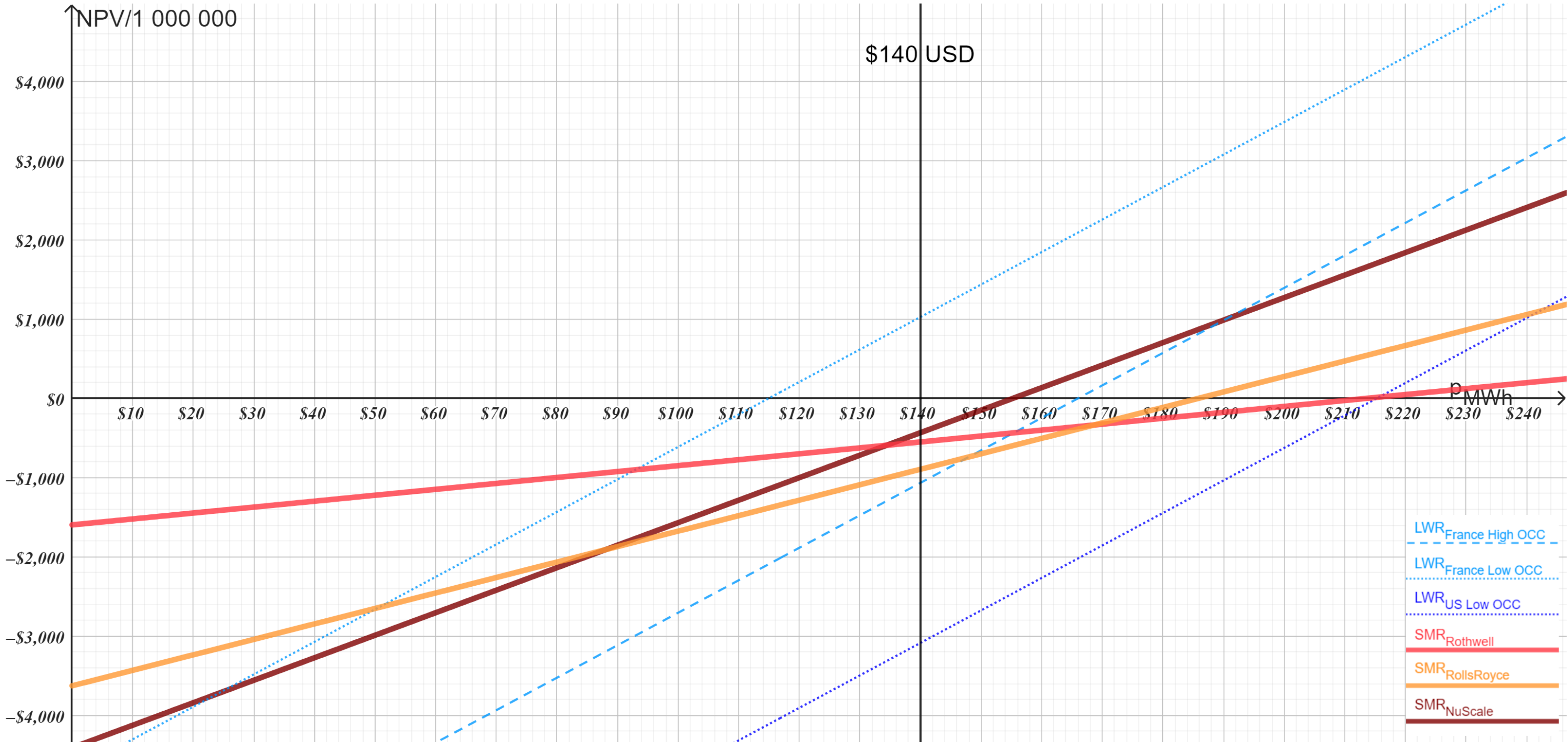


Figure 6: NPV sensitivity to retail electricity market demand, p_{MWh}



5. Discussion

5.1 The uncertainties of construction

It is hard to provide an assured recommendation of constructing any type of power plant, as construction is such a complicated process. As discussed in the theoretical chapters, both construction costs and construction times are hard to predict, especially for nuclear power plants. My impression of the energy supply debate is that there is insufficient disclosure of the uncertainties of building any type of power plant or technology that can support carbon-neutral power grids. My assumed overnight construction costs for LWRs have a wide range, from the very optimistic lower OCC of France justified by steady or even sinking OCCs observed in South Korea, to a drastic OCC growth pattern of 9,2% annually which is likely skewed by the Three Mile Island accident. I have used a wide range of estimates to underline how little consensus there is on what the price of nuclear power is. I can in no way guarantee that OCCs cannot be observed outside of this range in the future, or that there has not been higher or lower OCCs in countries where we have little available data, like Russia or China. However, it seems highly likely to me that any new LWR construction will have an OCC within the range if constructed in Europe or North America. The smaller range between the OCCs I have used for SMRs, accounts for some of the promises made for how SMRs will be. This is not really representative of how uncertain the costs of SMRs are. We simply do not know if SMRs will differ from LWRs in terms of costs before we try to mass-produce SMRs.

Construction times and OCC appear very dependent on the nature of regulatory frameworks and their changing nature, which could differ even between different regions in many countries. However, even when trying to account for as much detail as possible in predictions, the literature points to uncertain uncertainties, and it seems we are currently unable to know all the reasons why these factors are so unpredictable. The historical construction times I have used for LWRs are undoubtedly skewed by different factors. The sample size is small, the mean is heavily skewed by the short construction time observed in Asia, and it is easy to see that the maximum construction time I have used was caused by the Three Mile Island accident, and is therefore skewed like the US OCC. To see for yourself, just subtract the 43,5 construction years in Table 1 from 2019, the Three Mile Accident was in 1979. Another unrealistic implicit assumption of my modeling is that OCC and $\bar{n}$ are changed independently of each other. As discussed, the literature suggests there is some correlation between these factors, and it appears likely that they are dependent on each other. There being a correlation seems likely, but any causality is not obvious, as there could be other explanatory factors. I leave it to further research to explore the correlation, and possible causality, between overnight construction costs and construction times.

5.2 Financial assumptions

I have applied primarily two simplifying financing assumptions. The first one is assuming financing is entirely annuity debt, while the second is using a universal real interest and discount rate, instead of separating this rate into the interest rate and the real discount rate. Financing through debt only is very costly for the primary investor, as they would have to pay interest on all debt used to cover the costs of construction over a long period of time. Equity financing has no repayment obligation, reducing both the potential loss and the potential gain for the primary investor. It is probably unrealistic for a private primary investor in nuclear energy to not include a percentage of equity financing, as including it would lower the high financing costs of nuclear power. Assuming the debt to be in the form of annuity debt seems reasonable to me, but assuming the interest rate to be as low as the discount rate and this implying the length of the downpayment period does not matter, could be unrealistic.

5.2.1 The universal real interest and discount rate

The second primary simplifying financing assumption is the real interest and discount rate. From an investor’s perspective, the alternative cost to investing in nuclear power can be shown in the form of the real WACC. The real WACC used for time-value discounting, seems appropriate as if the average annual returns of the investment do not beat the real WACC, then the investor’s money is better spent elsewhere where the returns are higher. It should also be possible to have a real WACC account properly for inflation for a long-run average of inflation, but I have largely assumed away the responsibility of approximating this inflation rate. Predicting inflation over such a long timeframe as that of an investment in nuclear power, should not be too difficult, as this is really just long-run macroeconomics where short-term changes should be smoothed out over time. As I am using the real WACC of Rothwell (2015) I am at the mercy of his assumptions and calculations, which should be noted when considering the implications of my thesis. The discount rate plays an essential role in estimating the costs of any nuclear power investment, and choosing a different discount rate could change the outcome of my modeling analysis, as I discussed in the sensitivity analysis. The interest rate should be separate from the discount rate, as the bank lending has to suffer the additional risk of not having complete control of or insight into how the debt is being spent, implying the interest rate should be higher than the discount rate. If social costs and benefits were to be included to a larger degree, then the discount rate would need to account for the impatience for benefits, and the increased willingness to incur costs if they are far in the future. As discussed previously, this social discount rate could be a lot smaller.

5.3 Demand & revenue

Is the 60% cut of the retail price going to generation a realistic reflection of wholesale markets for nuclear energy? For the US market it should reflect reality at least for the year it was observed, namely 2022 as discussed earlier. The real average retail price for the US is also reasonable as it is based upon 22 years of historical data for the US. However, there are probably large differences between states, as it likely is between countries, not to mention regions within those countries, for Europe as well. The European real average wholesale price is itself based on about 8 years of historical data that I have generalized for Europe as a whole. The countries included in the dataset are Austria, Belgium, Bulgaria, Switzerland, Czechia, Germany, Denmark, Spain, Estonia, Finland, France, Greece, Croatia, Hungary, Ireland, Italy, Lithuania, Luxembourg, Latvia, North Macedonia, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, and Sweden (Ewen, 2023). Larger countries that are not included are Russia, the United Kingdom, and Türkiye, also Bosnia-Hercegovina, Montenegro, Kosovo, and Albania, and some islands and small countries like Cyprus. Wholesale prices are measured in EUR per MWh in the dataset, and I have adjusted them for inflation myself. I would deem this estimate for a historical wholesale price for Europe as pretty realistic, even though it generalizes the wholesale markets in Europe into a single market, which is not very realistic when considering the French market for example. By using the same methodology for just the French market I get an average real wholesale price of electricity of roughly €94,58 per MWh, compared to the roughly €87,78 per MWh for all the countries included in the dataset. These differences are unlikely to change the outcome of the analysis substantially.

Whether wholesale prices represent 60% of the retail price of electricity in Europe is another generalization that will likely differ greatly between countries depending on how different countries handle taxation and grid rent, for example. I have chosen to use the retail price instead of the wholesale price as the retail price is what is met by consumers. By choosing to use this price for measurement I sacrifice some accuracy because of how G is unlikely to be the same between countries and regions. However, I consider this price to be in a sense more relevant for public policy debate, as it is more transparent and understandable to the consumers than the wholesale price, which might appear deceivingly small when used out of proper context.

A central assumption for the demand side of the equation is for prices to follow historical levels and rise at the pace of general inflation. Electricity prices rising in pace with general inflation could be considered both realistic and unrealistic depending on how strongly other prices will follow the price of energy, which is a macroeconomic question. Whether the future long-run rate of inflation is higher than current inflation is hard to predict. Equinor ASA. (2022) expects electricity demand to nearly double by 2050. However, for supply to reach the same level by 2050 while being carbon-neutral, a drastic shift from the status quo is needed, and it is not unreasonable to suggest that the price of electricity might rise at a higher rate than what we have seen historically. It is hard to separate general inflation from electricity prices as they are so fundamental to our modern economies and exploring the effects of energy price inflation on general long run inflation and the implications of this for nuclear energy, seems like a fascinating area of research that should be explored further. If this pushes the retail price in my models up to more than $200 at least, my results suggest nuclear power, both SMRs and LWRs, might be competitive without policy intervention. An underlying assumption here that I have not stated explicitly, is that I have assumed these nuclear power plants are not price setters but rather price takers. Meaning the power plants must adjust to the electricity markets by being competitive, while the electricity markets themselves do not adjust themselves to the increased electricity supply from nuclear energy without policy intervention. This assumption does not seem unreasonable to me, as consumers might prefer the emissions of fossil fuels to a very expensive carbon-neutral power grid, and as long as this is a viable option nuclear power should not have a lot of market power.

I have not modeled flexibility in deployment for SMRs, but I have tried to model the improved flexibility in meeting demand by using the CF of 0,95 promised by both NuScale and Rolls-Royce, as discussed in the theoretical chapter. First, the model implies that OM_{MWh} is directly linked to CF which is not entirely true according to Rothwell (2015), as a lot of the operation and maintenance must be conducted regardless of output level. More importantly, under a grid primarily dominated by solar and wind the capacity factor is expected to be lower for both LWRs and SMRs as they will have to significantly lower output intermittently to meet the intermittent nature of solar and wind, as predicted by the World Nuclear Association (2022). I have tried to sample the implication of this by setting a CF of 0,5 for the Rolls-Royce SMR with a 5,5-year construction time, with all other parameters set as with the earlier modeling. The resulting $p_{MWh}^{NPV\geq 0}$ becomes about \$353 instead of the \$186 seen in case 16 of Table 5, nearly doubling the cost of electricity. The CF tells us how much of the difference between the variable operational costs per MWh and the revenue per MWh (times the megawatt electric capacity and average number of hours in a year) becomes profit annually. Therefore, it is important to consider the possibility of a lower CF, and the implications of this, which is another important area for continuing research on the implementation of SMRs.

5.4 The social costs and benefits

I have not modeled other social costs or benefits than the benefit of achieving carbon-neutral power grids, and the social costs internalized in NPP construction costs through safety regulation. As discussed, the primary reason for this is how hard it is to measure the social costs and benefits of nuclear power. Lévêque (2015) argues that the social costs and benefits of nuclear power can range from increased security in energy supply, to risk of terrorism at NPPs and storage facilities of nuclear waste. Safety concerns regarding nuclear power might be the most important social cost of NPPs. I find it important to underline that I separate the safety concerns of power plants operating today under current safety standards, and fearful or negative perceptions and impressions of nuclear power, from the social cost internalized in NPP construction costs through safety regulation. The internalized social cost is the external costs and societal damages of a higher likelihood of nuclear accidents, which is averted today by strict safety regulation standards. However, I do not imply by this that there is no risk of, or perception of risk of, nuclear accidents. While my model includes a risk premium for off-site damages including major nuclear accidents under current safety standards, namely the PIN, my model does not internalize the social costs of fearful or negative perceptions and impressions of nuclear power. Public perception of electricity sources is continuously measured, as seen in Leppert (2022) for example, but the social costs of this is hard to monetize accurately. A related point of interest for the debate between SMRs and LWRs is how the improved safe features of SMRs might reduce this social cost of nuclear power. I leave exploring this for future research.

Finally, as part of my cost-effectiveness analysis, I have not monetized the singular big benefit the cost is incurred to achieve, namely the value of every clean MWh added to the baseload electricity supply. Boardman et. al. (2018) states that in order to make a meaningful economic recommendation based on cost-effectiveness, the analyst must know the shadow price of the effectiveness measure. The shadow price refers to the estimated value of something that is not regularly traded in a market. For greenhouse gases the value of abatement changes constantly as global warming progresses. Therefore, even though SMRs might be a cost-effective solution to security of supply issue in achieving carbon-neutral power grids, it is up to the situational researcher or decision maker to determine whether the benefit of carbon-neutral power grids justify the cost of policy intervention.

5.5 Recommendation

My findings suggest that nuclear power, neither LWRs nor SMRs are likely to be competitive without policy intervention. However, compared to LWRs and all-renewable battery-based solutions with insufficient renewable baseload capacity, SMRs appear to be cost-effective in ensuring carbon-neutral power grids. To increase the viability of carbon-neutral power grids, policymakers should incentivize carbon-neutral solutions and disincentivize fossil fueled electricity production. A possible approach is to apply carbon taxation in combination with carbon quotas on fossil fueled electricity, improving the relative competitiveness of nuclear power and other carbon-neutral solutions. This approach could be favorable as it requires as minimal intervention in free markets as one could expect for ensuring carbon-neutral electricity power grids, but energy policy intervention and regulation is hard to implement and might have unforeseen consequences (Perman et al., 2011). I recommend for the reader to explore and contribute research on strategies for carbon regulation, such as carbon taxation, carbon quotas, and their foreseen and unforeseen effects. Finally, an important distinction I must underline in my recommendation is that even though SMRs can be cost-effective in achieving carbon-neutral power grids, this does not mean investing in SMRs is a generally economically efficient allocation of resources. Further research on distributional effects and other possible externalities of incentivizing nuclear power or disincentivizing fossil fuels should be explored and conducted to explore these aspects to a greater degree.

6. Conclusion

The aim of this master’s thesis was to answer whether small modular nuclear reactors can be a cost-effective solution to the security of supply issue in achieving carbon-neutral power grids. Through using a cost-benefit analysis framework, I have modeled the economics of nuclear power, projecting 13 cases for traditional large-scale reactors and 6 cases for small modular reactors. My findings suggest that traditional nuclear power plants require a retail electricity price of anywhere between $101 and $2806 per MWh, for investors to want to invest in nuclear power instead of alternative allocations of capital. SMRs’ promises require a retail electricity price of anywhere between $147 and $213 per MWh. Meanwhile, combining lead-acid batteries with intermittent wind and solar under ideal conditions, might require a retail electricity price of $575 per MWh.

In contrast to the required demand for these technologies to be financially viable, historical real electricity prices observed in the US and Europe suggest retail electricity prices are somewhere around $140 per MWh on average. More likely than not, neither traditional nuclear power plants nor small modular nuclear reactors are competitive without policy intervention. However, when there is insufficient renewable baseload electricity available, the small modular reactor can be a cost-effective solution to the security of supply issue in achieving carbon-neutral power grids.

My thesis contributes a basis for further research on carbon taxation, small modular reactors, the benefits of mass production, and economies of scale within nuclear energy. I have intended to underline the importance of transparency when debating energy solutions, how we cannot bet exclusively on one technology or solution in securing carbon-neutrality, and how there is no universal price of nuclear energy. My approach has been restrained to exploring the possibilities and role of small modular nuclear reactors broadly in our world. Further quantitative research should be conducted before any financial investment or specific policy intervention is recommended. However, my research suggests that nuclear energy should neither be dismissed nor overly praised as an electricity source of the future.

Ultimately, my thesis highlights the necessity of a diversified energy strategy, emphasizing transparency and caution against exclusive reliance on any one solution. As we navigate the complexities of the energy transition, this work guides us to recognize nuclear energy's measured place, neither disregarded nor overly idealized, in the quest for a sustainable and economically efficient energy landscape.

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