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Master's Programme in Engineering Physics

Effects of Regulatory Differences on Nuclear Power Plant Construction Costs and Schedules

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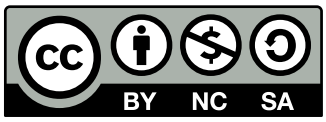

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Abstract

Estimating the costs and schedules of nuclear construction projects has proven to be challenging in numerous recent Nuclear Power Plant (NPP) construction projects. Significant overruns in both costs and durations are common and discourage investing in the construction of new nuclear energy. To support companies, financiers and decision-makers in the evaluation of new NPPs, more reliable estimates are needed.

An important aspect affecting nuclear construction projects is the regulatory environment. Nuclear energy production is a strictly regulated field, and multiple different authorities control nuclear construction. To accommodate for different regulatory environments, changes in the reactor designs are often required, sometimes resulting in a completely new reactor architecture. These design changes make it challenging to estimate project outcomes and utilize learning gained from previous construction projects.

In this thesis, the impact of regulatory differences is studied for four different NPPs. These are the APR1000 and APR1400, modeled as general designs, as well as the EPRs at Hinkley Point C (HPC) and Taishan sites, modeled as case examples of the same reactor type. To compare these nuclear construction projects, their overnight costs and construction schedules are estimated using the Nuclear Cost Estimation Tool (NCET) developed at the Massachusetts Institute of Technology.

The results obtained with the NCET show clearly higher overnight costs per unit of power for the APR1000 compared the APR1400. A significant fraction of this difference is explained by the addition of a core catcher and a double containment in the APR1000 design, both included to accommodate the plant for European regulations. The overnight costs of the HPC EPR are substantially higher than those of the Taishan EPR, largely explained by the differences in commodity and labor prices. However, lower risks at the Taishan site achieved with stable supply chains decrease the construction duration, reducing also the related indirect costs. These results emphasize the effects of regulatory differences and demonstrate the construction cost and duration reductions achievable by building multiple similar units.

Keywords nuclear energy, nuclear construction, cost estimation, schedule estimation, megaprojects, regulation

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Ydinvoimaloiden rakennusprojektien kustannusten ja aikataulujen arvioiminen on monien viimeaikaisten projektien valossa osoittautunut haastavaksi. Merkittävät kustannusten ylitykset sekä aikataulujen viivästymiset ovat yleisiä eivätkä rohkaise sijoittamaan uuden ydinvoiman rakentamiseen. Yritysten, rahoittajien ja päätöksentekijöiden tukeminen näiden projektien suunnittelussa vaatii luotettavampia arvioita.

Paikallinen regulaatio on merkittävä ydinvoimaprojekteihin vaikuttava tekijä. Ydinenergian tuotanto on tiukasti säänneltyä, ja sitä valvotaan tarkasti eri viranomaisten toimesta. Jotta ydinvoimalaitos soveltuu paikalliseen lainsäädäntöön, reaktorimalli vaatii usein muutoksia, mahdollisesti johtaen myös täysin uuden reaktorityypin kehittämiseen. Nämä reaktorimalliin tehdyt muutokset hankaloittavat rakennusprojektien arviointia sekä aiemmista rakennusprojekteista kerätyn tietotaidon hyödyntämistä.

Tässä diplomityössä tutkitaan regulaatioerojen vaikutusta neljään eri ydinvoimalaan. Tutkittavat ydinvoimalat ovat APR1000 ja APR1400, joita mallinnetaan geneerisinä laitostyyppeinä, sekä EPR:t Hinkley Point C:n (HPC) ja Taishanin ydinvoimalaitoksilla, joita mallinnetaan case-esimerkkeinä samasta laitostyypistä. Näiden ydinvoimaloiden rakennusprojektien vertailemiseksi niiden korottomia kustannuksia sekä aikatauluja arvoidaan Massachusetts Institute of Technology -yliopistossa kehitetyllä Nuclear Cost Estimation Tool (NCET) -koodilla.

NCET-koodilla saadut tulokset osoittavat selkeästi APR1000-reaktorin korkeammat tehoon suhteutetut kustannukset APR1400-reaktoriin verrattuna. Merkittävä osuus tästä erosta johtuu APR1000-malliin lisätyistä sydänsiepparista ja ulommasta suojarakennuksesta, jotka molemmat perustuvat eurooppalaiseen regulaatioon. HPC-laitoksen kustannukset ovat merkittävästi Taishanin laitoksen kustannuksia suuremmat, mikä johtuu pitkälti rakennusmateriaalien ja työvoiman hintaeroista. Taishanin laitokselle arvioidut pienemmät riskit rakennusprosessissa kuitenkin lyhentävät arvioitua aikataulua, mikä osaltaan pienentää projektin epäsuoria kustannuksia. Tulokset korostavat regulaatioerojen vaikutusta sekä demonstroivat useiden samanlaisten laitosyksiköiden rakentamisella saavutettavia kustannusvähennyksiä ja aikataulun tehostumista.

Avainsanat ydinenergia, ydinvoiman rakentaminen, kustannusarviointi, aikatauluarviointi, megaprojektit, regulaatio

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Espoo, 9 October 2025

Laura Heikkilä

Contents

Symbols and abbreviations

Symbols

$ USD, United States Dollar
£ GBP, Great British Pound

Abbreviations

APR	Advanced Power Reactor
ARIS	Advanced Reactor Information System
CCGT	Combined Cycle Gas Turbine
DC-PWR	Double Containment Pressurized Water Reactor
EDF	Électricité de France
EEDB	Economic Energy Data Base
EPR	European (or Evolutionary) Pressurized Reactor
EU-APR	European Advanced Power Reactor
EUR	European Utility Requirements
FOAK	First-of-a-Kind
FSAR	Final Safety Analysis Report
GA	Genetic Algorithm
HPC	Hinkley Point C
IAEA	International Atomic Energy Agency
I&C	Instrumentation & Control
KEPCO	Korea Electric Power Corporation
KHNP	Korea Hydro & Nuclear Power
LASR	Large Active Safety Reactor
LCOE	Levelized Cost of Electricity
NCET	Nuclear Cost Estimation Tool
NOAK	Nth-of-a-Kind
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
O&M	Operation & Management
ONR	Office for Nuclear Regulation
OPR	Optimized Power Reactor
PPI	Produce Price Index
PWR	Pressurized Water Reactor
SMR	Small Modular Reactor
STUK	Säteilyturvakeskus (Radiation and Nuclear Safety Authority)
TBM	Tunnel Boring Machine
VVER	Water-Water Energetic Reactor
WENRA	Western European Nuclear Regulators' Association

1 Introduction

Climate change is one of the most crucial challenges needed to be solved to avoid severe environmental problems, capable of causing a global humanitarian crisis. To mitigate these risks, states, unions, and organizations have set goals and agreements to achieve concrete results. Because the impacts of climate change are complex and many of them difficult to quantify, several key indicators describing the changing climate are used to track the progress. These indicators include, for example, temperature rise, produced carbon emissions, and sea water levels.

Probably the best-known climate change treaty is the Paris Agreement, originally adopted at the Climate Change Conference of the United Nations in 2015 and today signed by 195 parties [1]. The main goal is "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels" [2]. In Europe, the European Union (EU) has established the European Climate Law, the aim of which is to achieve net zero greenhouse gas emissions by 2050 [3]. As a step towards this goal, the law also states that net emissions should be reduced by 55% by 2030 compared to the levels of 1990. In addition to these international agreements, many countries have set their own national goals to limit climate change. In Finland, this is established through the Climate Act, which legally binds Finland to gradually reduce greenhouse gas emissions and to achieve carbon neutrality by 2035 [4].

To achieve these goals, effective measures are required. By far the most important source of greenhouse gas emissions is energy production [5], which is still largely based on fossil fuels. One way to address this issue is by increasing the share of renewable energy, which is an effective strategy especially considering the shorter-term targets, such as the 2030 EU goal. However, renewable energy poses its own difficulties, and may not be sufficient on its own to solve the environmental crisis. With current technology, increasing the amount of nuclear power can serve as an important approach for ensuring electricity grid stability and guaranteeing a reliable energy supply, while helping to minimize carbon emissions.

Although Small Modular Reactors (SMRs) would potentially allow for shorter construction times and lower absolute costs compared to larger reactors, many SMR designs and concepts are still under development. As of 2024, there were only two SMRs operating commercially, one in Russia and one in China [6]. To fully utilize the advantages offered by smaller reactors, further development and concrete steps toward construction are needed.

For larger Nuclear Power Plants (NPPs), there already exists a well-established foundation of commercially operating plants and companies operating them. Due to the high investment costs and long construction times, new companies entering the nuclear sector may be more likely to pursue constructing SMRs rather than invest in large-scale reactors.

The uncertainties associated with the construction of nuclear reactors can make investing in new reactors even less appealing. Delays in construction schedules are more the rule than the exception, a problem that has been recognized for decades. For example, in 1979, the Congressional Budget Office of the United States published

a report discussing the issue of NPP project times having increased from 6–7 years to 10–11 years during the previous decade [7]. More recent examples of delayed NPP projects include Olkiluoto 3 in Finland, which started operation 14 years behind schedule [8], and Flamanville 3 in France, which started operation 12 years behind schedule [9]. Both of these reactors are European Pressurized Reactors (EPRs), also known as Evolutionary Pressurized Reactors, and were the first of their type to begin construction, probably contributing to the long delays.

Due to the high investment costs of new nuclear reactors, delays also often cause large financial losses. Compared to the original budgets, the final costs are estimated to be three times greater for Olkiluoto 3 [10] and four times greater for Flamanville 3 [9]. Regulatory changes, modifications to the reactor design and site layout along the way, and shortages of materials, components, and labor can increase the cost associated with NPP construction projects either directly or through delays. As a capital-intensive technology, nuclear power costs are also more sensitive to the market environment compared to other technologies.

Both international and national laws and regulations guide the planning and construction of new NPPs. Neglecting regulatory requirements can result in significant overruns both in terms of time and costs. Moreover, differences in regulatory frameworks between countries may require modifications to plant designs, even to the extent that a new type of NPP is designed to meet the local laws and regulations. Although these plants resemble each other and often originate from the same design, the changes in designs can cause major differences in the construction process. Because of this, it is difficult to estimate the extent to which know-how and information from previous NPP construction projects can be utilized.

In this thesis, different reactor designs are compared, especially focusing on the effects of regulatory differences. The comparison includes two Advanced Power Reactors (APRs), APR1000 and APR1400, with power outputs of 1,000 MW and 1,400 MW, respectively. Both of these designs are Pressurized Water Reactors (PWRs) developed by Korea Electric Power Corporation (KEPCO) with its subsidiary Korea Hydro & Nuclear Power (KHNP). The APR1000 is developed based on design and operating experience of the APR1400, as well as the 1000 MW Optimized Power Reactor (OPR), another design by KEPCO and KHNP [11]. The APR1000 is designed focusing on European conditions by enhancing its safety, especially considering the latest requirements by the European Utility Requirements (EUR) Association, International Atomic Energy Agency (IAEA) and Western European Nuclear Regulators' Association (WENRA) [12].

In addition to the APRs, the comparison includes two versions of the EPR, a 1,650 MW PWR originally designed by Framatome and Siemens [13]. These versions are the two Hinkley Point C (HPC) EPRs in the United Kingdom and the two Taishan EPRs in China. As the reactor model behind these two plants is the same, the direct effects of regulatory differences are easier to compare.

The comparison is performed by estimating the costs and durations of the construction processes. In addition, the risk of cost and schedule overruns is estimated by performing an uncertainty analysis. To estimate the costs and schedules, an open-source Nuclear Cost Estimation Tool (NCET), developed by W. R. Stewart

and K. Shirvan at the Massachusetts Institute of Technology [14], will be used. The methodology behind the tool is further explained in [15] and [16]. In Stewart's thesis, the cost estimation is performed for different advanced NPP designs. These designs include a Large Active Safety Reactor (LASR), similar to the APR1400, and a Double Containment PWR (DC-PWR), similar to the EPR. The input files of these reactors are utilized in this thesis and modified based on available data to obtain results for the APR1000 and the two versions of the EPR.

This thesis is organized as follows. First, Section 2 introduces the background of nuclear construction projects, the regulatory framework, and the details of the reactor designs. Section 3 provides a closer look at the methodology, focusing on the NCET and modifications made to the inputs based on reactor designs. In Section 4, the results are presented, followed by analysis and discussion in Section 5. Finally, the work is concluded and the key findings summarized in Section 6.

2 Background

In this section, background on nuclear construction projects as well as other large-scale projects is provided, with a particular focus on the project costs and schedules. In addition, the regulatory framework is introduced, and the details of the reactor designs modeled in this work are presented.

2.1 Megaprojects

In addition to NPPs, there exist many other large-scale projects, also called megaprojects. There is no one exact definition for a megaproject, but the typical characteristics include technological and logistical demandingness, a cost of more than a billion USD, and a duration of more than five years [17]. Although many megaprojects primarily involve the construction of new infrastructure, the development processes of new products, such as vaccines or aircraft, can also be considered megaprojects.

As pointed out in [18], megaprojects are not just magnified versions of smaller projects. Instead, the complexity of megaprojects in all areas is much broader than for regular projects. In terms of project management, experience on large projects is crucial for ensuring effective coordination of all subtasks and seamless cooperation among different stakeholders, such as contractors, financiers, and regulators. If the interests of different stakeholders do not coincide, the decision-making process might be delayed. Additionally, with long projects, it is possible that the people responsible for the project management change during the project. This may cause delays in the transfer of information and decision making, threatening the fluid continuity of the project.

Megaprojects often produce infrastructure or utilities critical to a specific area or society. The end products may be critical in terms of transportation, energy production, national health or other factors, explaining why megaprojects are often more strictly regulated compared to smaller-scale projects. The aim of strict regulation is to minimize the risks associated with different factors, such as human error, natural disasters, and terrorist attacks, while also ensuring the continuity of critical functions as well as the safety of people and the environment in the event of a potentially harmful occurrence. As they provide critical infrastructure, megaprojects often involve the use of public funds, also explaining the strict regulation of these projects by the state. To comply with these regulations, megaprojects often require extensive administrative work at all stages, and the preparatory work required to obtain a permit for the project may end up consuming substantial time and resources.

Especially in large construction projects, such as bridges, airports, and power plants, logistics and scheduling have a critical role. In some cases, new infrastructure is built on a site lacking existing road network or other connections to the neighboring areas, which has to be accounted for in project planning. Supply chains of construction materials and equipment require thorough planning and coordination, particularly for critical components with long lead times, for which delays can halt the entire project. If the project requires custom-made components without pre-existing active supply chains, experiencing delays is more probable. Planning an effective construction

schedule is crucial for ensuring smooth progress of the project and efficient workforce utilization. Keeping a large workforce on standby because preceding tasks have not been completed or required materials and equipment are not yet available can become costly. For one-of-a-kind megaprojects requiring a lot of workforce and specific know-how, the construction personnel might need special training before beginning work.

It is also common for megaprojects to experience cost overruns. Cost overruns of over 50% are not uncommon, and for example the Sydney Opera House experienced a cost overrun of 1400% [18]. Megaprojects are often unique by nature and consist of a large number of dependent tasks, making the estimation of the final cost difficult. As stated in [19], the risks associated with technological innovations in many megaprojects are often not properly accounted for in the cost estimates.

When estimating the viability of a new megaproject in terms of funding, the schedule of the project is an important factor. In megaprojects, a large portion of funding is often based on external loans, making interest rates a critical factor when estimating total financing costs. Consequently, long delays can significantly threaten the financial stability of the project. The financial risks caused by delays and cost overruns might make many megaprojects unappealing investments to financiers, potentially leading to higher interest rates for the loans.

2.2 Nuclear Construction Projects

Nuclear construction projects are not an exception to the megaproject challenges explained in the section above. However, the nature of nuclear construction projects poses further uncertainties and risks in these areas. In terms of financing, predicting the outlook of the electricity markets after multiple years can be difficult, making the estimation of payback period and total financing costs more complicated. It is also possible that nuclear power generation faces sudden legislatorial changes, impacting the feasibility of the project. An example of this is the nuclear phase-out in Germany after the Fukushima accident in 2011. The decision of the phase-out was made in the year of the accident, and the final reactors were taken offline in 2023 [20].

Nuclear power generation is among the most strictly regulated industries [21], which adds additional stages to the design, construction and operation of NPPs. Strict regulations highlight the importance of proper planning, as mistakes during the construction phase can end up being costly in terms of both time and money. The decision to build a new NPP involves multiple stages with many different factors and perspectives affecting the overall feasibility of the project.

The issues in nuclear construction projects are clearly visible when comparing the final costs and construction times of recent NPP projects to their initial budgets and schedules. In Figure 1, the estimated budgets and construction times of recent NPP projects are compared to the final values based on information from [22]. As can be seen, the delays are significant for all the NPPs in question, and many plants also faced major cost overruns. The largest delay was 220% for Olkiluoto 3, and even the smallest delay was 80% for both Sanmen 1&2 and Shin Kori 3&4. The largest cost overrun was 360% for Flamanville 3, and the smallest one was 30% for Shin Kori 3&4. The

most significant challenges, especially in terms of cost, are clearly associated with the two EPRs in Europe, with the AP1000 in the United States following closely behind.

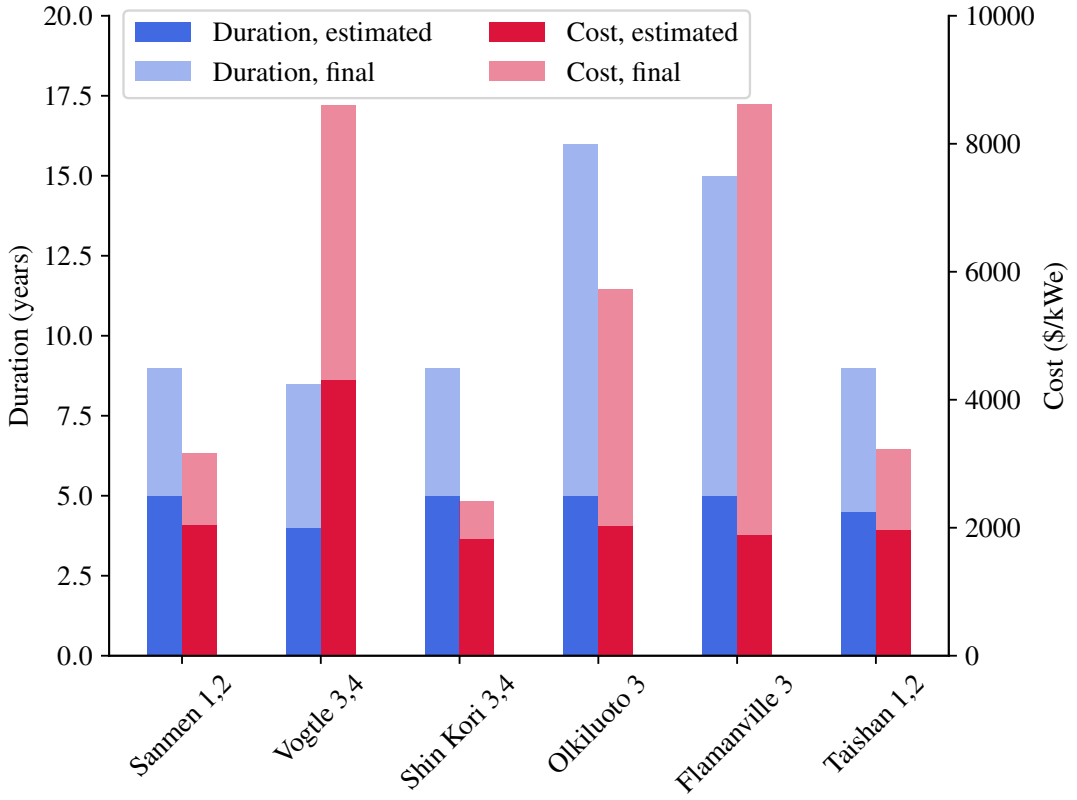


Figure 1: Estimated and final durations and costs of modern NPP construction projects. Data retrieved from [22].

To address the issues presented above, multiple different approaches have been suggested. An example of a partial solution is reactor modularization, where parts of the reactor are fabricated elsewhere and brought to the site, where they only need to be installed. This shortens the on-site construction period and enables faster progress to subsequent tasks. However, the transportation of larger components may be costly, and the factories may also experience delays, affecting the timeline of the whole project. SMRs, as the name suggests, are designed to utilize modularization, but the same approach can be used for larger plants as well. However, due to the larger size, some tasks can only be performed at the site of the reactor.

Learning-by-doing is another important way to improve the efficiency of nuclear construction. By building similar plants, the plant design and the supply chain will become more stable, the workforce more experienced, and the construction process better defined [16]. Learning effects can be applied to individual components as well, even when the reactor design is unique compared to previously constructed models. This is especially true if the component in question is similar to those on other types of power plants, increasing the reliability of the fabrication process. Existing demand often means more stable production chains and facilities, and the components are

more likely to be produced on time and without flaws. Building multiple NPPs on the same site is also a commonly used approach to reduce construction costs and shorten the construction schedule, as the same site and plant infrastructure can be used, and some of the workforce's learning can be also be applied.

2.3 Regulatory Framework

At the global level, the IAEA is the key organization promoting nuclear safety. The IAEA publishes Safety Standards, which "provide the fundamental principles, requirements and recommendations to ensure nuclear safety" [23]. These Safety Standards cover a wide range of topics from NPP site evaluation to nuclear waste management. However, the IAEA does not have the legislative authority to make these standards mandatory for its member states. Nevertheless, many countries base their national legislation and regulations on the IAEA recommendations.

The EUR Association combines regulations from national nuclear authorities to harmonize and increase the transparency of European design requirements. Although these requirements are not mandatory to follow, they help vendors navigate the European market more easily and facilitate the assessment of new reactor designs.

Each country maintains its own specific nuclear regulations, often based on, or adapted from, broader international standards and recommendations. In most countries, there exists an organization in charge of regulating the nuclear industry. Examples of these include Radiation and Nuclear Safety Authority (STUK) in Finland, Nuclear Regulatory Commission (NRC) in the United States and Office for Nuclear Regulation (ONR) in the United Kingdom.

While many aspects of nuclear industry are governed by laws and regulations specifically addressing nuclear topics and issues, general legislation regarding construction and industrial practices must also be considered. For instance, fire safety regulations must be addressed separately from nuclear-specific requirements. Likewise, these general regulations may vary significantly between countries. Additionally, labor conditions, such as salaries, working hours, and workplace practices also differ from country to country and can have a large impact on the final cost and schedule of the nuclear construction project.

2.4 Cost of Nuclear Power

As shown in Section 2.2, the final cost of an NPP construction project is difficult to estimate and is often subject to unexpected changes. The costs can be divided into two categories: direct and indirect costs. Direct costs include components, materials, and labor required for the physical construction of the reactor. Indirect costs include tasks supporting the construction, such as administration and supervision. The latter is more vaguely defined, and the exact definition may differ between different sources, making comparison more difficult. Owner's cost, including e.g. project management and land costs, are not included in the NCET due to their strong dependency on site and utility instead of reactor architecture [16].

Capital costs, which cover costs from site preparation to commissioning as well as financing, are clearly the most significant share of nuclear energy costs. This is due to the complexity and scale of the construction project, also tied to long construction times. Compared to these capital costs, the operating costs of an NPP are significantly smaller. In [24], it is stated that capital cost can account for more than 80% of the cost of energy produced by an NPP. The remaining costs consist of Operation and Management (O&M) costs, including staffing and fuel costs. Due to high overnight costs, interest rates play a large role in determining the final project costs. The current version of the NCET only estimates overnight costs, omitting interest from the final costs. This way, the costs of new NPP projects are determined by the reactor architectures as well as local regulations and construction conditions, and the uncertainty and variation of interest rates do not have to be considered.

The most common metric for comparing different means of electricity production is the Levelized Cost Of Electricity (LCOE). LCOE gives the total cost of the plant with relation to the total electricity output over the lifetime of the plant, taking into account all the costs of building and operating the plant. LCOEs of different plants are compared as an example in [25]. Compared to other baseload technologies, namely coal and natural gas-fired Combined Cycle Gas Turbine (CCGT), the median LCOE of nuclear is the lowest at 3% interest rate and highest at 10% interest rate. At 7% interest rate, the median LCOE of nuclear is close to the two others. However, the regional variations are large, causing a wide range of LCOEs in each scenario. With each interest rate, LCOEs of CCGT and coal are similar with relation to each other, but the LCOE of nuclear switches from the least expensive to the most expensive. This highlights the important role of capital cost and interest rates in nuclear industry.

Lifetime extensions are a common practice in nuclear industry. For example, in Finland, all four NPPs that have reached their originally planned lifespan have been granted a lifetime extension. In such cases, the LCOE drops significantly, as the operational costs are minor compared to the capital costs, even when the costs required to achieve the extension are taken into account. In the original LCOE estimates, however, the possible lifespan extensions are not taken into account, and the final LCOE can only be determined when the whole lifespan of the NPP is known.

Due to the strictly regulated nature of nuclear construction, same materials tend to be more expensive compared to non-nuclear construction. For example, structural steel used in nuclear construction is reported to be over twice as expensive per unit of mass compared to non-nuclear steel [26]. In addition, requirements for the construction workforce are often stricter, resulting in higher salaries and increased total costs. Installation rates of nuclear commodities are lower than non-nuclear commodities [26], further extending the construction times and thereby increasing both labor and financing costs.

As in other industries, another important factor in nuclear power costs is the economy of scale, referring to the cost advantages achievable with NPPs of higher power output. For many components and structures, the costs do not necessarily increase proportionally to the output power of the plant. In addition, utilizing multi-unit sites can reduce total costs, as NPPs on the same site can share buildings and safety systems. Additionally, a significant fraction of the costs associated with the site,

such as costs of licensing and building the required infrastructure, can be shared. Naturally, constructing a larger reactor or multiple reactors on the same site poses its own challenges and remains more costly in absolute terms, limiting the application of both strategies.

2.5 Reactor Designs

Due to the sensitive nature of nuclear power, detailed information on different reactor designs and their specific features, components, and structures is not always easily available. In Europe, the EUR Association handles design assessments for new reactor designs. Acceptable candidates for the assessment are reactors that are developed enough for a detailed assessment and for which the vendor intends to be present on the European market [27]. The EUR Association has certified both the EPR and the APR1000 for European use, but for the APR1400 only a modified version, also known as EU-APR, has been certified [28]. However, design assessments are not publicly accessible, restricting the amount of data available.

In the United States, the NRC regulates nuclear power plants and other uses of nuclear materials, and issues design certifications for NPP designs. The NRC has issued a design certification for the APR1400, and the design control document for this design is available. The document includes more detailed information about the reactor design, but security-related information has been withheld [29]. The U.S. EPR has not received a design certification, but the Final Safety Analysis Report (FSAR), submitted to the NRC by Areva, is publicly available [30].

The IAEA upholds an Advanced Reactor Information System (ARIS) database, which provides descriptions of various advanced nuclear reactors. The database includes technical data on the EPR [13], APR1400 [31] and APR1000 [32], providing valuable details also utilized in this thesis.

2.6 Nuclear Power Plant Comparisons

In this work, the comparison of the NPPs is mostly performed in two parts. Although the same output values are reported for all four plants, direct comparison between the APRs and the EPRs is challenging, as the APRs represent generalized reactor designs, while the EPRs refer to specific plants either operational or under construction. Thus, the APRs are mostly compared with one another as general designs with shared origins, and the EPRs are compared with one another as different variants of the same reactor type.

2.6.1 APRs

The first comparison is performed between the APR1400 and APR1000, both developed by KEPCO and KHNP. There are currently eight operational APR1400 units worldwide, four at Barakah in the United Arab Emirates, two at Shin Kori and two at Shin Hanul, the latter four located in South Korea. In addition, two more units are under construction in Shin Kori, and two more are planned to be built in Shin Hanul [33]. There are

currently no operating APR1000 reactors, but KHNP has signed a contract to build two APR1000 units in Czech Republic [34].

In addition to output power, the key differences between the two APRs include double containment and core catcher, both of which are only features of the APR1000 design [11, 35]. These modifications are intended to make the APR1000 more suitable for the European market and serve as key examples of modifications made to the reactor design based on regulatory differences. In Finland, for example, STUK requires that "any leaks of radioactive substances from the gas space of the primary containment shall be led to the secondary containment" [36], a requirement addressed by including the double containment into the design. Similar formulation can be found from a report by WENRA, stating that "the containment penetrations should be surrounded by secondary structures to collect the potential leakages from the containment" [37].

In addition to avoiding leakages, the double containment can work as a safety system against airplane crashes. STUK requires that an airplane crash with its consequences shall be the design criteria for an NPP so that crucial safety functions can be activated and significant radioactive releases can be avoided [38]. Although this regulation does not explicitly require a double containment, it can contribute to achieving the required integrity.

Similarly to the double containment, the core catcher addresses a STUK requirement stating that "a nuclear power plant shall be equipped with systems to ensure the stabilisation and cooling of molten core material generated during a severe accident" [36]. The exact wording of these type of regulations may, however, vary between countries. Often, specific safety systems are not prescribed to achieve the required safety functions, but the additional systems incorporated into the design can be seen as a result of these requirements.

Other important differences between the APR1400 and APR1000 include the site layout, building dimensions, and key component parameters, such as reactor pressure vessel size as well as the number of fuel assemblies and control rods inside the core. In terms of building dimensions, distinguishing modifications driven by regulatory requirements from general differences in reactor architectures is often difficult.

Further support for these design differences arising specifically from regulatory requirements can be found by examining another reactor model by KEPCO and KHNP, European APR1400 (EU-APR). Like the APR1000, the EU-APR is developed to comply with European regulations. The design of the EU-APR, however, more closely resembles the APR1400 than the APR1000. Nevertheless, the same additional safety systems, including both the double containment and the core catcher, appear in its design modifications [39].

2.6.2 EPRs

The second comparison is between two EPRs designed by Framatome and Siemens, later merged to form Areva: HPC in the United Kingdom and Taishan in China. On both sites, there are two EPR units. HPC is still under construction, but the first unit at Taishan was connected to the grid in 2018 and the second in 2019, making Taishan the first site worldwide with operational EPRs. The other two operational EPRs are

located at Olkiluoto in Finland and Flamanville in France.

Since the reactor design is the same, the differences between the two EPRs compared in this work are mainly structural. These structural differences include different cooling water tunnels, large protective sea wall at HPC, and some differences in the main buildings, namely the thickness of the substructure concrete and the double containment structure. Apart from structural differences, the only distinction between the reactors at the two sites is the doubled Instrumentation & Control (I&C) system at the HPC site. In addition, variations in labor and commodity costs affect the project outcomes.

3 Methodology

In this section, the methodology used to obtain results is explained. This includes the principles of the tool used for the estimation but also the required modifications to the input files based on the reactor designs.

3.1 Nuclear Cost Estimation Tool

As explained in [16], the NCET is developed to model advanced nuclear power plants under uncertainty, providing insights into both investment and reactor design decisions. The modeling is performed by scaling existing cost and labor data based on the specific reactor design. The model consists of multiple parts, estimating costs, schedule, and risks separately.

3.1.1 Economic Energy Data Base

The NCET cost and schedule estimates are based on Economic Energy Data Base (EEDB) [40], gathered by United Engineers & Constructors Inc. for the U.S. Department of Energy. The purpose of the EEDB was to collect both technical and cost information from nuclear projects and to allow comparison with other energy production methods. The final version of the EEDB was published in 1986.

The EEDB consists of multiple data sets collected for different generic power plants designs, all located on the same hypothetical standard site. All data sets consist of a large number of accounts, each providing the total site labor hours together with the total cost as a sum of site labor, factory equipment, and site material costs. In this work, the data set collected for a PWR based on the Westinghouse Seabrook Station NPP [41] is used as a basis for the cost and schedule estimation. For the PWR, the EEDB provides industry data based on both median and best case experiences, which can be used together to estimate learning effects from First-of-a-Kind (FOAK) to Nth-of-a-Kind (NOAK) plants.

The PWR median experience is used as a basis for the cost estimation. From the over 1,400 cost items included in the EEDB, the 235 highest-cost items were selected for the NCET. These 235 items account for nearly 90% of all costs [16], sufficient for the purpose of this work. These cost items are modeled with cost accounts that divide the items into smaller tasks. At the highest level, the cost accounts are categorized into direct and indirect cost, but at lowest levels the subaccounts can be very specific, representing particular tasks in the construction of a structure or component. Each direct cost subaccount falls under one of the six main accounts presented in Table 1. The number 2 at the beginning of the index refers to the general account number for direct costs.

Since the data from the EEDB is relatively dated, cost escalation must be accounted for when estimating total costs in current prices. It is often suggested that the nuclear industry faces cost indices higher than the general inflation levels [42], which is why the indices used should be chosen with caution. In [16], the costs from the EEDB are scaled using Produce Price Indices (PPIs) for specific commodities and the Bureau of

Table 1: Main direct cost accounts and their descriptions.

Account number	Description
21	Buildings and structures
22	Reactor equipment
23	Turbine equipment
24	Electrical equipment
25	Miscellaneous equipment
26	Heat rejection system

Labor Statistics indices for specific labor types. The latest inflation adjustment extends to 2023, and these scaled base costs are also used in this work.

3.1.2 Input Parameters

To allow an accurate scaling of the costs and labor hours, a set of input parameters has to be provided for the NCET. The parameters include basic characteristics of the NPP, such as its thermal and electric power, the number of fuel assemblies, and the size of the reactor pressure vessel. For some cost accounts, one of the basic characteristics is used for scaling, while for others, additional plant parameters are used as inputs. Finally, details about possible learning effects or modularization of particular components can be specified.

Defining all input parameters is not necessary, since costs and labor hours can either be assumed fixed or they can be scaled based on the plant power. Using these methods is helpful when the values of all input parameters are not publicly available, which is often the case especially with more recent reactor designs. In this work, the scaling method is applied particularly to the APR1000, as many of its parameters are unknown, and using the APR1400 parameters would not necessarily yield reliable results due to differing reactor designs.

3.1.3 Direct Cost Estimation

In the NCET, five different methods for determining the costs of each account are implemented [16]. The first method is fixed cost, which assumes that the cost of the account in question does not depend on the reactor design and is the same as the inflation-adjusted cost of the reference PWR. In this work, the accounts assuming fixed costs are the same as in the original input files, which are based on EEDB suggestions [16].

The second method is direct cost, which allows the user to directly give the cost of the account as an input. This is useful particularly when a vendor has given an estimate for the cost of a system or a component, or if the cost can be obtained from another source. In this work, direct costs are used only for accounts not originally included in the EEDB, as these lack a base value that could be used either as a fixed cost or for scaling.

The third method is presented in [43] and uses the following formula:

$$C = A(B + DP^n), \tag{1}$$

where C is the estimated cost of the account, A is a nuclear adjustment factor, B, D, and n are constants defined in [43], and P is a reference parameter. Examples of parameters that could be used as a reference include mass, diameter, surface area, and capacity. The value of n is directly obtained from [43], but for the values of B and D, the inflation is accounted for and the new values are calculated in [16]. The nuclear adjustment factor A is added to the formula in [16], as the original formula from [43] is not nuclear-specific. An estimate for the value of A is obtained in [16] by comparing the values from the EEDB with estimates calculated using Equation 1 without nuclear adjustment. Equation 1 can only be used for certain components, such as vessels, pressurizers and cranes, for which the required parameters have been defined.

Instead of directly estimating the costs, as in the third method, the last two methods are based on scaling the costs reported in the EEDB. In the first of these two methods, the scaling is performed using the parameter P, a value of which is known for both the reference PWR and the NPP being modelled, and which can be assumed to correlate with the cost of the account. The scaling is performed according to the following formula, also given in [43]:

$$C = C_{\text{EEDB}} \left(\frac{P}{P_{\text{EEDB}}} \right)^n, \tag{2}$$

where C_{EEDB} is the cost of the corresponding account from the EEDB, P_{EEDB} is the value used for scaling for the reference PWR, and n is a constant specific for the account in question. The values of n for different accounts are based on multiple sources, further explained in [16].

The final method is a modification of Equation 2, where the parameter P is either the thermal or electrical power of the plant. This method is often used when no other value suitable for the parameter P is known, but the costs of the account can be assumed to depend on the power of the plant.

3.1.4 Schedule Estimation

In addition to costs, the EEDB also reports the labor hours required for each account. In the NCET, these are assumed to have the same dependencies as the costs and are therefore scaled using the same methods [16]. This way, the accurate labor hours for each account are obtained.

To estimate the duration of the whole NPP construction project, the tasks corresponding to each account have to be appropriately organized. For this purpose, the NCET requires multiple parameters and additional information as input.

First, the dependencies between tasks need to be identified in order to determine the optimal order in which to complete them. Thus, for every task, a preceding task is assigned. In addition, the percentage of completeness required to move on to the next task is specified.

Furthermore, space limitations constrain how many workers can operate at the same time in each building. The maximum number of workers in each building is estimated based on the building area. For each task, a specific building is assigned as a location, limiting the number of workers for that task and other tasks possibly being carried out simultaneously in the same building. However, it is possible to override the maximum limitation of workers by allowing overstaffing up to a certain limit. A resulting decrease in construction efficiency can be assigned by the user.

Finally, the total number of workers is limited by two constants: maximum number of workers allowed at the site and maximum labor change per month. These are more closely related to project management and labor availability.

In the NCET, the optimal schedule is obtained in two steps. First, a full-scale Genetic Algorithm (GA) is performed. The GA produces a population of solutions, the best of which are chosen for the next iteration and randomly mutated. The NCET repeats this process until the convergence criteria is met, requiring that neither the total construction duration nor the lengths of individual tasks change by more than a month within 20 consecutive generations [16]. The full-scale GA is only performed for the FOAK unit.

The second step of the optimization problem includes a subproblem GA. For this, the converged solution from the full-scale GA is used as a starting point. The schedule is then split into four parts, and the GA is performed separately for each of them. This reduces the number of variables, making the algorithm more efficient. This subproblem GA is repeated individually for each unit from FOAK to NOAK, taking into account the increased efficiency achieved with the learning effects.

3.1.5 Indirect Cost Estimation

Since indirect costs depend on the construction duration of the project, they can only be estimated after the schedule has been determined. Like direct costs, the indirect costs are divided into labor, material, and factory costs.

A major fraction of indirect labor costs consists of temporary construction facilities, which can be assumed to depend on site labor hours. Based on the EEDB, the fractions of indirect labor hours for both the median and the best-performing industry experience PWRs are almost equal. As given in [16], the indirect labor costs and hours are estimated by scaling the direct labor costs and hours by a factor of 0.36, obtained from the EEDB data.

Indirect material costs are obtained similarly, by scaling the direct material costs. For these costs, however, the fraction of indirect costs is larger for the median experience PWR compared to the best industry experience. In the median experience case, 33% more workforce is utilized, explaining a greater need for tools and other equipment, which consequently increase the indirect costs [16]. The fraction of indirect costs for the best experience PWR, 0.79, is used as a basis for the scaling factor. To account for the differences in workforce, the costs are also scaled by the ratio of the average number of workers in the NPP in question to the corresponding number for the reference best experience PWR. In the case of the median experience PWR, this fraction would be 1.33.

Indirect factory costs include supervision and quality assurance, so they are assumed to depend on the direct labor costs [16]. Using a process similar to the estimation of indirect material costs, the direct labor costs are scaled by a factor of 1.32, which is the ratio of indirect factory costs to direct labor costs for the best estimate PWR. Again, an additional factor is used to account for the increase in total construction duration compared to the best experience PWR. For the median experience PWR, this factor is 1.36.

3.1.6 Uncertainties and Risks

When interpreting the results produced by the NCET, uncertainties of both the methodology and input parameters must be taken into account. These uncertainties are addressed by randomly sampling the values of uncertain input parameters, as well as those included in the cost scaling, using distributions found from literature when available. The values and sources for each uncertainty are not repeated here but can be found from [16]. To obtain the uncertainties for the final costs, Monte Carlo methodology is used until sufficient convergence is achieved.

In addition to cost uncertainties, construction risk is estimated. Possible risk factors are estimated based on bi-annual reports by Georgia Public Service Commission [44], regarding the construction of the delayed Vogtle plants in the United States. In addition, a report from the canceled construction of NPPs on the V.C. Summer site [45], also in the United States, is utilized to estimate the risk factors. Based on the analysis of these reports, four types of risks are identified in [16]: supply chain delays, human error, change orders, and productivity.

A supply chain delay refers to a situation in which the supplier does not deliver the required components on time. This risk is especially high for nuclear-specific components, which often lack stable supply chains due to low demand. To estimate the delays caused by issues with the supply chains, any new component without an existing supply chain is estimated to experience a delay with a probability of 1/3 [16]. The delay time is sampled from a Poisson distribution, the mean of which depends on the number of units that have already been constructed. For every unit, the mean drops by one half compared to the previous unit [16]. This is based on the assumption that delays are managed more efficiently and the disturbance to the overall construction process is reduced compared to earlier units.

In [46], FOAK technology is estimated to cause a 23% delay in construction. It is reasonable to assume that the increased FOAK risk is largely caused by human error, as there is not yet experienced workforce available for the construction. In [16], the delay of 23% is assumed to yield from a 46% risk of delay, while the time of occurrence for the error is drawn from a uniform distribution. The distribution covers the whole range from the beginning of the task until the end, yielding a mean of 50% task completion before the error occurs. The probability of the delay is assumed to depend on the labor hours of the plant, so the probability of 46% for the PWR median experience is scaled using the labor hours of the NPP in question.

In [16], low productivity is assumed to be a result of change orders, and therefore these two factors are analyzed together. Based on results from [47], the increase in the

duration of a task experiencing a change order is estimated. The number of change orders for each cost account is estimated based on license amendments for Vogtle 3 NPP [48] in the United States. The number of license amendments is chosen as the mean for the Poisson distribution for each account. The additional time spent on a task due to a change order is estimated to be equal to the time already spent on the task before the change order is issued. The times of change orders are drawn from an exponential distribution with a mean of 20%, as it can be assumed that change orders are issued closer to the beginning of the task [16].

3.1.7 Learning Effects

When multiple units of the same NPP are built, a certain level of learning can be expected, reducing the risk of errors and delays and making construction overall more efficient. This is known as learning-by-doing. Although learning-by-doing has been studied in many industries, NPP construction projects cannot be directly compared to smaller projects, in which the same crew usually constructs multiple units of the same product. In nuclear industry, the projects are much larger, and the same crew is not necessarily participating in the construction of the next unit. In this case, the learning is more dependent on the increased know-how of project management instead of individual construction workers.

Learning-by-doing is modeled using a learning rate r. Based on empirical observations, different energy technologies frequently show a log-linear relationship between the unit costs and the installed capacity [49]. The learning rate represents the cost reduction achieved by every doubling of production, meaning that the most notable reductions are achieved for the first units, after which the reductions quickly decrease for the later units. The log-linear relationship can be expressed as

$$C_N = C_1 N^k, \tag{3}$$

where N is the cumulative experience, C_N is the cost achieved with this experience, C_1 is the original cost, and k is a constant [49]. In this work, the gained experience refers to the number of units build, and therefore N refers to the unit number. As the learning rate r gives the cost reduction for every doubling of the production, the cost ratio $(1 - r)$ must be of the form 2^k. Solving k and inserting it into Equation 3 yields

$$\frac{C_N}{C_1} = N^{\log_2(1-r)}. \tag{4}$$

Estimated learning rates for nuclear industry differ depending on the source. In [50], the learning rates are estimated to be from 2% to 15% depending on the technology and construction rate. However, some sources are also suggesting negative learning rates, which might be explained by the system complexity inevitably increasing when more nuclear units are built [51]. In [16], different methods for estimating the learning rate are compared against data from two consistent reactor series, Korean OPR1000 and French P4. The OPR1000 series consists of 12 reactor units constructed between 1989 and 2008 [52], and the P4 series consists of 20 units constructed between 1977 and 1993 [51].

With the chosen method, learning rates together with maximum learning limitations for factory, labor, and material costs are assessed. Some of these parameters are approximated based on the cost development observed between the PWR median and best industry experiences within the EEDB, and the rest of the parameters are solved as a minimization problem using the OPR1000 and P4 data. The parameters obtained in [16] are presented in Table 2. In addition to the learning rate r, the table includes a limitation for the maximum relative cost reduction obtainable from the first unit to the Nth unit, marked with m. The table also includes the starting index for the learning rates, N_1. This is crucial for the factory costs, for which the observed learning rate in the EEDB is significantly lower than the rates for the other two cost categories. This can be explained by the workforce remaining mostly the same in a factory environment, enabling more efficient learning. Therefore, the cost reductions achieved for the first units are smaller, as if the learning process began at unit 100 rather than unit 1. The decrease in labor hours achieved with learning-by-doing is estimated using the same parameters as obtained for the labor costs.

Table 2: Parameters chosen for modeling the learning-by-doing of different cost categories. Parameter values from [16].

	Factory cost	**Labor cost**	**Material cost**
N_1	100	1	1
r	16%	13.1%	7.1%
m	100%	45%	27%

3.2 Input Modifications

To produce results for the NPPs, the NCET requires various different input files for different stages of the calculations. For the APR1400 and EPR, input files for the corresponding LASR and DC-PWR plants have already been defined in [16], but some modifications are implemented in this work to account for additions and site-specific details. For the APR1000, a completely new input file is created based on the LASR input file.

3.2.1 General Modifications

First, some general modifications are applied to the input files of all four reactor architectures. In the previous versions, the costs of accounts under I&C were partially estimated by scaling the EEDB PWR reference costs by using the number of control rods. Although some correlation between the costs and this number can be presumed, as both are expected to increase as a function of plant power, the number of control rods is not directly connected to the complexity of the I&C. Therefore, the parameter used for scaling is switched to the number of safety trains in the reactor. For the reference PWR, this number is two [53], but for all the NPPs modeled in this work, the number is four [11, 54, 55].

Publicly available information about the costs of I&C systems is limited, but the I&C digitalization at Oconee-1 PWR in the United States in 2011 has been reported to cost $250 million [56]. Using the original EPR input and scaling the relevant accounts by the number of control rods yields $152 million as the total for all I&C related accounts, whereas scaling by the number of safety trains results in $213 million. Based on this comparison, using the number of safety trains for scaling seems to yield results closer to the reference information. Since replacing an existing I&C system is likely to be more expensive than installing a completely new system as part of the construction of a new plant, having costs lower than the reference value is reasonable.

As a core catcher is not a part of the reference PWR design, there does not exist an account for it in the original EEDB data. However, for more recent plant designs, core catcher is a commonly employed safety system. Due to its location under the reactor core, the installation of the core catcher can have a significant impact on the construction schedule and costs. This highlights the importance of accurate modeling of the core catcher, especially in terms of construction schedule and risks.

Of the four NPPs modeled in this work, only APR1400 does not have a core catcher. For the remaining three plants, a cost account for the core catcher is added to the input files. Although the core catchers of the EPR and APR1000 do have some differences, in this work, their costs and construction times are assumed to be the same due to the lack of detailed information.

The limited availability of information makes estimating the cost and construction duration of the core catcher challenging. The only publicly available information about core catcher construction and installation is from Russian Water-Water Energetic Reactors (VVERs), for which the structure of the core catcher is different to those of the EPR and APR1000. The VVER core catcher is better suited for modularization, speeding up the construction at the site. For example, the core catcher for the El Dabaa Unit 4 VVER-1200 in Egypt was manufactured in Russia for 14 months, but the installation at the site was estimated to take less than two months [57]. Based on this, close to 90% of the VVER core catcher construction could be modularized. In this work, the corresponding percentage for the EPR and APR1000 core catchers is estimated to be 30%, as these core catchers require significantly more concrete and consequently more on-site labor.

Due to the differences in the core catcher designs, utilizing the information from the VVER core catcher construction may not yield reliable results. For the EPR and APR1000, the core catcher labor hours are estimated in a way that the total on-site construction duration is approximately 10 months for both plants. When risks are accounted for, the construction duration may increase from this number.

The site labor cost of the core catcher is estimated based on the total labor hours by using the average hourly salary of the other accounts, $63 per hour. The other costs, namely factory equipment costs and site material costs, are estimated to be $20 million in total. This way, the labor costs are approximately 72% of the total cost. This is a reasonable estimate for a component which, while not particularly expensive in terms of material costs and complexity, requires significant amounts of on-site work and concrete pouring.

To accurately model the impact of the core catcher on the overall construction

schedule, it should be placed correctly on the timeline. It is assumed that 80% of the containment building substructure concrete has to be poured before the construction of the core catcher may begin. After 90% of the core catcher construction is finished, the proceeding task may be started. This proceeding task is the pouring of the superstructure concrete, which in the original schedule would have been started after the substructure concrete pouring. The modification to the schedule now considers the cruciality of the core catcher installation for the construction of the containment building and, consecutively, the entire NPP unit.

Together with the addition of the core catcher, other minor improvements were made to the schedule. The first modification allows the construction of the double containment to begin earlier. In the previous version of the schedule, beginning the construction of the double containment required full completion of the containment building superstructure concrete work. For the EPR, however, the construction of the two containments progresses more in parallel, as e.g. concurrent concrete pours mentioned in [58] suggest. To accommodate for this, the required completion of the inner containment superstructure is reduced to 20% before the construction of the double containment can begin. The same approach is implemented for the APR1000 schedule.

Another modification to the schedule concerns the dependency between the containment building construction and the installation of reactor equipment. Previously, the installation of the reactor pressure vessel required only 50% completion of the containment building superstructure concrete. However, the installation of the EPR reactor components requires a complete containment, after which the components are transported inside with an equipment hatch at the side of the containment building [59]. To account for this, the installation of the pressure vessel is updated to require a full completion of the superstructure concrete. Consequently, other components proceeding the installation of the pressure vessel are being postponed simultaneously. The same approach is applied to all four NPPs analyzed in this work.

In addition to structures and components, the labor limitations are updated. In [16], the maximum number of workers on the NPP site is limited to 4,500 for larger plants. In this work, however, the limit is set to 6,000 for the APR sites, both hosting one unit, and to 15,000 for the EPR sites, both hosting two units. The reported maximum of 25,000 workers at the Barakah site [60], hosting four APR1400 units, supports the higher limitations for the APRs. The high limitation for the EPR sites is explained by the construction of two units on both sites, and is also in accordance with the maximum worker estimate for the HPC site by Électricité de France (EDF) [61]. The maximum labor change per month is 800 for the APRs, the same as estimated in [16], and 1,600 for the EPRs.

3.2.2 Modifications to the APR1000 Input

To create an input file for the APR1000, the APR1400 input file is used as a basis. Based on available information from K-Next [11] and IAEA ARIS [32], the required input parameters are updated to correspond those of the APR1000. When no information is available, the costs and labor hours are estimated using the plant power scaling method

explained in Section 3.1.3.

To confirm that using plant power scaling for all accounts with unknown parameters gives accurate results, this method is tested for the corresponding cost accounts of the APR1400. All accounts to which the scaling is applied fall under the main account 22. The total direct costs for both the whole plant and accounts 21 and 22 are presented in Table 3.

Table 3: Comparison of direct costs for APR1400 with original input and scaled accounts.

Account	Original ($M)	Scaled ($M)	Relative difference
21	1,650	1,647	–0.2%
22	1,343	1,300	–3.2%
Total	4,869	4,823	–1.0%

The small difference in the costs of account 21 arises from fuel storage pool liner, the cost of which is determined by pool volume, a parameter under account 22. Apart from that, the costs of subaccounts under account 21 are generally based on building measurements. For main accounts 23–26, the performed scaling does not have an effect. The results presented in Table 3 show that the relative difference in costs is small, particularly at the whole-plant level. Thus, the plant power scaling is a reasonable approach when required parameters are unknown.

The measurements of the buildings are obtained from the site layout presented in [32]. The height of the containment building, double containment, and the buildings directly connected to them are obtained based on the cross-section of the containment building, also presented in [32]. The heights of other buildings are assumed equal to the height of the structures surrounding the containment building, as no other information is publicly available.

Due to the data limitations concerning foundation and superstructure thicknesses of the APR1000 buildings, corresponding values of the APR1400 are used. To assess whether these values are reasonable estimates for the APR1000 as well, they are compared against the corresponding values in the EPR input. Based on this comparison, foundation thicknesses of two buildings and the superstructure thickness of one building are increased to match the values used for the EPR. Like APR1000, EPR is also originally designed for the European market, and therefore these two plants can be assumed to comply with similar regulations. However, it is not possible to know for certain whether the differences between the values of EPR and APR1400 are caused by regulatory differences, different reactor designs, or differences between the sites these units in question have been designed for.

3.2.3 Modifications to the EPR Inputs

The input parameters for the EPRs are mostly based on the original U.S. EPR input, defined in [16]. In this work, it is assumed that most of the components stay the

same for the HPC and Taishan NPPs, but the dimensions of the structures are updated based on the site layout of HPC, given in [62]. In the original EPR input, the double containment is assumed to lay on top of the surrounding buildings, making it notably lower in height than the containment building. However, based on the reactor building cross-section layout of the U.K. EPR [63], the double containment seems to cover the full height of the containment building. Thus, for the HPC EPR, the height of the double containment is increased to match the layout.

In the original U.S. EPR input, the foundation thickness is specified as 3 meters for most of the main buildings. However, at HPC, the thickness of the common raft under the nuclear island is reported to be 4 meters [64]. Thus, in the HPC input, the foundation thickness is increased to 4 meters for the buildings belonging to the nuclear island. For the Taishan units, the foundation thickness is not modified.

At the HPC units, installing both analog and digital I&C systems is required [65], which is taken into account in the HPC model by doubling the I&C system. This modification, together with the addition of the core catcher and the updated scaling of the I&C costs, is the only non-structural modification carried out.

At the HPC site, a sea wall is constructed on the coastline to protect the land platform from erosion [66]. A corresponding EEDB account does not exist for the reference PWR, so a new account for this structure is added to the input files of the HPC EPR. The length of the sea wall is reported to be 780 meters and it is constructed using pre-casted concrete blocks together with on-site construction work [67]. The project cost is stated to be approximately $1.1 million, but taking into account the on-site work and the concrete required, in this work, the total cost is estimated to be closer to $10 million.

Both at the HPC and Taishan sites, the reactor cooling system is implemented through cooling water tunnels. As with the sea wall, a new cost account is created for these tunnels. At HPC, there are two intake tunnels under the Bristol Channel, one for each unit, and a shared outfall tunnel. The lengths of both intake tunnels are 3.5 km and the length of the outfall tunnel is 1.8 km, and they are excavated using a Tunnel Boring Machine (TBM) [68]. In addition to these offshore tunnels, there are 0.6 km of onshore tunnels [69], which are included in the cost and schedule estimation. The costs of these tunnels are estimated using data presented in [70]. Based on the linear fit of the United Kingdom data, the tunnels of this length are estimated to cost approximately 22 M£/km. The data is from 2010, so the price escalation until 2023 has to be accounted for. Based on the general construction PPIs from years 2010 and 2023 [71], the price escalation factor is 1.69. After this, the average conversion rate from GBP to USD in 2023 is used to obtain the costs in dollars, yielding $434 million as the final cost of the tunnels.

At the Taishan site, there are two water delivery tunnels, 4.3 km each [72]. Their costs are estimated similarly to the HPC tunnels, yielding a final cost of $398 million. It should be noted, however, that this number will be scaled in the simulation to account for the Chinese working and construction conditions.

Both the HPC and Taishan sites host two EPR units, which has to be considered in the model. For both sites, the two units are modeled separately to ensure that the NCET addresses both units and their structures separately, and possible delays at one

unit do not affect the other unit. Additionally, the separation of the units enables an offset to be defined between the construction start dates of the two units. At HPC, the construction of unit 2 began a year after the construction start date of unit 1 [73]. In this work, this offset of one year is assumed for both the HPC and Taishan sites. To account for buildings and other structures shared between the units, all of these shared structures are assigned to the unit whose construction begins first and excluded from the input of the second unit. To address this in the worker limitations, the maximum number of workers is set to 9,000 for the first unit and to 6,000 for the second unit, with maximum monthly labor change of 800 for both units. Both units are assumed to be FOAK units, as an offset of one year is not enough to fully incorporate the learning effects.

The implementation of uncertainties and risks in the NCET is explained in Section 3.1.6. For the Taishan EPRs, some of these parameters are modified. First, assuming a local and effective supply system [74], the supplier delay mean is set to zero. Second, the mean of change orders for all structures and components under accounts 21 and 22 is similarly set to zero, since the designs of these systems are assumed to be relatively stable and already sufficient to meet the Chinese regulations.

In addition to the lower risk, overstaffing is enabled for the Taishan EPR in the NCET simulation. The overstaffing factor is set to 1.5, allowing a maximum of 50% increase in labor compared to the limit estimated for each building. This does not necessarily imply more people working simultaneously, as the increase in labor can also result from longer working hours or the use of multiple work shifts. In the NCET, overstaffing is estimated to reduce work efficiency to 90%, as both overcrowded workspaces and extended working hours can lower productivity, and the use of multiple shifts can disrupt workflow [16].

Finally, the total costs are scaled to consider the lower commodity prices and salaries in China. Based on data collected in [24], the construction labor costs in China are 5–18% of labor costs in the United States. The upper limit, 18%, is chosen for the scaling. To capture this in the factory costs as well, the fraction of labor costs from factory costs is estimated to be 30% based on results presented in [75]. Lastly, the commodity prices are estimated to be 25% lower than in the United States [16].

4 Results

In this section, results from the NCET modeling are presented. The findings from the cost and schedule estimations are shown separately, after which the commodity results are presented briefly. The results presented for the APRs include a single reactor unit, meanwhile the results of the HPC and Taishan EPRs include both of the two units on the site, unless otherwise mentioned.

4.1 Cost Estimation

The results from the overnight cost estimation for the four reactor architectures are presented in Figure 2. These estimates include both direct and indirect costs, normalized per kilowatt of electric power (kWe). All four reactors are assumed to represent FOAK plants to omit learning effects from the comparison. The results are deterministic, meaning the risks are not yet accounted for.

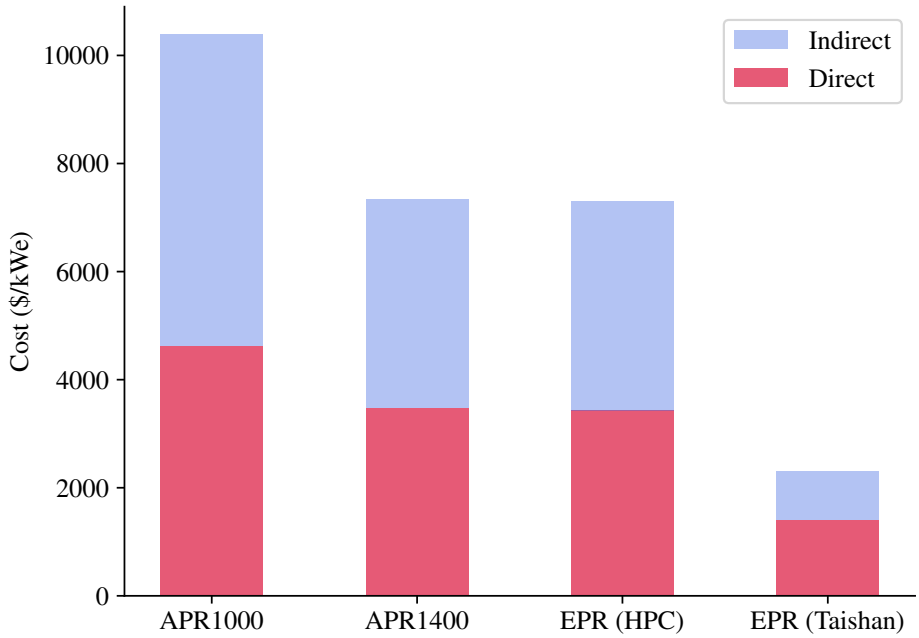


Figure 2: Deterministic direct and indirect overnight costs for the four FOAK reactor architectures, normalized per kW of electric power.

The APR1000 architecture has the highest overnight cost relative to plant electric power, approximately $10,400/kWe. It is followed by the APR1400 and the HPC EPR, both at around $7,300/kWe. The Taishan EPR has clearly the lowest cost, only $2,300/kWe. Direct costs cover slightly less than a half of the total costs for all three architectures except the Taishan EPR, which is the only plant with direct costs exceeding indirect costs.

4.1.1 APR Comparison

Relative to electric power, the APR1000 has significantly higher total cost than the APR1400. In terms of absolute costs, the two plants are very close to each other, the APR1000 still being slightly more expensive. To better understand the relatively high costs of the APR1000, the cost accounts with higher values than those of the APR1400 are identified. The largest five of these accounts are presented in Table 4, along with the direct costs of each account and the differences between these costs.

Table 4: Direct cost accounts with the highest values for the APR1000 compared to the APR1400.

Cost account	**Costs ($M)**		
	APR1000	APR1400	Difference
Reactor Shield Building	156.2	0.0	156.2
Turbine Room & Heater Bay	308.4	188.0	120.4
Primary Auxiliary Building & Tunnels	524.2	432.4	91.8
Core Catcher	71.1	0.0	71.1
Waste Process Building	124.6	65.0	59.6

These five accounts alone contribute to a total of $500 million increase in the direct costs of the APR1000 compared to the APR1400. The components added specifically for the APR1000, namely the double containment and the core catcher, are both among the cost accounts with the largest differences. The double containment is the largest single contributor to the direct cost difference, increasing the costs of the APR1000 by more than $150 million. Other accounts increasing the costs of the APR1000 are mostly structures with areas larger than those of the APR1400. Buildings with the largest impact on the costs include turbine room and heater bay, primary auxiliary building, and waste process building.

4.1.2 EPR Comparison

Due to the similarity of the EPR inputs for the HPC and Taishan sites, accounting for the country-specific scaling for the Taishan NPP is a major factor affecting the costs. Without scaling, the total FOAK direct costs for the Taishan NPP would be $10.7 billion, and the indirect costs $12.0 billion. Compared to HPC, the direct costs are approximately $600 million lower and the indirect costs approximately $800 million lower. The total costs, normalized per unit of electric power, would then be $6,900/kWe.

To exclude the effect of the scaling and focus on the structural differences, the costs are compared here before applying the scaling factors. Again, five cost accounts with the largest differences between the two EPR plants are presented in Table 5. The double I&C at HPC has a significant impact on the I&C-related costs of both the reactor and turbines. Concerning structures, the largest difference in costs is caused by the taller double containment at HPC. Smaller cost increases for HPC are caused

by the longer cooling water tunnels and the thicker substructure concrete slab under the nuclear island, which the primary auxiliary building is a part of. In total, these five cost accounts increase the total costs of the HPC NPP by approximately $570 million.

Table 5: Direct cost accounts with the highest values for the HPC NPP compared to the Taishan NPP, before scaling.

Cost account	**Costs ($M)**		
	HPC	Taishan	Difference
Reactor I&C	510.2	262.2	248.0
Reactor Shield Building	357.2	180.3	176.8
Turbine I&C	170.3	89.4	80.9
Cooling Water Tunnels	434.0	398.0	36.0
Primary Auxiliary Building	1076.2	1049.0	27.2

4.1.3 Learning Effects

The total deterministic overnight costs for the four reactor architectures from FOAK to 10-OAK units are shown in Figure 3. The costs are normalized by the number of reactor units built on the site, which is one for the APRs and two for the EPRs.

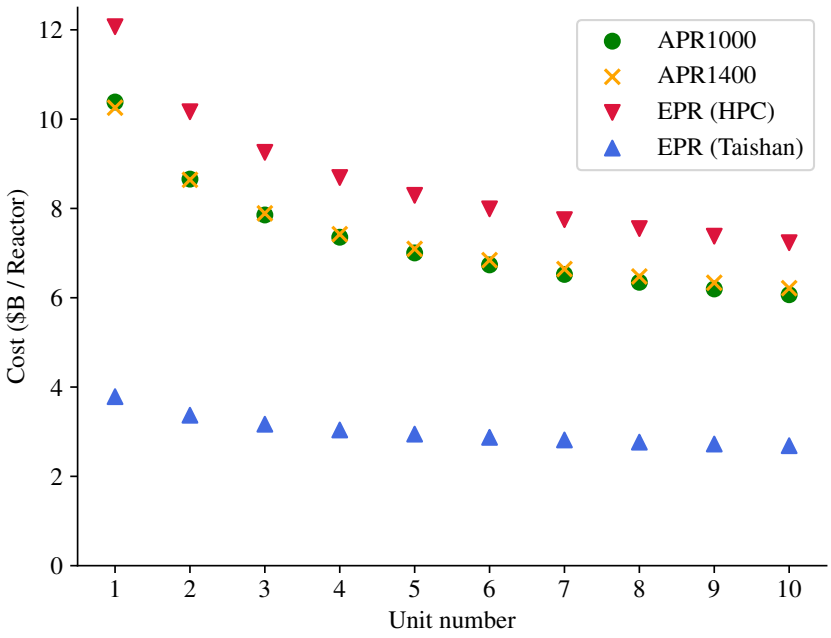


Figure 3: Deterministic overnight costs for the four reactor architectures from FOAK to 10-OAK units, normalized by the number of reactor units built on the site.

The costs of the two APRs and the HPC EPR follow a similar decreasing trend, with larger reductions for the early units and smaller ones for the later units. The costs of the HPC EPR remain the highest, while the costs of the APRs stay close to each other. However, the costs of the APR1000 decrease slightly faster and eventually drop below those of the APR1400. The cost reductions for the Taishan EPR are relatively small even for the early units.

To understand how the achieved cost reductions are divided between direct and indirect costs, a more detailed comparison between the costs of the FOAK and 10-OAK units is presented in Table 6. For all four reactor architectures, the reductions in indirect costs are clearly larger than the reductions in direct costs. By the 10th unit, the indirect costs of all plants have decreased to less than a half of the corresponding FOAK costs. The two APRs and the HPC EPR achieved slightly larger relative reductions than the Taishan EPR in both direct and indirect costs. The achieved reductions in the direct costs are also clear: over 20% for the APRs and the HPC EPR, and 15% for the Taishan EPR.

Table 6: Deterministic overnight direct and indirect costs for the FOAK and 10-OAK units and the relative decrease in costs.

NPP design	**Direct costs ($B)**			**Indirect costs ($B)**		
	FOAK	10-OAK	Decrease	FOAK	10-OAK	Decrease
APR1000	4.6	3.6	23%	5.8	2.5	56%
APR1400	4.9	3.9	21%	5.4	2.3	56%
EPR (HPC)	11.3	8.8	22%	12.8	5.6	56%
EPR (Taishan)	4.6	3.9	15%	2.9	1.4	51%

4.1.4 Cost Overrun Risks

The risks for cost overruns are estimated based on the deterministic costs and the risk-adjusted construction durations. The overnight costs for the deterministic baseline scenario and for the median risk scenario, normalized per kW of electric power, are presented in Figure 4.

Accounting for the risk increases the overnight costs significantly especially for the two APRs and the HPC EPR. For the APR1000 and HPC EPR, the relative increase in costs is 57%, and for the APR1400 it is slightly lower, 49%. For the Taishan EPR, the cost increase is substantially lower, approximately 30%.

The overnight costs from FOAK to 10-OAK units for the median risk scenario are shown in Figure 5. The costs are again normalized per reactor units built on the site. The patterns shown in the plots are similar to those presented for the deterministic costs in Figure 3 for all four reactor designs. However, the cost reductions are achieved at a faster rate and the relative decreases in costs from the FOAK to 10-OAK units are greater. Although the APR1000 has slightly higher costs than the APR1400 for the first unit, for the later units there is no significant difference.

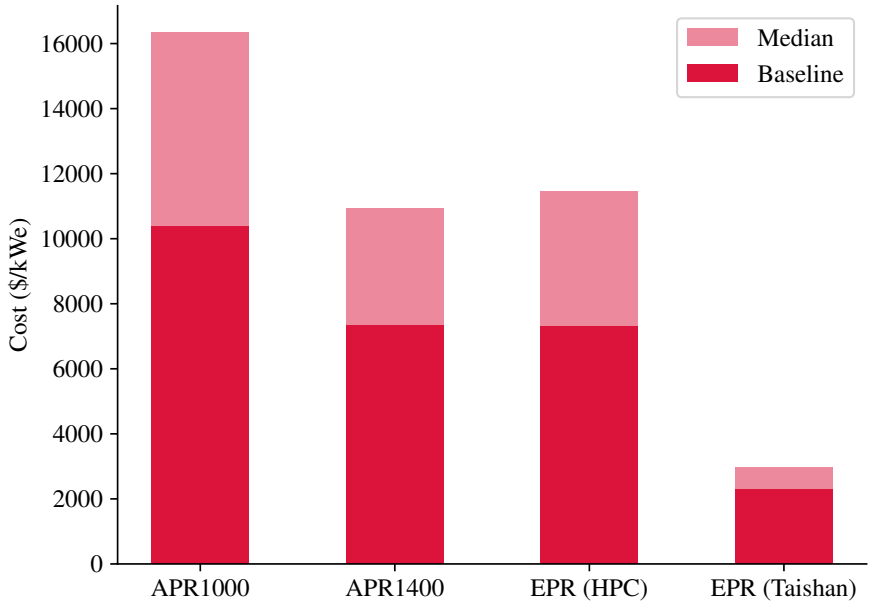


Figure 4: Overnight costs in the deterministic baseline scenario and median risk scenario for the four FOAK reactor architectures, normalized per kW of electric power.

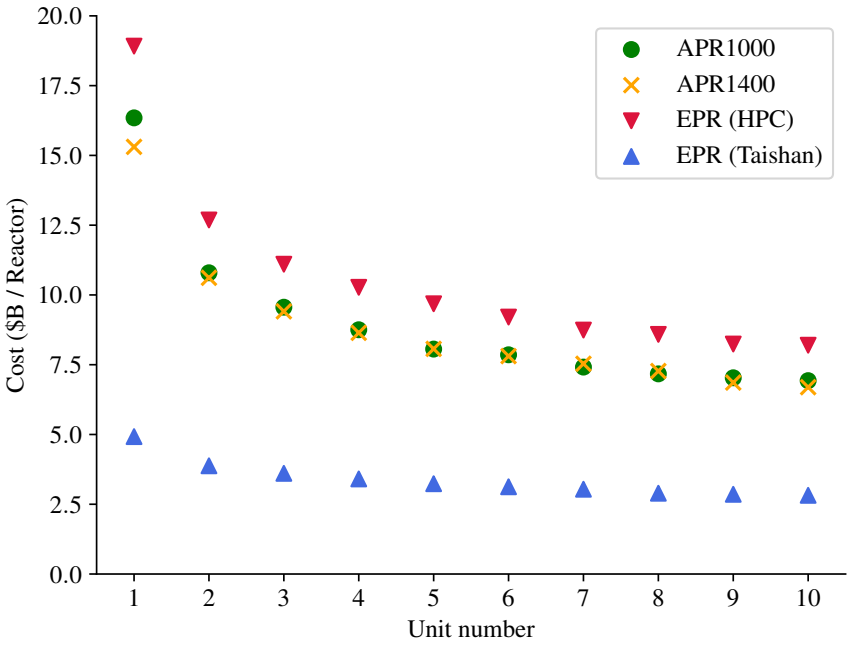


Figure 5: Overnight costs with median risk for the four reactor architectures from FOAK to 10-OAK units, normalized per number of reactor units built on the site.

A more detailed comparison between the FOAK and 10-OAK costs for the median risk scenario is presented in Table 7. Similarly to the deterministic costs given in Table 6, the reductions in indirect costs are significantly larger than the reductions in direct costs for all reactor designs. By the 10th unit, the two APRs and the HPC EPR have achieved reductions of almost 70% in indirect costs, and approximately 40% in direct costs. For the Taishan EPR, these relative reductions are 62% and 26%, correspondingly. All four reactor architectures achieved greater cost reductions for both direct and indirect costs compared to the deterministic scenario.

Table 7: Overnight direct and indirect costs in the median risk scenario for the FOAK and 10-OAK units and the relative decrease in costs.

NPP design	Direct costs ($B)			Indirect costs ($B)		
	FOAK	10-OAK	Decrease	FOAK	10-OAK	Decrease
APR1000	6.6	3.9	41%	9.7	3.0	69%
APR1400	6.4	4.0	38%	8.9	2.7	70%
EPR (HPC)	15.9	9.6	40%	21.9	6.8	69%
EPR (Taishan)	5.4	4.0	26%	4.5	1.7	62%

4.2 Construction Schedule

First, the baseline construction duration without risks is estimated, after which the possible risks delaying the construction are accounted for. The baseline durations, together with the risk-adjusted median and 90% confidence durations, are presented in Figure 6 for the four FOAK plant designs.

The baseline durations of the two APRs are almost identical, around 5.5 years, but the risk-adjusted durations for the APR1000 are marginally higher. The baseline duration of the Taishan EPR is slightly higher than those of the two APRs, approximately six years, but the risk-adjusted estimates are lower. The HPC EPR has the highest durations for the baseline estimate, close to seven years, and also the highest values for the schedule overruns. For all four designs, the increase in duration from the baseline scenario to the median risk scenario is significant, varying from 60% increase for the Taishan EPR to almost 90% increase for the APR1000.

4.2.1 Learning Effects

Figure 7 shows how the risk-adjusted median durations change from FOAK to 10-OAK units. Since the risks are estimated using Monte Carlo method, there is some inconsistency in how the estimates behave between the units. However, a clear decreasing trend in the durations can be seen for all four designs. By the 10th unit, all designs have achieved a duration lower than the FOAK baseline presented in Figure 6. For the Taishan EPR, the achieved duration reductions are slightly smaller than for the other designs, as eventually both APRs achieve lower durations.

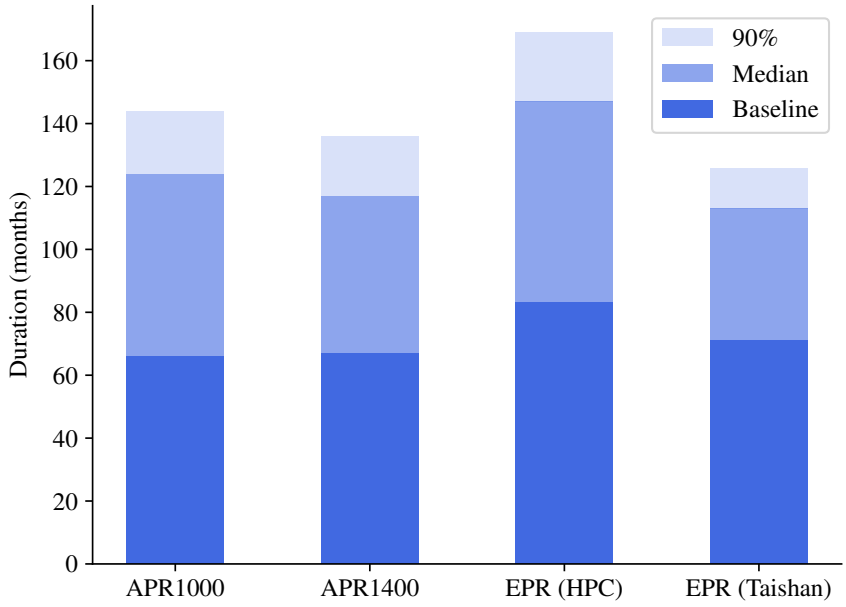


Figure 6: Baseline construction durations and schedule risk (median and 90% confidence interval) for the four FOAK plant designs.

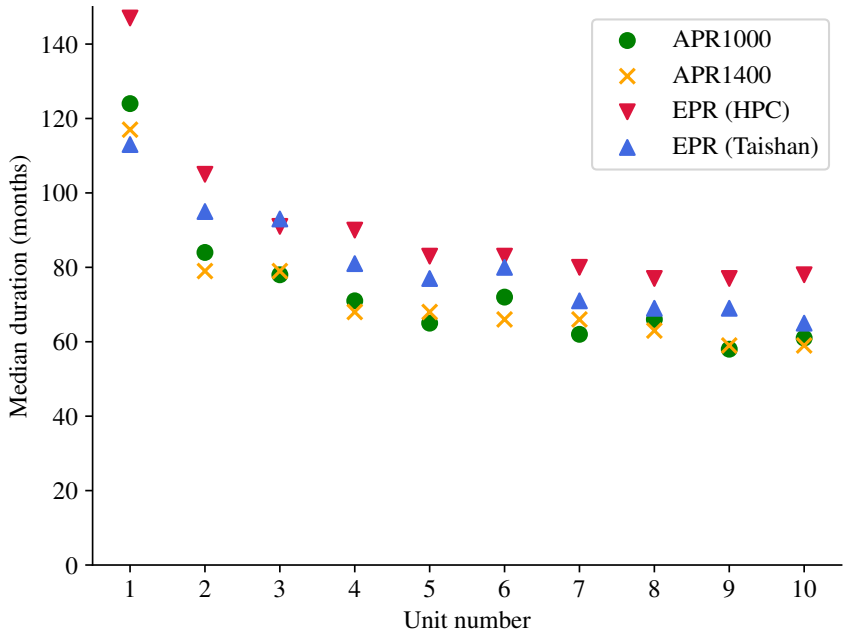


Figure 7: Median construction durations for the four plant designs from FOAK to 10-OAK units.

4.2.2 Impact of the Core Catcher

Core catcher is one of the new systems implemented for the APR1000 and the EPRs. Due to its critical position on the construction path of the containment building, it poses a risk of delaying the whole construction process. To estimate the extent of possible delays, the numbers of months spent on the core catcher construction in the baseline scenario, together with the median and 90% confidence durations for the risk-adjusted schedules, are presented in Table 8. The table includes only the core catcher construction of the APR1000, as the core catchers of the EPRs are modeled similarly.

Table 8: Baseline and risk-adjusted construction durations for the APR1000 core catcher.

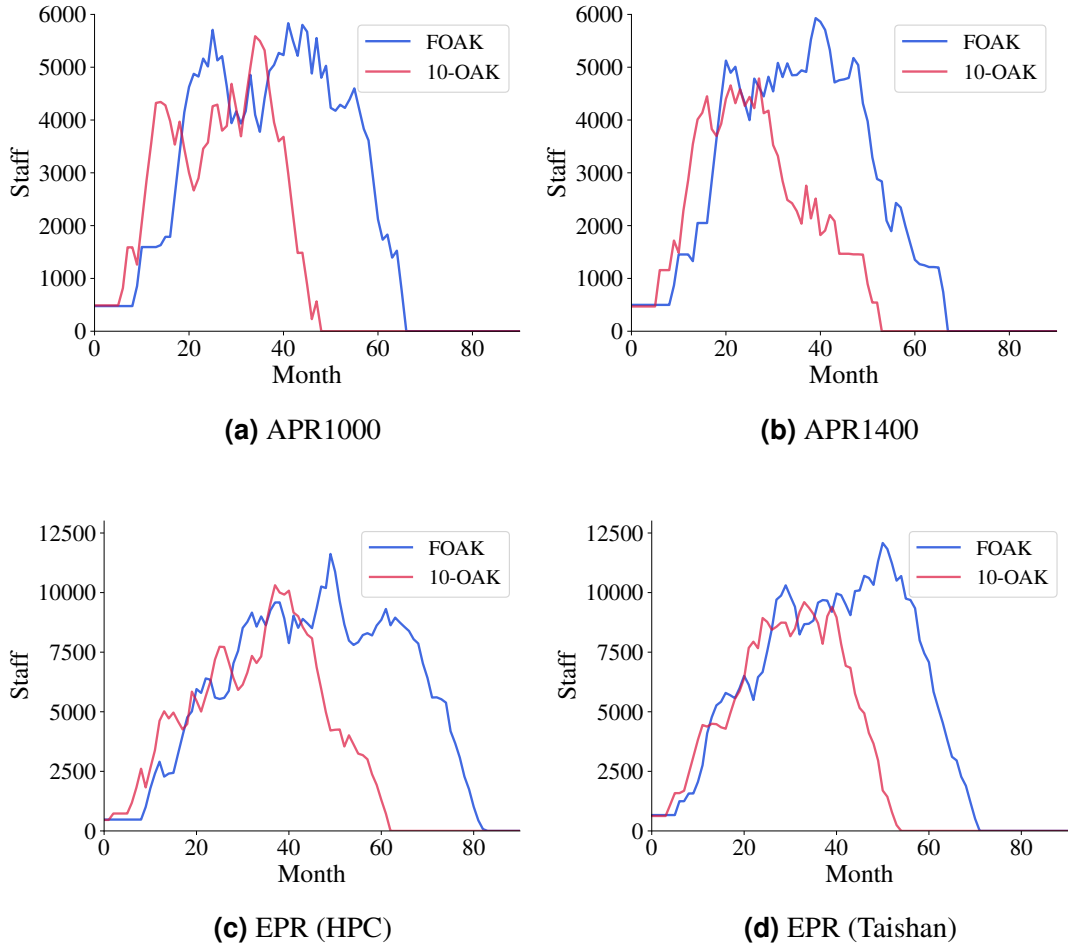
Unit	**Duration (months)**		
	Baseline	Median	90%
FOAK	10	20	33
10-OAK	6	6	11

For the FOAK unit, the overrun risks for the core catcher construction are significant compared to the deterministic baseline scenario of ten months. This baseline construction duration is doubled in the median risk scenario, and more than tripled in the 90% confidence level scenario. For the 10-OAK unit, the risks of overruns in the core catcher construction are clearly lower. The median risk duration of six months is equal to the baseline case, exceeded by five months in the 90% confidence level risk scenario.

4.2.3 Staffing

While solving the optimization problem to obtain the schedule, the NCET records the monthly staffing levels at the unit. These staffing levels for the four NPP sites in the deterministic baseline scenario are presented in Figure 8 for both FOAK and 10-OAK units. The plots of the HPC and Taishan sites include both of the two units on these sites, with an offset of one year. In this work, it is assumed that there is no significant learning between the two units, and the 10-OAK scenario refers to a situation where both units are individually modeled as 10-OAK.

The significant decrease in construction time and the lower peak staff for the 10th unit can be clearly distinguished from the plots. Both of these aspects help to reduce the total hours needed to finish the project. The numbers of staff for the FOAK units of the two APRs come close to the maximum staffing limit of 6,000, but for the two EPRs the corresponding number is approximately 12,000, lower than the set limit of 15,000. It should be noted that the staffing plots may vary between runs, as the optimal schedule found by the algorithm is not necessarily the same each time. Thus, the exact shapes of the plots should be interpreted with caution.



(a) APR1000 **(b)** APR1400

(c) EPR (HPC) **(d)** EPR (Taishan)

Figure 8: Staffing plots for the four NPP sites for FOAK and 10-OAK units in the baseline scenario.

4.3 Commodities

In addition to cost and schedule estimates, the NCET produces estimates for the amounts of commodities, namely the volume of concrete and the mass of steel. These are presented in Table 9 for the FOAK and 10-OAK units of the four reactor architectures. Compared to the APRs, the two EPRs have significantly more concrete and steel due to the two units on the sites. After normalizing my the number of units, the volumes of concrete are still clearly higher than those of the two APRs. The HPC EPR has slightly more concrete and steel than the Taishan EPR. However, the two APRs have a significant difference: especially the volume of concrete is much greater for the APR1000 compared to the APR1400. For all four reactor architectures, both the volumes of concrete and the masses of steel decrease for the later units, as the risk of having to start over tasks is lower.

Table 9: The estimated amounts of concrete and steel for the FOAK and 10-OAK units.

NPP design	FOAK		10-OAK	
	Concrete (m^3)	Steel (t)	Concrete (m^3)	Steel (t)
APR1400	288,108	74,016	207,907	52,200
APR1000	416,604	95,607	290,090	66,467
EPR (HPC)	1,091,208	191,947	807,410	135,127
EPR (Taishan)	1,034,315	173,786	766,849	122,304

5 Discussion

In this section, the obtained results are further analyzed. First, the estimated costs and construction durations are anchored to real-world references. Subsequently, the results are evaluated from a regulatory point of view, and potential sources of uncertainty are assessed.

5.1 Comparison with Available Data

Since no APR1000 plants have yet been constructed, comparison with realized costs is not possible. However, a contract recently signed by KHNP to build two APR1000 units in the Czech Republic is reported to be worth $18.6 billion [34], corresponding to a relative cost of $9,3000/kWe. This is slightly lower than the deterministic estimate of $10,400/kWe obtained using the NCET. Nevertheless, given the frequent cost overruns in nuclear construction, the final costs may exceed the agreed contract price and possibly even reach the risk-adjusted median cost estimated by the NCET.

Like the APR1000, the APR1400 modeled in this thesis is a general NPP design and does not represent a particular plant constructed or under construction. In [22], the final construction cost for the two Korean APR1400 units, Shin Kori 3 and 4, was reported to be $2,400/kWe. This is significantly less than the deterministic estimate of $7,300/kWe produced by the NCET, and even less than the final cost achieved by the Taishan EPR [22]. The four APR1400 units constructed on the Barakah site were reported to cost approximately $5,700/kWe [76], clearly more than the Shin Kori units, but not as much as the deterministic NCET estimate. Since the modeling of the APR1400 did not account for country-specific conditions, exact comparison should be avoided.

For the HPC EPR, the original published estimate for the project costs was £18 billion in 2015 prices [77], corresponding to a cost of approximately $8,800/kWe in 2024 prices. After this, the cost estimate has been updated, with the most recent estimate from 2024. According to this estimate, the costs could reach £46 billion in 2024 prices [78], yielding approximately $17,300/kWe. The deterministic estimate of $7,300/kWe produced by the NCET is slightly lower than the original estimate, whereas the cost of $11,500/kWe in the median risk scenario exceeds the original estimate but is clearly lower than the most recent one.

For the Taishan EPR, the reported estimate for the cost was $1,960/kWe, whereas the final construction cost was $3,220/kWe [22]. The deterministic estimate obtained with the NCET, $2,300/kWe, is somewhat higher than the original estimated cost but remains lower than the realized cost. Accounting for the median risk increases the cost estimate to $3,000/kWe, close to the final realized costs.

Regarding the schedules, the two APR1000 units planned for the Czech Republic are initially expected to begin construction in 2029 [34], with the first unit entering test operation in 2036 [79]. This would imply a construction duration slightly longer than the baseline estimate of 5.5 years but shorter than the median estimate of approximately ten years.

The APR1400 units used for the cost comparison, Shin Kori 3 and 4, were originally planned with a five-year construction schedule, but the final construction duration was between 8 and 10 years [22]. These align well with the baseline NCET estimate of approximately 5.5 years and the median risk estimate of less than 10 years.

At HPC, the first unit was initially scheduled to start up by the end of 2025, implying a construction duration of seven years, but delay scenarios until 2029–2031 have later been announced [80]. The baseline construction duration obtained with the NCET for the first HPC unit matches the original published estimate, and the median risk estimate of 12 years is in the range of 11–13 years currently proposed for the construction. According to [80], a 15-month delay was caused by the Covid-19 pandemic, a factor not included in the NCET estimates.

For the Taishan EPR, the initially announced construction period was 4.5 years, but the actual construction lasted 9 years [22]. The original estimate is slightly shorter than the NCET baseline of nearly six years, while the final construction duration is close to the modeled median of approximately 9.5 years.

Based on the comparison, the results obtained with the NCET mostly align with the real-world values, with some exceptions. In most cases, the baseline estimates are close to the original cost and schedule estimates proposed for the projects, and the observed values align more closely with the risk-adjusted median estimates. Exact comparison of costs and schedules is challenging, as the final values for the APR1000 in the Czech Republic and the HPC EPR have not yet been realized. In addition, the comparisons of the APRs with specific constructed or planned NPPs is only approximate, as the model specifications are not chosen to resemble these exact units.

When comparing the schedules, it should be noted that the time period between the completion of the construction and the startup of the reactor can be significant. In [81], the length of the startup period for an AP1000 FOAK unit is estimated to be over two years. The NCET only accounts for the construction period, which should be taken into account in the schedule comparison.

The exact comparison of costs is also challenging, as the announced budgets and final costs are often vaguely defined. Indirect costs, in particular, can be defined inconsistently in different sources, and publicly available data often lacks specifications of what is included in the costs. The NCET only estimates the overnight costs, but some sources include capital expenses as well, making financing decisions a critical aspect of the estimate. With the large fraction of indirect costs, their vague definition can cause major differences in the cost estimates.

5.2 Impact of Regulatory Differences

The impact of regulatory differences is mostly analyzed in two parts: first for the APRs with the same origins, and after that for the EPRs utilizing the same reactor design. For the two APRs, the effects of the regulatory environment are obvious, as the APR1000 is specifically designed to comply with European regulations. Key modifications implemented into the APR1000, the core catcher and the double containment, are a clear consequence of the regulatory requirements.

In absolute terms, the APR1000 is slightly more expensive than the APR1400, and per unit of electric power the cost difference becomes clear. This shows that lower output power does not necessarily imply lower costs. To understand what causes the relatively high costs of the APR1000, the main cost accounts increasing its costs were extracted. The cost comparison of these accounts shows that the double containment is the single most important factor increasing the direct costs of the APR1000.

Although the core catcher does not affect the direct costs as much as the double containment, it is still among the five key accounts increasing the costs. The significance of the core catcher becomes evident when its construction duration is examined: for the FOAK unit, the baseline duration is doubled in the median risk scenario, and over tripled in the 90% confidence level risk scenario. The increase in indirect costs caused by such delay can be much more significant, and the delay of a component on the critical construction path may be harmful to the timeline of the whole project.

The rest of the key factors increasing the direct costs of the APR1000 are structures, which also have a significant impact on the costs. These cost increases are mainly based on larger areas of the buildings, for which the reasoning is more complicated to define. Generally, reducing the output power allows for smaller building areas, as many components and safety systems can correspondingly be smaller in size. Thus, increasing the size of buildings for a reactor with smaller power output could partly be explained by safety changes. These could be, for example, fire safety regulations or the implementation of more comprehensive safety systems. If these are assumed to result from the European regulations as well, the impact of the regulatory environment to the direct costs is obvious.

As the results show, the smaller power output of the APR1000 does not imply shorter construction duration either. The baseline durations for the FOAK units are nearly equal, and the risk-adjusted estimates are even slightly longer for the APR1000 than for the APR1400. The modifications implemented into the APR1000 design are visible especially in the beginning of the construction: in the baseline case, the superstructure concrete work of the reactor containment building is started during the 14th month of the APR1400 construction process, whereas for the APR1000 it cannot be started before the 24th month. This is caused by the 10-month construction duration of the core catcher and emphasizes the effects of implementing this component into the reactor design.

For the EPRs, a large fraction of the cost difference is explained by the lower labor and commodity prices in China. However, differences in the costs of some structures and systems can still be identified before applying the country-specific scaling. The most important of these is the double I&C system implemented at HPC, resulting from regulatory requirements. After the I&C system, the most important contributor to the increased costs is the taller double containment at HPC. Although exact requirements for the double containment are not available, it can be assumed that the extension of this safety measurement is explained by safety regulations.

The rest of the differences in costs are relatively small, caused by the slightly longer cooling water tunnels and the thicker concrete slab under the nuclear island at HPC. The differences in these structures may be a result of regulatory requirements, but they can also originate from site-specific circumstances, such as the type of soil on

the site.

Both EPRs have the advantage of having two units on the site, which helps to decrease some of the costs. The EPR also has a high power output of 1,650 MW, which decreases the relative costs of some accounts that assume fixed costs despite the plant power. This also explains why the relative costs of the APR1000 are higher than those of the HPC EPR, even though the latter comes with some costly elements and large structures.

There are also some differences in the construction schedules of the HPC and Taishan EPRs. The baseline FOAK duration of the HPC EPR is a year longer than the corresponding duration of the Taishan EPR, and the difference is even greater for the risk-adjusted estimates: almost three years in the median risk scenario, and over 3.5 years for the 90% confidence interval. This is due to the risk parameters chosen for the Taishan EPR, which decrease the risks of supplier delay and change orders. It is challenging to extract the effect of regulations from these risk factors, as they are also connected to the general construction environment in China. However, it is possible that the regulatory environment makes it easier to establish stable supply chains, which then lower the risk of possible delays.

The shorter construction duration at the Taishan site simultaneously decreases the indirect costs. This explains why the Taishan EPR was the only one of the four NPPs with indirect costs lower than the direct costs. The achievable cost reductions for further units are not as clear as for the other three NPPs, since a significant fraction of the risks have already been eliminated for the FOAK unit.

When focusing on the learning effects visible in the cost and schedule estimates, the benefit of stabilized designs is obvious. Significant reductions in costs and construction durations can be obtained already for the second unit, and by the 10th unit the advantages of constructing similar units are even clearer. Same applies to the amounts of concrete and steel, which significantly decrease by the 10th unit due to the lower risk of having to start over tasks. Regulation-based design changes can be harmful for the learning effects, as the know-how from previous units cannot be fully utilized. When the risks and uncertainties are accounted for, the cost reductions achieved by learning are even larger, highlighting the importance of solid designs even more.

5.3 Sources of Uncertainty

The single most significant issue in the modeling process was the lack of available data. Due to the nature of nuclear construction projects, detailed information on NPPs and their specific systems and structures is limited in publicly available sources. Although delays and cost overruns are frequently reported in the media, the underlying reasons are often left without detailed explanation. This especially complicates the verification of the risk parameters and distributions used.

Due to the lack of detailed data, obtaining the results requires many assumptions and estimates, each of which affects the reliability of the final values. When exact information is not available, many of the cost and schedule estimates are based on either fixed costs or scaling the original values. The choice of parameters used for

scaling may, in some cases, be somewhat arbitrary and not always sufficient to give an exact estimate. For most structures and components, specified information on costs or required labor hours is not available. Because of this, it is challenging to assess how accurate the individual scalings are. However, the verification performed for the APR1400 reactor equipment scaling in Section 3.2.2 indicates that the scaling can work effectively.

Although the most significant design changes have been accounted for in the updated inputs, this is only a small fraction of all modifications implemented to the plant designs. For example, at HPC, there were reportedly 7,000 design changes required by British regulations [78]. Such a large number of design changes inevitably affects the construction process, but it is not possible to include all these changes into the model. The HPC EPR is not the only NPP exposed to design changes, and all of these changes may impact the project outcomes. Design changes implemented before the beginning of the construction reduce the benefits of learning effects, and design changes during the construction process may cause cost overruns, delays, and loss of already completed work.

All the cost and schedule estimates produced by the NCET are ultimately based on the EEDB data from 1986. Although cost escalation, also specifically nuclear cost escalation, has been accounted for, the nature of nuclear construction projects has likely evolved over the past four decades. Construction practices may have changed, existing systems have been enhanced, and entirely new components have been introduced. All of these factors may eventually lead to some errors in the estimates.

The limitations of the NCET were also recognized in [16], stating that the cost estimates are "best viewed relative to one another and not as standalone absolute cost estimates of a given architecture". Although both realized and estimated costs and construction durations from real-life projects are used as reference points in this work, the most important results are the relationships between different reactor architectures.

Properly benchmarking the results is challenging and limited by data availability. For example, no APR1000 units have yet been constructed, and the final cost and duration of the HPC construction have not yet been realized. In addition, the publicly available NPP construction costs are often vaguely defined, further complicating the benchmarking. The cost estimate produced by the NCET only consists of overnight costs and excludes Owner's cost and interest. Public sources do not often specify whether these factors are included in the reported values. Additionally, the contract prices do not always reflect the true construction costs, which may be left unmentioned. For example, KEPCO and KHNP have refused to reveal financial records related to the Barakah construction, making it difficult to asses the feasibility of the project [82].

Benchmarking the obtained schedules is equally challenging, as the full project schedule consists of multiple phases. The NCET only estimates the duration of the construction phase, but the reported project durations may be estimated starting e.g. from the construction permit, or sometimes even from the final investment decision. Even after the construction, the reported duration may also cover later phases, such as the first fuel load or the start of commercial operation. Each of these phases can last from several months to even years, making schedule comparison challenging if the project duration is not clearly defined.

6 Conclusion

The aim of this thesis was to model construction projects for different NPP designs and evaluate their differences in terms of costs and construction durations. Specifically, the focus of the comparison was to evaluate how regulatory differences may affect project outcomes. The results were obtained using the NCET and by modifying the existing input files based on available data. The reactor architectures chosen for this comparison were APR1000, APR1400, and two different EPRs: HPC in the United Kingdom and Taishan in China.

The APR1000 illustrates how new reactor designs are developed to comply with local laws and regulations. Although the APR1000 is based on the APR1400, European standards for NPP construction are taken into account in its design. Some design changes, such as the additions of the core catcher and the double containment, are clearly results of regulatory differences. These factors may lead to significant delays, and they also explain a significant fraction of the relatively high costs of the APR1000 compared to the APR1400. However, since the APR1000 and APR1400 are distinct reactor designs, it is difficult to separate all design changes driven by regulatory requirements from those arising from the overall architectural differences.

The comparison between the two EPR designs provides further insight into the possible differences of construction projects for NPPs that use the same reactor type. Both in terms of costs and construction duration, the difference between the HPC and Taishan NPPs is significant. The difference is largely explained by the lower labor and commodity costs in China, but regulatory differences also affect these results. However, although the HPC construction process and the regulations are well documented, the limited information available on the Taishan EPRs makes it challenging to account for all differences between the plants.

The results presented in this thesis show the importance of the regulatory environment in the nuclear construction projects. Design changes, whether introduced during the design process, regulatory adaptation, or reactor construction, can cause delays and significantly increase project costs and duration.

Although the impact of regulatory environment is clear from the results, explicitly distinguishing the effects of regulatory differences is challenging. The results are suitable for comparison between the reactor designs, but the absolute results should be interpreted with caution. Benchmarking the results and using them as standalone estimates requires further data from real-world projects. Data availability in the nuclear industry is limited, and the approximations and estimates used may not produce fully reliable results. With more detailed information, the accuracy of the results could be improved.

The results obtained in this thesis give valuable information on how the differences between the reactors affect the construction project outcomes, and especially how the NCET code manages to capture them. This provides a solid basis for further study on the costs of regulatory changes and the use of the code for evaluating the outcomes of different choices in reactor design.

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