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COST-BENEFIT ANALYSIS OF DEVELOPING A NUCLEAR POWER PLANT IN ESTONIA

Bachelor thesis

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I have written this Bachelor Thesis independently. Any ideas or data taken from other authors or other sources have been fully referenced.

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Introduction

As global environmental concerns intensify, nations worldwide are seeking sustainable solutions to meet their energy needs while reducing carbon emissions. Estonia is at a crossroads in deciding the future of its energy sector. The transition to green energy has become a pressing issue, driven by international commitments to mitigate climate change and ensure energy security. In this context, nuclear energy has emerged as a viable alternative to fossil fuels, offering a low-carbon solution with the potential to significantly reduce Estonia's reliance on non-renewable energy sources.

The Estonian Ministry of Climate highlights that a lion's share of power plants in Estonia use oil shale as its fuel. The ministry further explains that in the long term, only one of the currently active oil shale power plants will be operational. There is also an option to transfer to biogas and hydrogen-based power plants, but the primary use case for these would be to cover frequency reserves. However, there is a baseline energy consumption that needs to be filled. For this, a nuclear power plant is one of the most efficient and affordable solutions. (Kliimaministeerium, 2023)

On a national scale, Estonia has set a goal to cover the entirety of the population's energy consumption using renewable energy by 2030. By current estimates, there will be an additional of 2000 MW of wind energy production added to the energy mainframe. However, it must be mentioned that even at such magnitudes of production, there will be stints when there is no wind. This is a problem as the reserves produced by the wind farms can only last from a few hours to a few days and currently there is no alternative to cover these windless periods. Small modular reactors (SMRs) can also be used to produce frequency reserves or with additional development, reserve capacities can be improved significantly. (Kliimaministeerium, 2023)

Previous studies on nuclear energy and green energy transitions have explored theoretical frameworks (Serrano & Zaveri, 2020), phases of transition (Markard & Rosebloom, 2022), cost-benefit analyses (Posner, 2000), and regional influences - like the geopolitical context - (Coenen, Hansen, Glasmeier & Hassink, 2021), but they do not fully address Estonia's unique energy context and strategic goals. Similarly, frameworks for net-zero energy transitions highlight general strategies without assessing how nuclear power could complement renewables in smaller economies like Estonia (Markard & Rosebloom, 2023). While international cost-benefit analysis (CBA)[1] provides methodologies for nuclear projects, they do not account for Estonia's energy, environmental, and economic conditions (World Nuclear Association, 2023). Additionally, regional studies overlook Estonia's reliance on energy markets, the absence of low-cost fossil fuels, and the potential for SMR This thesis addresses these gaps by conducting a localized CBA tailored to Estonia, examining the integration of nuclear power with renewables to manage intermittent supply, and evaluating the financial, environmental, and social feasibility of nuclear energy as part of a diversified energy strategy. It offers sector-specific insights and bridges theoretical and practical dimensions to provide possibly actionable recommendations for Estonia's energy future.

This thesis aims to carry out a cost-benefit analysis of nuclear energy development in Estonia. By examining both the financial and societal implications, this study assesses whether the construction of a nuclear power plant is a feasible solution for the country's long-term energy strategy.

To achieve the aim, the following tasks are set:

- To explain the concept of cost-benefit analysis with emphasis on nuclear energy development
- To give an overview of different types of nuclear reactors and the potential costs and benefits related to them and to compare region specific differences of building a nuclear power plant
- To give an overview of the current energy landscape in Estonia
- To analyse and give a summary of the costs and benefits related to nuclear power plant development with a narrow focus on the specificities of Estonia
- To hold an interview with a Fermi Energia representative to get an overview of costs and benefits related to a nuclear power plant development in Estonia.

As Fermi Energia is the project leader for developing a nuclear power plant in Estonia, conducting interviews gives the unique perspective necessary to focus this thesis on the unique matters of Estonia. The long-term financial projections of Fermi Energia give invaluable insight into the benefits proportion of the CBA. This study has the potential to

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[1] In some cases, CBA is referred to as benefit-cost analysis (Shively 2013; Vining and Weimer, 2010). Shively (2013) describes BCA as an economic evaluation tool focused on comparing the financial outcomes against the financial consequences of a project.

make the development of a nuclear power plant more appealing to the general public and policy makers. By getting a comprehensive grasp of all benefits related to building a nuclear power plant, a true long-term solution may emerge to the energy crises and high electricity prices in Estonia.

The first chapter of this thesis gives an overview of academic definitions of the concept of CBA. It covers the arguments of proponents and opponents of the method. It gives an historic overview of CBA and uses for it. The focus is on applying the CBA to public projects and more specifically to a nuclear power plant construction – which costs and benefits need to be accounted for. The first part then covers various definitions and present them in a tabular form to display varying views in a more visually appealing way.

The second part of the thesis starts with a summary of the current energy landscape in Estonia. The second part then moves to empirical analysis of costs and benefits which follow the development of a nuclear power plant with specific focus on Estonia. To start, an overview of data and methodology is given. The thesis then moves to give an overview of the data – relevant available literature, public data sources and an interview held with Fermi Energia. Then the analysis of related costs and benefits of developing a nuclear power plant follows. The thesis assesses based on the data acquired regarding costs and benefits, financing and energy grid scenarios whether nuclear power is a viable long-term energy solution for Estonia. The assessment is done using monetary terms. The moral and social objections are not ignored, but key focus will be on monetary values.

Keywords: nuclear power plant, cost-benefit analysis, Estonia.

1. Cost-Benefit analysis of building a nuclear power plant – theoretical background

1.1 Approaches to cost-benefit analysis

The CBA approach has been silently used for economic, political and social decision making for centuries – by weighing pros and cons of a situation. Essentially a decision maker can understand whether the benefits from an action outweigh the costs. However, a study done by Majerova and Abdrazakova (2021) highlights that the first practical use of a CBA in the US was recorded in 1936 for a dam construction. Since then, CBA has become a common practice to support decision-making for governments, presidents and institutions (Majerova & Abdrazakova, 2021).

Posner (2000) supports the idea of using the CBA approach to evaluate government projects like medical research, weapons systems and regulations dealing with health and environment. Meanwhile, Dunn and Sullins (1982) emphasise that in order to understand the CBA approach, the following needs to be understood:

1) at any given point in time, society experiences a certain level of welfare based on the output its resources are producing;
2) the resources available are not infinite, yet the demand is;
3) rational choice requires that investments are made so that maximum general welfare is gained.

Drèze and Stern (1987) claim that CBA provides a reliable framework for evaluating decisions and projects from the perspective of their consequences. It is fair to say that in broader terms, CBA covers an enormous scope of decision making, from personal, to microeconomic to macroeconomic levels. This thesis focuses on applying the CBA methodology to evaluating a public energy project. This application is also supported by Drèze and Stern (1987) as they state that the most common and most vital application of CBA is measuring public sector projects. A project should only be accepted if its benefits outweigh the costs.

To effectively apply CBA to the development of a nuclear power plant, the total economic effects of the plant on the energy sector – supply, demand and prices – must be understood. One must compare the economy with the project and without it (Drèze & Stern, 1987). From the perspective of this thesis, an energy sector that consists of a divided share of nuclear energy and renewable energy and an energy sector that relies solely on renewable green energy. Alder and Posner (1984) highlight a shortfall of CBA - CBA is a debatable moral or political theory like utilitarianism.

Drèze and Stern (1987) describe CBA as a structured approach to evaluating decisions based on their consequences, focusing on public sector projects. Sen (2000), meanwhile, criticises mainstream applications of CBA for overly relying on market analogies and restrictive valuations. Sen (2000) advocates for a more inclusive approach that incorporates broader informational inputs and social choice elements, arguing that traditional CBA limits its potential by excluding significant considerations such as motives, rights, and intrinsic freedoms. Dunn and Sullins (1982) provide a different viewpoint from Sen (2000) as they emphasize the role of CBA in identifying investments that maximize social welfare by assessing costs and benefits through rational decision-making frameworks. They underscore the importance of societal resource allocation, aligning closely with economic efficiency but maintaining a distinct focus on the potential Pareto improvements generated by public investments.

Posner (2000) takes a more pragmatic approach, framing CBA as a method rooted in the Kaldor-Hicks criterion of efficiency. The Kaldor-Hicks criterion of efficiency states that a change in resource allocation is considered an improvement if the benefits from the change are sufficient to compensate any costs, regardless of whether compensation actually occurs (Coleman, 1980). This approach allows trade-offs where some individuals may be worse off as long as the overall societal benefit increases (Coleman, 1980). This logic can very well be applied to a nuclear project as the population surrounding the plant are more averse to risk while the larger population benefits. Posner (2000) stresses its application for evaluating government projects and decision-making processes, highlighting wealth maximisation while deliberately excluding considerations of distributive justice. His focus on efficiency prioritizes practical policymaking over addressing equity concerns. Similarly, Majerova and Abdrazakova (2021) emphasize the analytical and practical aspects of CBA, portraying it as a comprehensive tool for welfare assessment and decision-making across domains such as health, environment, and public investment.

A similar concept of benefit-cost analysis (BCA) is also found in literature. BCA offers a methodical way to assess policies or projects. Shively (2013) portrays BCA primarily as an economic evaluation tool focused on comparing the positive financial outcomes against the negative financial consequences of an undertaking. He suggests its purpose includes judging the fundamental economic value of a project and enabling comparisons between different investment choices, whether in business, public ventures, or environmental regulation. In contrast, Vining and Weimer (2010) conceptualise BCA specifically as an organized structure for judging the efficiency of government policies. They emphasize its increasing application to complex social initiatives, like early childhood or offender rehabilitation programs, acknowledging its capacity to highlight investments that provide substantial societal returns. However, Vining and Weimer (2010) also draw significant attention to the difficulties encountered when using BCA for social policies - the inherent uncertainty involved in making predictions based on diverse data and estimated non-market values, which are frequently core goals of social policy but may not be fully captured by a BCA. Therefore, while both perspectives position BCA as a comparative evaluation framework geared towards societal improvement, Shively's (2013) description offers a general economic foundation, whereas Vining and Weimer (2010) concentrate on its specific use for judging the efficiency of public and social policies and the distinct practical obstacles this entails.

Scholars collectively depict CBA as a multi-dimensional tool. Most of the covered definitions focus on CBA being a tool to maximising public resources. In Table 1 there is a comparison of academic definitions.

Table 1

Comparisons of definitions of cost-benefit analysis

Author(s)	Definition	Conceptual emphasis
Drèze and Stern (1987)	CBA is a consistent procedure for evaluating decisions based on their consequences, focusing particularly on public sector projects using shadow prices to measure impacts on social welfare.	Focuses on shadow prices and their operationalization in project evaluations, emphasizing planner's preferences and societal welfare.
Sen (2000)	CBA is a general discipline based on foundational principles, allowing parametric variations for broader acceptability, and critiqued for its reliance on market analogies for valuation.	Critiques the traditional approach, advocating for greater freedom of valuation and inclusion of broader informational inputs beyond market mechanisms.
Dunn and Sullins (1982)	CBA evaluates the extent to which social welfare is maximised by identifying and measuring the costs and benefits of investments, emphasizing rational allocation of resources.	Highlights its application in public investments and resource allocation while emphasizing rational social choices and potential Pareto improvements.
Posner (2000)	CBA is defined as a method of pure evaluation or decision-making using the Kaldor-Hicks criterion, focusing on wealth maximization without emphasizing distributive justice.	Centers on pragmatic applications, utilizing Kaldor-Hicks efficiency and wealth maximization, often excluding distributive justice considerations.
Majerova and Abdrazakova (2021)	CBA is an analytical tool to appraise investments, assessing welfare outcomes based on economic fundamentals like net present value, producer and consumer surplus and social discount rates.	Combines theoretical and practical aspects, emphasizing CBA as a tool for welfare assessment and decision-making across diverse domains.

Source: Compiled by the author

CBA has played a foundational role in decision-making for centuries by comparing the benefits and costs of actions. Scholars emphasize that CBA serves as a structured framework to maximise social welfare, focusing on rational resource allocation and potential Pareto improvements. While advocates of CBA highlight its efficiency in policymaking, critics like Sen (2000) argue that CBA often excludes critical aspects like rights and freedoms, relying excessively on monetary valuations. It entails that moral aspects are often excluded when conducting a CBA. Applying CBA to public energy projects requires not only measuring economic impacts but also addressing the moral and political implications of such evaluations.

1.2 Literature overview on nuclear energy development and costs vs benefits of nuclear power plant construction

Nuclear reactors started emerging at the beginning of the Cold War. In the early years, the global powerhouses – the Soviet Union, the United States and the United Kingdom – all built different kinds of reactors (Ho, Obbard, Burr & Yeah, 2019). The first reactor was built in 1954 in the Soviet Union, a graphite-moderated light water reactor which produced 6 MW in electricity output (Murakami, 2021).

In 1956, a graphite-moderated carbon dioxide gas cooled reactor was built in the United Kingdom which produced 60 MW in electricity output (Murakami, 2021). A year later, in 1957, world’s first boiling water reactor was built in the United States producing 24 MW in electricity output (Murakami, 2021). The United States was the first to hit the mark as they developed light water reactors which later became the mainstream in the world of nuclear reactors (Murakami, 2021). The reason behind the early success of United States is their atomic bomb program during World War 2 (Bodansky, 2004). The United States was able to effectively translate their comprehension of atomic bomb into nuclear energy. It is fair to say that the general competitive trends of the Cold War translated into nuclear energy as well.

However, nuclear power-based electricity only started growing in popularity in the 1970s through the 1980s (Bodansky, 2004). This gap between the first plants and the commercialisation of nucleus indicates initial difficulties in utilizing the immense potential of nuclear energy. A book by Bodansky (2004) on nuclear energy highlights the rapid growth during that period – in total world nuclear power generation multiplied 9 times from 1973 to 1990. An average increase of 14% per year. During this period and after that, up until 2002, the leading region in building new plants was Asia and Japan (Bodansky, 2004). Respectively, the Asian region increased its nuclear power capacity by 34% per year during the 1973-1980 period and Japan increased its nuclear power capacity by 36% per annum during the same period (Bodansky, 2004). This period was accompanied by a new trend in the field of nuclear power. Light water reactors became state of the art during the time thanks to innovations in uranium enrichment technology (Murakami, 2021). The costs of uranium enrichment dropped drastically owing to a treaty signed by Germany, Netherlands and the UK in 1970 (Murakami, 2021). The lower costs reached market in 1972 and looking at the data provided by Bodansky (2004) and Murakami (2021), it is made clear what was the protagonist of the rapid increase in the spread of nuclear power. A year after the enrichment costs of uranium dropped, the increase in nuclear power development started. Uranium enrichment was critical as light water does not perform at satisfactory levels as a moderator in a natural uranium core (Murakami, 2021). This treaty was the turning point in the history of nuclear energy as nowadays light water reactors are the norm. Murakami (2021) additionally highlights two factors alongside decreased costs - refuelling quantities also dropped to further support the economic viability of light water reactors and the simplicity of reactor design. By the end of the 1970s, approximately 76% of all nuclear reactors were light water based – pressurised water reactors (49%) and boiling water reactors (27%) (Murakami, 2021).

Innovation never stops and that applies to nuclear power builds. Vendors must find ways construct reactors faster and simpler (Ho, Obbard, Burr & Yeah, 2019). The idea behind SMRs is to move the building process away from the reactor site and move onto mass-production of nuclear power plants (Ho, Obbard, Burr & Yeah, 2019). This is made possible thanks to the parts being modularised and standardized (Cooper, 2014). The lower unit cost of SMRs allows for countries with smaller economies like Estonia, to also potentially reap the benefits of nuclear power. The said parts can be transported via trucks or trains to the plant site (Cooper, 2014). However, it must be stated that according to multiple sources, Cooper (2014) and Mignacca & Locatelli (2020), say that SMRs can only produce up to 300MW of energy output. Meanwhile current generation reactor types usually produce 1000MW of energy output or more (Cooper, 2014).

Vinoya, Ubando, Culaba and Chen (2023) highlight another aspect that supports SMR builds – since 1970 overnight capital costs have increased from 1000 $/kW to as high as 10 000 $/kW. Figure 1 below illustrates this growth in overnight capital costs of large nuclear plant builds.

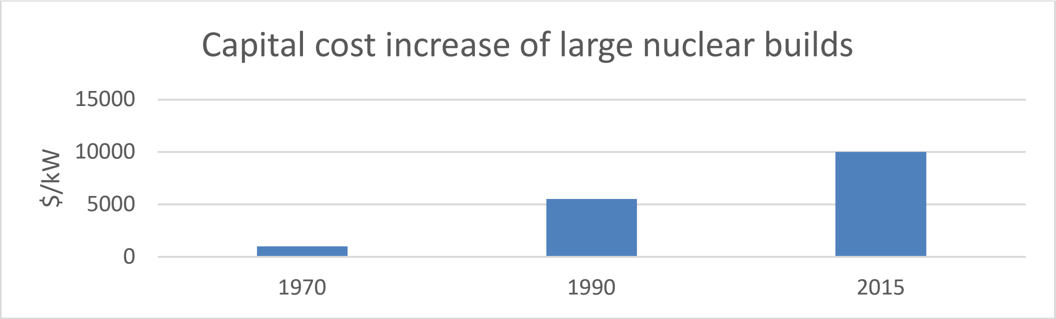

Figure 1. Illustration of the increasing capital costs of large nuclear builds.
Source: Compiled by the author based on the data provided by Vinoya, Ubando, Culaba & Chen (2023).

Finland provides a clear example for Estonia to consider in nuclear power development. First, Finland has set specific laws to ensure safety and maximised public benefit of nuclear power. Particularly the Nuclear Energy Act (990/1987) and Nuclear Energy Decree (161/1988), set strict rules for safety, governance, and public benefit (Lampinen, 2009). -These laws were written after the Chernobyl incident in 1986 and these laws require a Decision-in-Principle (DiP) for reactors which have an output of more than 50 MWth (Lampinen, 2009). The DiP process demands both government and parliamentary approval, ensuring that new facilities meet societal needs (Lampinen, 2009). Kojo and Litmanen (2009) highlight the importance of public and parliamentary discussions leading up to the approval of the fifth reactor build. One of the key arguments of Kojo and Litmanen (2009) is that the fifth reactor gained acceptance because of its alignment with climate goals. This is a key learning point for Estonia as Estonia as well aims to achieve the climate goals set by the European Union.

However, the nuclear history of Finland started even before the mentioned laws. The first four reactors were built in the 1970s (Lampinen, 2009). This aligns with the period when nuclear power was the key energy trend as mentioned before. The construction of the fifth reactor, Olkiluoto-3, demonstrates the impact of modern regulations (Kojo & Litmanen, 2009). This reactor is expected to provide 13 TWh of electric output annually, meeting 15 percent of Finland’s electricity demand (Lampinen, 2009). The Finnish government supported the project by emphasizing energy supply stability, climate goals, and job creation (Lampinen, 2009). Estonia can take inspiration from Finland by creating clear laws, conducting environmental reviews, and engaging the public to address their potential concerns.

In the nuclear sector, costs are divided into four groups: capital costs, operation and maintenance costs, fuel costs and decommissioning costs (Mignacca & Locatelli, 2020). Capital cost is explained as construction, owner's, contingency and first core cost (Generation IV International Forum, 2007). When estimating construction costs, the most likely direct and indirect costs only, are considered (Generation IV International Forum, 2007). Owner costs meanwhile are land, site preparation works, project management and administration buildings (Mignacca & Locatelli, 2020).

Locatelli, Bingham & Mancini (2023) conclude that the capital costs of a SMR is considerably higher than that of a large reactor (LR) according to the economies of scale principle. This means that even in monetary terms a LR is more expensive but the energy production per dollar is the same or less than in the case of a SMR. According to Mignacca & Locatelli (2020) capital costs make up 50-75% of all life cycle costs. Operation and maintenance costs include non-fuel related costs like staff, operating materials, equipment, repair jobs, external services, insurance, taxes and other possible unforeseen costs (Mignacca & Locatelli, 2020). When comparing a LR with an output of 1340 MW of energy and 4 SMR with an output of 335 MW of energy, each, the operation and maintenance costs are 19% higher for the SMRs (Locatelli, Bingham & Mancini, 2023). Fuel costs are made up of activities like mining the uranium, uranium enrichment, manufacturing of nuclear fuel and the final nuclear waste disposal (Mignacca & Locatelli, 2020).

However, this is not final as the economic viability of SMRs largely stands on their production being commercialised (OECD, 2011). It appears that in the case of a large-scale production the capital costs of SMRs can decrease significantly. Extreme parallels can be drawn from the early stages of automotive industry where the mass production of cheap affordable cars like Fords proved to be the winning formula. When comparing the economic performance of SMRs and LRs, they are quite similar (Locatelli, Bingham & Mancini, 2023). However, the financial risk of a SMR is lower due to lower initial capital investments and decreased dependability on the profitability of the project (Locatelli, Bingham & Mancini, 2023). Below in Table 2 there is a description and overview of quantifiable costs related to nuclear power plant development.

Table 2

Overview of quantifiable costs associated with a small modular reactor development

Author(s)	Cost	Brief description of the cost
Generation IV International Forum (2007)	Capital Costs	Encompasses construction, owner's costs, contingency and first core cost
Mignacca & Locatelli (2020)	Operation and Maintenance	Includes non-fuel related costs like staff, operating materials, equipment, repair jobs, external services, insurance, taxes and other unforeseen costs
Mignacca & Locatelli (2020)	Fuel Costs	Comprises of activities like uranium mining, enrichment, manufacturing of nuclear fuel and final nuclear waste disposal

Source: Compiled by the author

The concepts of first-of-a-kind (FOAK) and nth-of-a-kind (NOAK) reactors are also pivotal in understanding the economic lifecycle and costs of new nuclear power plant designs. FOAK reactors include initial prototypes and signify the earliest deployments of a particular design. They bear significant upfront design, engineering, and certification costs (NEA, 2016; Rosner & Goldberg, 2011). These initial builds are crucial for the learning process, where manufacturing techniques, supply chain efficiencies and construction methods are refined FOAK projects often resulting in higher initial costs and schedule uncertainties (Rosner & Goldberg, 2011; Stewart & Shirvan, 2022). In contrast, NOAK reactors represent a mature stage where the learning curve has been surmounted (Rosner & Goldberg, 2011). NOAK cost estimates assume that efficiencies and lessons learned from previous builds are fully integrated - reflecting optimized and stable costs often used in vendor projections (NEA, 2016; Stewart & Shirvan, 2022).

Alongside costs of nuclear power development, there are also various benefits. The first benefit of nuclear energy is its fuel – uranium. Firstly, uranium does not interfere with natural biological cycles which rely on hydrogen, oxygen, carbon and nitrogen Sandklef (1999). Sandklef (1999) estimated that the uranium reserves would sustain active use for 250 years, and when uranium and plutonium is recycled this number increases to 10000 years.

This is longer than current form of civilization has been in existence. Sandklef (1999) argues that uranium can possibly be regarded as an unlimited fuel source owing to its possible reserves in the ground, phosphates and sea water. Gabriel, Baschwitz, Mathonnière, Fizaine & Eleouet (2013) support this argument as they state that even as the density or uranium in seawater is low, it still represents nearly 4,5 billion tonnes of uranium. In Table 3 there is a comparison of different fuel sources to highlight the enormous energy density of uranium.

Table 3

Comparing the energy intensity of different materials

Material	Output
Firewood	1 kWh
Coal	3 kWh
Oil	4 kWh
Uranium	50 000 kWh

Note: This output is from 1kg of each material

Source: Compiled by author based on the data provided by Sandklef (1999)

Policy makers around the world are looking to find ways how to reverse climate change and thus reduce greenhouse gas emissions. One of the potential ways to reduce fossil fuel dependency and reduce greenhouse gas emissions is nuclear energy. A study done by OECD (2007) says that nuclear energy is potentially a carbon-free substitute to fossil fuels. OECD (2007) further highlights how CO2 emissions could be reduced by up to 50-80% by 2050. Other authors, however, do not classify nuclear energy as carbon-free but rather classify it as a low-carbon energy source (Gabriel, Baschwitz, Mathonnière, Fizaine & Eleouet, 2013). Nuclear energy is seen as a key component in reducing CO2 emissions significantly (Rozylow, 2013). An analysis of nuclear power plant development done in Poland by Rozylow (2013) highlights how a nuclear power plant avoids emissions of several greenhouse gases like CO2, CH4 and NO2, all of which are directly linked to operating a coal powered power plant. Poland's example is extremely relevant from the perspective of this thesis as their energy, political and geopolitical landscape is fairly similar to that of Estonia. Contrary to wind and solar energy, nuclear power has the capability of large-scale deployment (OECD, 2011).

The evaluation of future energy strategies, including the potential role of nuclear power, occurs within a complex landscape defined by the recognized limitations of conventional and alternative energy systems. Dependence on fossil fuels frequently introduces significant market instability (Ganduri, 2015). These price fluctuations can create substantial socio-economic difficulties, particularly impacting the financial well-being of lower-income groups who may struggle to adapt to sudden cost increases, while also contributing to broader economic uncertainty (Ganduri, 2015). Concurrently, the transition towards renewable energy technologies, often promoted as a primary solution, is not without its own set of hurdles (Bradley, 1998). Many renewable options historically faced challenges in achieving economic parity with established energy sources without considerable governmental financial assistance through subsidies or mandates (Bradley, 1998). Furthermore, even favoured renewable sources carry specific environmental footprints and consequences, such as land use demands or impacts on ecosystems, complicating their deployment as a universally ideal replacement (Bradley, 1998). Considering these distinct challenges together - the socio-economic volatility tied to fossil fuels and the economic constraints and environmental trade-offs associated with scaling certain renewables—illuminates the strategic appeal of energy sources offering different operational profiles (Bradley, 1998; Ganduri, 2015). Specifically, this context derived from the limitations of other sources underscores the potential value of nuclear energy's capability to deliver stable, high-quantity electricity production (Bradley, 1998; Ganduri, 2015). This capacity for consistent, large-scale baseload power could serve to mitigate the economic volatility observed in fossil fuel markets and address some of the consistency and scalability limitations associated with other low-emission energy forms, thereby enhancing overall energy system reliability (Bradley, 1998; Ganduri, 2015).

Nuclear power offers significant risk mitigation from the perspective of energy security and independence. This is especially relevant today, when Eastern Europe faces an energy crisis due to Russia’s ongoing aggression in Ukraine. Several reports, such as OECD (2007), Rozylow (2013), and Gabriel, Baschwitz, Mathonnière, Fizaine & Eleouet (2013) highlight how the uranium resources are much less geopolitically concentrated than fossil fuels like oil or natural gas. The energy security of nuclear energy is also supported by its reliable and consistent output regardless of weather or other aspects (OECD, 2007). Rozylow (2013) supports the idea of energy security as he highlights Poland’s energy dependency on coal and Russian oil and gas. Natural gas, oil and other fossil fuels are known to be found only in specific regions throughout the globe with Russia being one of the examples. Uranium resources, however, are spread out and less geographically concentrated meaning regardless of the geopolitical situation, uranium sources are more easily attainable (Gabriel, Baschwitz, Mathonnière, Fizaine & Eleouet, 2013).

One of the key economic concerns for Estonia currently are the very high electricity prices. One hope of developing a nuclear power plant is to attain an energy source that can produce energy on large scale with less economic pressure on consumers. However, the initial costs of large reactors are huge. According to Locatelli, Bingham & Mancini (2023), SMRs through their modular build, offer a unique opportunity to decrease economic risks and high initial investment that come along with large nuclear builds. The smaller initial investment of a SMR attracts a broader investor base, like Estonia and the nuclear project leader in Estonia - Fermi Energia. In addition to financial benefits related to production of SMRs, nuclear energy provides unique job creating opportunities - Rozylow (2013) states that a construction of a nuclear power plant would create thousands of jobs directly and indirectly. Rozylow (2013) highlights sectors like construction, engineering and the long-term operation of the plant. This is supported by the OECD (2011) report, and they even add the regulatory sector as the beneficiary of nuclear development. A plan to construct and the construction of a nuclear reactor create a need for specific skills which need to be taught at local universities (Rozylow, 2013). Even though Estonia currently has no nuclear programmes in its universities, an accepted nuclear project would create demand for this kind of education. In Table 4 below, is an overview of the key benefits of nuclear energy highlighted in literature.

Table 4

Overview of benefits associated with a small modular reactor development

Author(s)	Benefit	Brief description of the benefit
OECD (2007); Gabriel, Baschwitz, Mathonnière, Fizaine & Eleouet (2013)	Low-carbon energy source	A substitute for fossil fuels-based energy sources
Bradley (1998); Ganduri (2015)	Stable and high-quantity electricity production	Capacity to produce stable and high amounts of electricity consistently
Bradley (1998); Ganduri (2015)	Energy security and independence	Contributes to overall grid reliability and offers significant risk mitigation
Rozylow (2013); Lampinen (2009)	Job creation	Provides unique job-creating opportunities.

Source: Compiled by the author

Several authors, Lee, Yoon & Shin (2016) and Lombaard & Kleynhans (2016) emphasize the widespread concern related to nuclear energy which is nuclear waste.

Lombaard & Kleynhans (2016) state that the key argument against nuclear energy development is the radioactive waste created by a nuclear power plant, the authors further highlight the environmental implications nuclear waste has. However, there are steps being taken to solve this concern. OECD (2007) report emphasize the controlled environment and processes in which nuclear waste is disposed of and they further highlight that with technological innovation, nuclear power can become one of very few sources of energy that has capabilities to provide large-sarge, low-carbon and low environmental impact electricity. This stance is supported by Gabriel, Baschwitz, Mathonnière, Fizaine & Eleouet (2013) as they highlight the technology of fast breeder reactors which reprocess spent fuel addressing the waste management issue. A reprocessing innovation like this extends the lifecycle of uranium making it more environmentally friendly (Gabriel, Baschwitz, Mathonnière, Fizaine & Eleouet, 2013). According to International Atomic Energy Agency (2021), the fast breeder reactor technology can be applied to SMR builds as well. This combination of technologies would entail developing a SMR that operates on a fast neutron spectrum which utilizes high-energy neutrons to sustain the fission process, thus having the capability to breed more fissile materials than they consume (International Atomic Energy Agency, 2021).

The papers by Lee, Yoon & Shin (2016) and Lombaard & Kleynhans (2016) – highlight the public safety concerns related to nuclear plant development. Lee, Yoon and Shin (2016) mention the Fukushima accident as an accelerator to public opposition. Meanwhile Lombaard & Kleynhans (2016) state that people in the European Union are against nuclear power while in the United States people are in favour of it. It appears that regions that have historically been closely affected by nuclear incidents are more suspicious of its development. However, according to the OECD (2011) report, the Fukushima incident was also a catalyst for improved safety in the following nuclear projects. The Generation IV reactors are designed with built-in safety measures to prevent meltdown even in extreme conditions (OECD, 2011). This is additionally supported for SMR builds by Cooper (2014) whose study states that SMRs have advanced safety systems that only use natural forces like gravity and convection to keep the core cooled without needing active intervention.

Nuclear power has a complex history of innovation and growth, from early reactors during the Cold War to modern advancements like SMRs. The global rise of nuclear power in the 1970s was driven by technological improvements, including uranium enrichment, which made reactors more efficient and cost-effective. Today, SMRs offer an economically viable solution for smaller nations like Estonia, because of lower capital investment and modular construction. Nuclear power contributes to energy security, reduced reliance on fossil fuels, and significantly decreased greenhouse gas emissions, however, concerns about safety, waste, and negative public perception remain. Lessons from Finland show how clear regulations, public engagement, and alignment with climate goals can help Estonia address these challenges while pursuing nuclear energy development.

2. Analysis of nuclear power plant as a long-term energy solution for Estonia

2.1 Description of methodology and data collection process

This study employs a CBA framework to evaluate the economic feasibility of developing nuclear power, specifically utilizing SMR technology, as a long-term energy solution for Estonia. CBA is selected as the primary methodology due to its established suitability for assessing large-scale public sector investments by systematically comparing their anticipated costs against potential societal benefits (Drèze & Stern, 1987; Majerova & Abdrazakova, 2021; Posner, 2000). The main objective of applying this framework is to determine whether the quantifiable and qualitative benefits derived from constructing and operating SMRs in Estonia are projected to outweigh the associated economic costs, thereby informing the assessment of nuclear power's viability as outlined in the research aim.

A mixed-methods research design underpins this analysis, integrating both quantitative and qualitative data sourced from secondary and primary materials. This approach was deemed essential to construct a comprehensive evaluation, enabling the specific context of the proposed Estonian project to be situated within and compared against theoretical principles and empirical findings related to nuclear energy economics.

Secondary data collection established the foundational understanding necessary for the analysis. This included a systematic review of academic literature and peer-reviewed journals. To describe the theoretical constructs and to collect generalized empirical data concerning the historical development and cost structures - capital, O&M, fuel and decommissioning. Additionally, the benefits - low-carbon energy, energy security, potential for price stability, and technological evolution in the form of SMRs. Key academic sources referenced include, but are not limited to, studies by Murakami (2021), Bodansky (2004), Mignacca & Locatelli (2020) and Cooper (2014). The mentioned quantitative data is gathered from publicly available academic literature. The data collected from the academic papers are compiled into a single word file and then used during the analysis process.

Complementing the academic review, publicly available data and official reports from reputable national and international bodies were utilized. These sources, including the International Energy Agency, Estonian Ministry of Climate, Elering, International Renewable Energy Agency, Organisation for Economic Co-operation and Development along with its

Nuclear Energy Agency and the International Atomic Energy Agency provided critical data for characterizing Estonia's current energy landscape and benchmarks for nuclear project costs and performance metrics.

Primary data collection was undertaken to acquire project-specific insights relevant to the SMR development planned by Fermi Energia, the firm advocating for nuclear development in Estonia. This was achieved through a semi-structured interview conducted with the Chief Financial Officer of Fermi Energia. This form of interview facilitated the acquisition of direct, nuanced information concerning the project's specific financial projections, including capital cost estimates, O&M cost structures, financing assumptions - interest rates, loan periods - target LCOE and anticipated qualitative benefits such as localized job creation and the potential stimulus for related educational program development. The interview protocol targeted specific information required for the CBA, focusing on cost components, operational parameters, and expected societal impacts. The interview was carried out following the ethical standards of University of Tartu – the interviewee signed the consent form and was given the participant information sheet, both of which are found in Annexes of this thesis.

The subsequent data analysis was conducted systematically within the established CBA framework. Initially, information derived from the literature review and public data analysis was synthesized to construct the theoretical and contextual background for the evaluation. Quantitative data including costs and operational metrics - capacity factor, annual energy production – are displayed in tables 5-8. Data is sourced from both the interview and secondary materials, it is then compiled, compared and analysed. This involves computational steps, such as deriving average costs from reported ranges and calculating project-specific annual O&M expenditures based on parameters provided during the interview. Qualitative data concerning benefits like enhanced energy security, price stabilization potential, decarbonization contributions and employment effects were integrated into the analysis to supplement the monetary evaluation. Potential electricity price variations dependent upon financing and capital cost assumptions are illustrated through scenario analysis. The scenarios are formulated based on the electricity price data provided by Fermi Energia during the interview. The potential scenarios are compared with Estonia's recent electricity prices. To gather this data during the interview, the following questions were asked to support the open discussion format of the interview:

1) What are your current cost projections for the plant development – capital costs, operations and maintenance costs etc.?

2) What will the societal benefits be once the plant is operational?
3) How many jobs will these plants create?

The core analytical step involved the comparison of identified costs and benefits, prominently featuring LCOE as a comparative metric against alternative energy sources which is visible in Table 9. The final assessment of economic viability was predicated on determining whether the benefits exceed the projected costs, interpreted through the lens of the Kaldor-Hicks efficiency criterion, which prioritizes net societal and economic welfare gains. This methodological approach acknowledges inherent limitations, notably the uncertainty surrounding FOAK vs NOAK cost trajectories for the evolving SMR technology (Stewart and Shirvan, 2022).

2.2 Overview of Estonia's current energy landscape

According to International Energy Agency (2023) only small proportion of the total energy production comes from low-carbon sources. Figure 2 gives a visual representation of the status of Estonia's energy sector. Even though the specific numbers vary from different sources, it is clear that Estonia is heavily reliant on coal to support its energy sector.

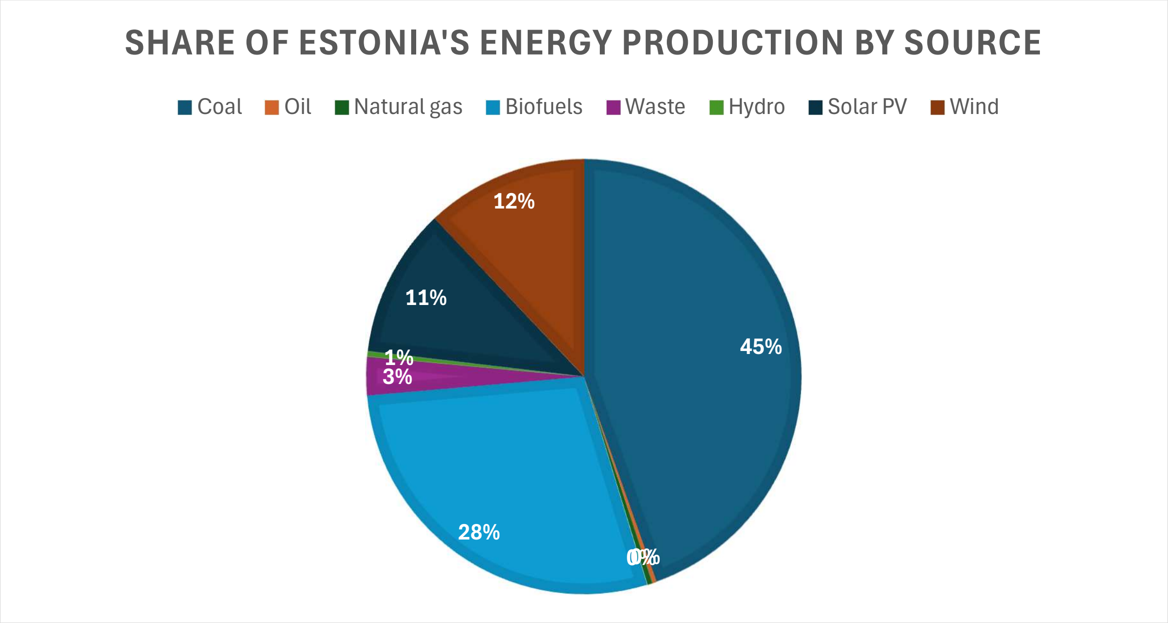

Figure 2. Visualisation of the share of Estonia's energy production by source

Source: Data from the International Energy Agency website as of 2023 and visualised by the author.

The closing down of the coal power plants and slowly moving to carbon neutral energy sources has had a negative effect on energy prices. The unreliability of wind and solar energy has created situations where during peak consumption, there's a strong deficit of energy production. These situations happen during periods when the demand for cheap energy is at its highest – late autumn to early spring. To illustrate the difference in production and consumption during 2024, data from Elering has been derived. Figure 3 below visualises the impact the current energy system has on Estonian society.

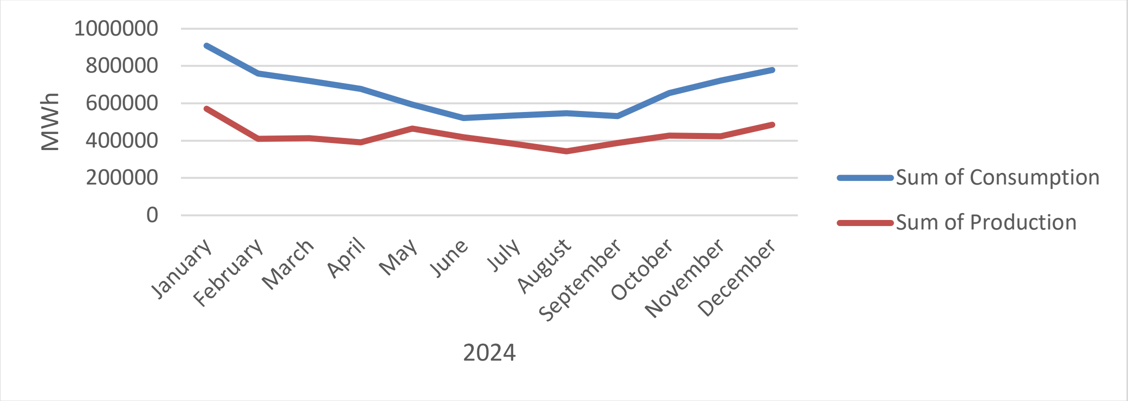

Figure 3: Visualisation of the electricity production deficit across the 12 months during 2024 Source: Data from Elering website for the 2024 period and visualised by the author.

This is an alarming illustration and further speaks to the need of a stable energy source. It is also worth noting that even during periods where production is seemingly at its highest, there is still a deficit. This means that there's never a situation where Estonia can continuously sell its energy. This is one of the potential benefits of a nuclear power plant. In case of surplus production, Estonia can sell its excess energy to neighbouring and boost its economy.

A good point of comparison is Finland. As touched upon in this thesis, Finland already has three nuclear power plants. According to the 2024 data provided by Elering, the average electricity price in Finland is almost two times lower than in Estonia and other Baltic countries. The average electricity price for Finland in 2024 was 45,57 €/MWh (Elering, 2024). Meanwhile in Estonia, the average electricity price during 2024 was 87,27 €/MWh (Elering, 2024). During 2024, this difference was highest in August, when electricity in Finland cost 12,53 €/MWh while in Estonia it cost 106,94 €/MWh. It is fair to say that the differences between two neighbouring countries with similar geographical and geopolitical situations, shouldn't be so clearly noticeable. To visualise this difference and draw attention to the entire 2024 year, Figure 4 has been compiled below.

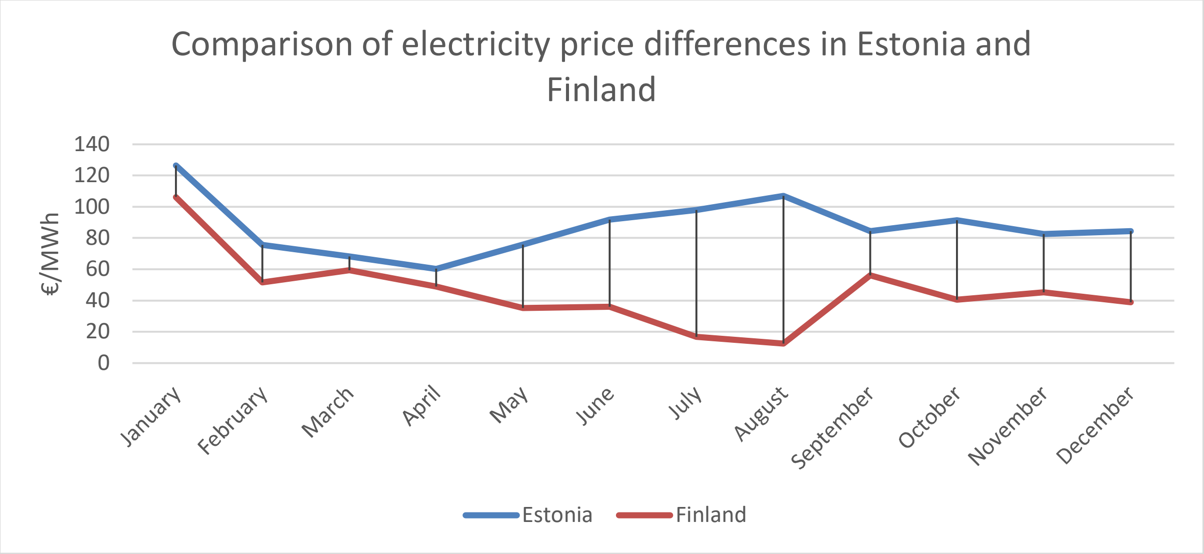

Figure 4: Comparison of electricity price differences in Estonia and Finland

Source: Data from Elering website for the 2024 period and visualised by the author.

Estonia produces 84.48% of its energy from fossil fuels and only 15.5% from low-carbon sources. Electricity production has dropped sharply—from 17.61 TWh in 1990 to just 6.48 TWh in 2023. The country has made progress in reducing oil shale use and increasing efficiency, but these gains have come at a steep cost. In August of 2024, the gap was even wider: 106.94 €/MWh in Estonia versus just 12.53 €/MWh in Finland. Solar and wind have not provided the stability needed during peak consumption months. As a result, Estonia faces ongoing production deficits and some of the highest electricity prices in the region. Without a stable, large-scale energy source, the country cannot secure affordable or reliable electricity.

2.3 Cost-benefit analysis of building a nuclear power plant in Estonia

The costs of small modular reactor development in Estonia

The following subchapter describes the costs related to nuclear power plant development based on available literature as well as an interview conducted with Fermi Energia's CFO. The interview was held to get insights into Fermi Energia's cost and benefits calculations. The numeric data regarding costs which was gathered during the interview is compiled into Table 5.

To begin the cost-benefit analysis, the costs provided during the interview Fermi Energia are analysed. It is important to note that Fermi Energia is planning to build two 300MW small modular reactors, with a total output capacity of 600MW. Thus, the total initial capital cost for the project is 3,000,000,000€. By knowing the total output capacity, capacity factor and the operation & maintenance costs per MWh, it is possible to calculate the total annual operation & maintenance cost for the plant. As seen from the calculation below, the annual O&M costs for the two plants will be 120,199,464€. It is important to note that the 25,41 €/MWh includes all costs related to fuel – decommissioning and waste fuel handling. At the time of the interview, Fermi Energia estimates the interest rate for their loan to be 5%, thus the annual interest payment will amount to 50,000,000€. According to Fermi Energia (2025), the loan period will be 20 years. Using this information, the annual running costs for the first 20 years of plant operation can be calculated. Regarding levelized cost of electricity (LCOE), this value will be higher, 82,6 €/MWh, during the first 20 years of the plant's lifetime. However, once the loan has been repaid, LCOE will drop to 72 €/MWh, which will translate to a cheaper electricity price.

The total costs for the first 20 years: 20*(interest cost + O&M) (Google, 2025).

The total costs for the first 20 years: 20*(50,000,000 + 120,199,464) = 3,403,989,280€

Annual O&M formula: (Output*capacity factor) *operation & maintenance cost (Google, 2025).

Annual O&M cost: (600MW * 0,9) * 25,41MWh = 120,199,464€

Table 5

Data regarding costs gathered during the interview with Fermi Energia's CFO

Data from the interview	**Cost**
Capital cost	1,500,000,000€/plant
Operation & maintenance	25,41 €/MWh
Interest cost	50,000,000 €/yr
WACC	7,25%
Levelised cost of electricity	82,6 €/MWh
Capacity factor	0,9
Annual O&M cost	120,199,464€

Note: Levelised cost of electricity was calculated by the author using the values provided by Fermi Energia. WACC stands for weighted average cost of capital

Source: Interview with Fermi Energia's CFO

The rest of the data has been gathered from several publicly available studies on small modular reactors. Tables 6-8 describe costs that have been found in more than one source for comparability and for more precise analysis. For accuracy purposes, data from public sources and the interview will be combined in doing the analysis.

As the first step in the analysis, capital cost needs to be understood. Rosner & Goldberg (2011) defined capital cost as the added costs of engineering, procurement and construction. This is an upfront one-time cost when building the plant. Some authors have calculated a range into which the capital cost may fall into. For example, Abdulla et al. (2013) have given a wide range of 960 million to 2,13 billion for a 300MW power plant. It needs to be noted that none of the studies has suggested a capital cost as low as the 960 million. However, Fermi Energia's CFO suggests that the capital cost for one 300MW plant would be 1,5 billion. This value is supported in literature as well as Aseuga et al. (2023) calculated the capital cost to be 1,45 billion dollars. Additionally, an analysis done by Nuclear Energy Agency in 2016 calculated the capital cost to be 1,58 billion dollars. However, these estimations need to be taken with a grain of salt as the FOAK small modular power plant is yet to be completed and the NOAK learning curve is still unclear. Stewart & Shirvan (2022) have calculated a more conservative capital cost at 2,2 billion dollars. Lastly, a meta-analysis of advanced nuclear reactor cost estimations done by Abou-Jaoude et al. (2024) has suggested the capital cost at 1,8 billion dollars. For the sake of simplicity, the arithmetical average of these values is used to get the most accurate capital cost and take into account the potential NOAK learning curve. The arithmetical average of the listed cost is 1,67 billion euros. For comparability purposes, the value provided by Fermi Energia's CFO is not used in calculating the arithmetical average. The costs are also listed in Table 6.

Table 6

Capital costs of small modular reactor development

Author(s)	Capital cost ($)
Abdulla et al. (2013)	960,000,000 - 2,130,000,000
Asuega et al. (2023)	1,453,200,000
Stewart and Shirvan (2022)	2,202,000,000
NEA (2016)	1,575,000,000
Abou-Jaoude et al. (2024)	1,800,000,000

Note: Capital cost is calculated from values given as $/MW or $/MWe

Source: Compiled by the author

In order to get an idea of the costs over the entirety of the project's lifetime, the levelized costs of electricity method is used (Locatelli, Bingham & Mancini, 2014). It also provides a great comparison point with other energy sources like solar and wind energy. This comparison will be done later in the analysis. Levelized cost of electricity represents capital expenditure, operation, maintenance, fuel decommissioning costs and the price of electricity needed to recover lifetime expenses of a power plant (Abou-Jaoude et al., 2024). This indicates that LCOE can be used in both, the costs and the benefits part of cost-benefit analysis. This is because it depicts the costs over the entirety of the project's lifetime as well as the price of electricity needed to recover the lifetime expenses of the plant. The LCOE value depicted in Table 5 accounts for decommissioning within the O&M proportion of the estimated costs. Also, the available literature lends a helping hand. Rosner and Goldberg (2011) and Asuega et al~~,~~. (2023) both suggest a similar LCOE 91 \$/MWh and 89,6 \$/MWh respectively. A study done by the National Energy Agency (2016) suggests that the LCOE be 110 \$/MWh for FOAK plants and decrease to 90 \$/MWh for NOAK plants. This is a positive sign for Estonia as the FOAK plant is currently being built in Canada (Canadian Nuclear Safety Commission, 2024).

LCOE = [(Capital recovery factor * Capital cost) + O&M] / annual energy production

Table 7

Levelised cost of energy of nuclear power

Author(s)	Levelised cost of energy
Rosner and Goldberg (2011)	91 \$/MWh
Asuega et al. (2023)	89,6 \$/MWh
NEA (2016)	90 - 110 \$/MWh
Abou-Jaoude et al., (2024)	103 \$/MWh

Source: Compiled by the author based on the papers indicated in the Author(s) column

Another important aspect to consider in nuclear energy is the fuel. Regarding the economics of it, is it a one-time cost or a continuous one? While fresh fuel is physically loaded into the reactor periodically during refuelling outages, every 18-24 months, for economic modelling, this expense is averaged over the energy generated between these outages (Pannier & Skoda, 2014). Therefore, it is treated as a variable operating cost (Pannier & Skoda, 2014). However, due to the novelty of the small modular reactor type, it is difficult to estimate what their fuel cost is going to be (National Energy Agency, 2016. In this thesis, the fuel cost is integrated into the cost-benefit analysis as an annual operating expenditure, determined by multiplying the plant's yearly electricity output by this \$/MWh value drawn from the average of values from Table 8. By calculating the average fuel cost based on Table 8, we find that the fuel cost for a small modular reactor is 8,86 \$/MWh. After multiplying the fuel cost with the annual energy output of a 300MW small modular reactor, operating at 0,9 capacity factor, it is found that the annual fuel cost will be 20,963,556 \$.

Table 8

Fuel cost of nuclear power

Author(s)	Fuel cost
Pannier and Skoda (2014)	5,84 $/MWh
NEA (2016)	9,75 $/MWh
Abou-Jaoude et al. (2024)	11 $/MWh
Annual fuel cost based on energy produced	20,963,556 $

Note: Annual fuel cost was calculated based on the output of a 300MW power plant

Source: Compiled by the author based on the papers indicated in the Author(s) column

Fermi Energia plans to construct two 300MW small modular reactors, providing a total output capacity of 600MW. For this project, Fermi Energia estimates a total initial capital cost of 3 billion euros, covering engineering, procurement, and construction for both units, 1.5 billion euros each. Comparing this to available literature, studies suggest a range of capital costs; an average calculated from several sources point to 1.67 billion euros per 300MW reactor. It is important to keep in mind that the first reactor built often costs more than subsequent ones due to learning effects. Regarding ongoing expenses based on Fermi Energia's figures, the annual O&M costs for the two reactors calculate to €120.2 million. With an anticipated 5% interest rate on their €3 billion loan over a 20-year period, the annual interest payment adds another €50 million. Combining these, the total annual running costs for the first 20 years amount to €170.2 million, leading to a total expenditure of approximately €3.4 billion over that loan period. Based on limited available data for new small modular reactors, the average fuel cost estimates to $8.86/MWh. For the planned 600MW plant operating at a 0.9 capacity factor, this translates to an estimated annual fuel cost near $41.9 million. However, data scarcity makes this figure an estimate. Finally, the LCOE helps understand costs over the plant's entire lifetime and allows comparison with other energy sources. LCOE represents the average price per megawatt-hour needed to recover all lifetime expenses, including capital, O&M and fuel. Literature suggests LCOE values for similar reactors range from $89.6/MWh to $110/MWh, with potential decreases for NOAK reactors.

The benefits of nuclear energy development

The following subchapter looks to analyse the potential benefits of nuclear energy development in Estonia and compare nuclear power with renewable energy sources. The emphasis in comparison is put on wind and solar energy due to their applicability to specificities to Estonia.

To start the analysis of nuclear energy benefits, the economic aspects of solar, wind and nuclear energy will be compared. This is because Estonia has set a goal to become climate neutral by 2050 and renewable energy sources have been identified as the solution to achieve this goal (Kliimaministeerium, 2022). To compare these energy sources, Table 9 has been created which includes some key economic figures. For comparison, the current biggest wind and solar parks in Estonia have been used in the analysis. The first key area to compare is the capacity factor. The capacity factor represents the annual energy output as a percentage of the energy source's maximum energy output (IRENA, 2023). The capacity factor is by far the highest for nuclear energy. The downside of the mentioned renewable energy sources is dependability of weather conditions. This especially relevant in Estonia where there is very little year-round sunshine. Nuclear energy provides certainty and energy price stability. Going back to Figure 4, which illustrates the current energy price fluctuations in Estonia. This potential energy stability is supported by the annual energy production of these energy sources. In this metric, nuclear power also supersedes its counterparts by 2,4 times, with wind and solar energy production outputs being combined. However, the most alarming metric to note is LCOE. As this metric considers the lifetime costs of an energetics project, and the price of electricity needed to recover lifetime expenses of a power plant. Keeping these considerations in mind, LCOE is the foremost metric to consider when considering the benefit on the societal level. The value depicted in Table 9 demonstrates the energy price following the loan period. However, even during the loan period, first 20 years of plant operations, the LCOE value is 82,6 €/MWh. This further supports nuclear energy as a viable long-term energy solution for Estonia.

The capital and operational expenditure values utilized in this comparative analysis in Table 9 are derived from recent industry assessments. For solar systems, a capital expenditure of approximately 876,000 €/MW and O&M costs of 13,200 €/MW are adopted, aligning with the 2022 global weighted averages of USD 876/kW and 13.2 $/kW, respectively (IRENA, 2023). The O&M expenditure for onshore wind of 36,000 €/MW corresponds to the higher end of typical ranges, such as the $35/kW-yr identified in Lazard's (2023) LCOE analysis. The selected onshore wind capital cost of 2,581,818 €/MW represents a higher-cost scenario. To calculate the capital and O&M costs as well as the LCOE, the power output of Estonia's biggest onshore wind farm and solar farm were used (Tuuleenergia Assotsatsioon, 2025; Tiidemaa, 2024).

Table 9

Comparison of nuclear, wind and solar energy

Energy source	Capacity (MW)	Capacity factor	Annual energy production (TWh)	Capital cost (€)	O&M cost (€/yr)	LCOE (€/MWh)
Nuclear	300	0,9	2,36	1,500,000,000	60,099,732	72
Wind	225	0,4	0,89	324,870,000	9,180,000	176
Solar	77,53	0,16	0,10	67,916,280	1,023,396	295

Note: For the comparison, the biggest onshore wind park and solar park in Estonia were used.

Source: Compiled by the author

The next benefit that would accompany nuclear energy development in Estonia are year-round stable energy prices. From the plant's developer's perspective, the benefits are the sales of electricity and heating. However, the price of said electricity and heating is dependent on the cost of capital and capital cost. According to the interview held with Fermi Energia, if the cost of capital remains at the currently planned 5% then the electricity price will be around 60-70 €/MWh. This is significantly less than the 2024 average of 87 €/MWh. Should the cost of capital rise to 10% or more, then the cost of electricity would also increase to 100 €/MWh or more. Fermi Energia also stated that similar principle applies to capital cost. In a scenario where one 300MW small modular reactor costs 1 billion euros, then the cost of electricity can be as low as 55-60 €/MWh. And if the capital cost for one plant increases to 2 billion euros, then the price of electricity will also be around 100 €/MWh. These possible scenarios are illustrated in Figure 5. The scenarios were chosen to illustrate, in which financing scenarios, nuclear energy development could prove to be a feasible long-term energy solution. The figure also visualises the importance of low cost of capital and the emphasis that needs to be put into achieving it. Fermi Energia has highlighted a possible way to achieve the low cost of capital - a partnership with the state of Estonia. The larger the stake of government, the lower the price of capital and thus, the lower the cost of electricity for the end consumer.

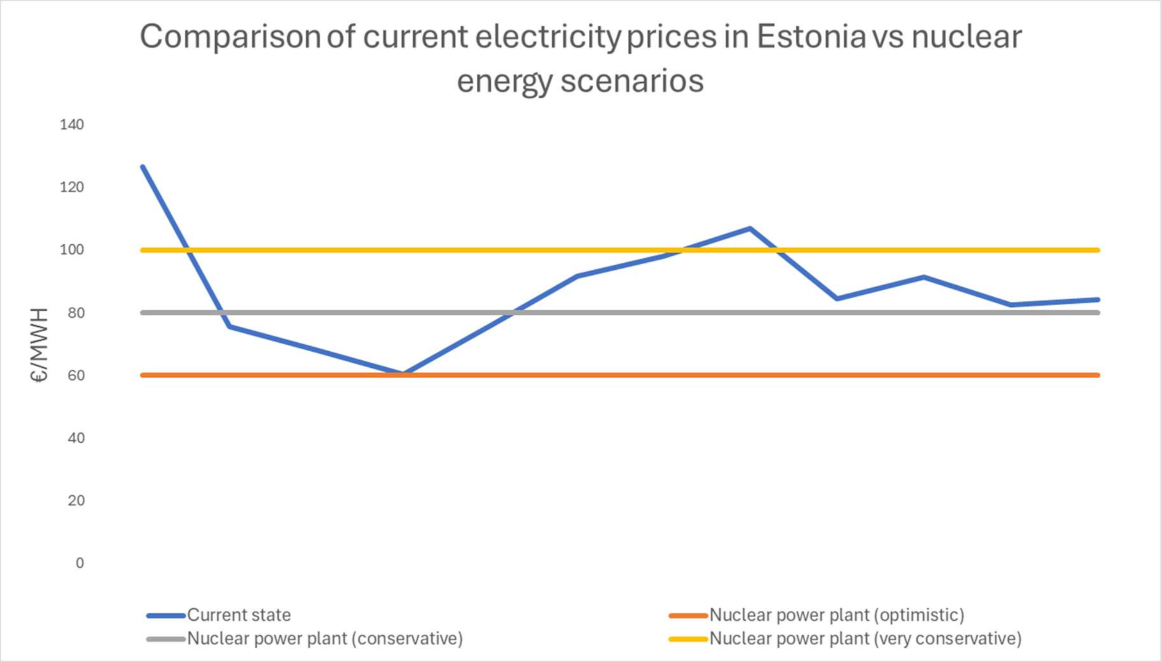

Figure 5: Comparison of current electricity prices in Estonia vs nuclear energy scenarios Source: Data from Elering website for the 2024 period combined with data received from the interview with Fermi Energia. Compiled by the author.

Beyond these direct pricing considerations, significant systemic benefits emerge when SMRs are integrated with renewable energy sources. A purely renewables-based system, which aligning with environmental goals presents substantial technical and economic challenges for Estonia, particularly concerning year-round supply reliability and the high investment required for extensive energy storage and grid upgrades (Burger, 2024; Agora Think Tanks, 2024). In contrast, a hybrid approach which incorporates SMRs offers a pathway to mitigate these challenges. The SMRs would provide reliable, low-carbon baseload power that can be adjusted as needed, thereby complementing the variable nature of wind and solar generation. This inherent stability from nuclear energy could reduce the necessity for large-scale energy storage solutions and lessen the need to overbuild renewable capacity compared to an energy grid that is dependent on fully renewable energy sources alternative.

Furthermore, by consistently producing power due to their high-capacity factor, SMRs enhance overall grid stability and bolster energy security, which can significantly reduce reliance on energy imports. The expected LCOE of 72 €/MWh for SMRs following the loan period, as indicated in the analysis, points towards more stable and potentially more affordable electricity prices for consumers in the long term. This integrated pathway allows for Estonia to leverage the reliability and energy density of nuclear power while continuing the development of its renewable energy, addressing the goals of decarbonization and energy security.

In chapter 2.2, Estonia's current energy production volume and proportion of energy sources were covered. Estonia currently produces 6,48TWh of electricity per year. As of 2023, 45% of the total production came from oil shale, which amounts to 2,9TWh. These facts present an argument that supports the development of nuclear power plant in Estonia. As highlighted in Table 9, one 300MW SMR produces 2,36TWh annually. This indicates that even a single SMR could replace almost the entirety of oil shale-based energy production in Estonia and provide a massive step towards Estonia's decarbonization goals. Another factor highlighted during the interview with Fermi Energia was the fact that the capacity factor of a SMR can increase over time. If the energy production capacity increase is deemed safe, then the capacity factor can be increased to 0,93. This would increase the energy production of one 300MW nuclear power plant from 2,365,200 MW per year to 2,444,040 MW per year.

A key benefit and learning point for Estonia is the case study of Germany. Germany's completion of its nuclear power phase-out in April 2023 removed a significant source of stable, baseload electricity generation from its energy mix (Agora Think Tanks, 2024). The increased reliance on intermittent renewable sources like wind and solar consequently presented substantial grid management challenges (Clean Energy Wire, 2024). During periods where domestic renewable generation was insufficient to meet demand, Germany experienced a heightened need for electricity imports to maintain grid stability (Burger, 2024). Notably, significant volumes of this imported power were sourced from the neighbouring France, whose grid benefits from substantial nuclear power capacity (Burger, 2024). This reliance on imports underscores the difficulties faced in replacing consistent nuclear output solely with variable renewables and managing the resulting implications for energy security and grid operation (Agora Think Tanks, 2024; Clean Energy Wire, 2024).

Based on the information gathered during the interview with Fermi Energia, the final benefits of nuclear energy development in Estonia are job creation and the inflow of nuclear related expertise. In the short-term, plant construction would create construction, housing and catering related jobs. Once the plants are complete, there would be 100 jobs created per reactor. In addition to the day-to-day plant employees, there would management, quality control, public relations, human resource management and sales jobs created which would amount to 20 to 30 jobs created. In total, the two plants create approximately 230 jobs that are directly related to running the plants. On top of that, there will be a need for a supervisory body on the government's level, which will create even more jobs.

Moreover, the inflow of nuclear physics specialists can create new higher education programmes in Estonia so that in the long-term Estonia does not have to outsource these jobs. Nuclear and reactor physics related programmes in Estonia could potentially be the first of its kind in the Baltics (Google, 2025).

In summary, nuclear energy presents several compelling benefits for Estonia's energy future. Compared to wind and solar, it offers significantly higher reliability and capacity factor, promising greater year-round energy price stability and substantial annual production volumes with a competitive long-term LCOE. Nuclear power provides a clear pathway to replace carbon-intensive oil shale generation, thereby making a major contribution to Estonia's decarbonization goals. The experience of Germany further underscores the value of stable baseload power for grid management and energy security. Beyond energy metrics, nuclear development in Estonia also carries the potential for significant job creation and the valuable inflow of specialized expertise, possibly seeding new domestic educational programs.

Conclusion

This thesis applied cost-benefit analysis principles to assess the development of a nuclear power plant, specifically using small modular reactors, within the Estonian context. The theoretical sections established CBA as a framework for evaluating public projects by comparing monetary and non-monetary consequences, highlighting the Kaldor-Hicks criterion for assessing societal welfare improvements even if compensation does not occur. The literature review identified key costs associated with nuclear power: capital, O&M, fuel, decommissioning and benefits: low-carbon electricity, high energy density fuel, enhanced energy security, potential for stable pricing and job creation. It also noted public concerns regarding waste and safety, alongside technological and regulatory advancements aiming to mitigate these issues, drawing parallels with Finland's experience.

An overview of Estonia's current energy landscape confirmed Estonia's difficult energy situation. The country still relies heavily on oil shale and even though this is decreasing, this leads to high carbon emissions and leaves Estonia vulnerable to energy shortages. This then results in electricity prices that vary a lot and are higher than in neighbouring countries like Finland. Also, the existing and planned renewable energy sources like wind and solar power are not always available because they depend on the weather. This creates problems for keeping the electricity grid stable and requires solutions for a steady power supply. This situation highlights why a stable energy source like nuclear power, could be highly beneficial for Estonia.

The analysis confirmed Estonia's current energy predicament: significant reliance on fossil fuels despite reduction efforts, resulting energy production deficits, volatile and high electricity prices compared to regional neighbours with nuclear capacity, and the intermittency limitations of existing renewable sources.

The empirical results, which combined data from the Fermi Energia interview with estimates from other sources, gave quantifiable values to conduct the CBA. Fermi Energia plans to build two 300MW SMRs, with an estimated capital cost of about 1,5 billion for each reactor. This price fits within the range found in other studies 0,96 billion to 2,2 billion per 300MW SMR, with an average price per plant of 1,67 billion. However, it is important to note the uncertainty about costs, especially the difference between the FOAK and NOAK plants. The operational costs include significant annual O&M costs of 120,2 million for both reactors and financing costs 50 million per year for the first 20 years, assuming a 5% interest rate on the loan. These costs lead to an initial LCOE estimate of 82,6 €/MWh. This cost is expected to fall to a more competitive 72 €/MWh after the loan is repaid. These LCOE figures are in line with other recent studies but depend on achieving the capital cost targets and achieving good financing terms.

The most important benefit of developing a nuclear reactor is the ability to produce stable electricity, shown by a high-capacity factor of 0,9 for nuclear energy, compared to 0,4 for wind and 0,16 for solar. This translates to a large amount of energy output -2,36 TWh per year from one plant. This stability could lead to electricity prices that are significantly lower and change less compared to Estonia's recent average price of 87 €/MWh in 2024. Prices could potentially be in the 60-70 €/MWh range if favourable financing is secured. This would directly help with Estonia’s current issues of high energy costs. Other benefits include helping Estonia meet its climate goals by replacing oil shale, improving energy security by using a fuel source less concentrated in specific regions than fossil fuels, creating new jobs - around 230 jobs for running the plants, plus construction jobs - and encouraging the development of nuclear expertise and education in Estonia.

By combining these results using the CBA framework leads to the conclusion that developing SMRs in Estonia appears to be a potentially viable long-term energy solution. The main economic advantage is the potential to provide electricity at a stable and competitive price, much lower than recent average prices in Estonia. This would reduce price swings and make energy more affordable. However, this positive outlook strongly depends on successfully managing the large initial capital costs and securing good long-term financing. Partnership with the state can prove to be vital in order to achieve this goal. The analysis shows SMRs have the technical ability to provide the reliable baseload power that Estonia's energy system currently lacks and combining with the current renewable energy sources.

To support the discussion around a SMR complimenting renewable energy sources, two scenarios are described below based on the findings of this thesis:

- Scenario 1, renewables: Aiming for a 100% renewable energy system using wind and solar power matches Estonia’s environmental goals but also rises significant technical and economic difficulties for Estonia. To ensure a reliable supply of electricity all year round, especially in winter, when there’s almost no sun and demand for heating is high, Estonia would need to build much more renewable capacity than is would be needed. This path also requires large investments in energy storage like batteries. The costs for keeping the electricity grid balanced, managing periods with very little renewable energy production, probably needing to import energy often, similarly to problems seen in Germany after its nuclear phase-out, as noted by Burger (2024) and Agora Think Tanks (2024). Also, upgrading the entire energy grid would likely lead to very high total system costs and possibly continued volatile prices for consumers. This avoids issues specific to nuclear power like long-term waste and the initial administrative hurdles.
- Scenario 2, SMRs with renewables: The SMRs would provide reliable, low-carbon baseload power that can be adjusted as needed, helping to balance the variable nature of wind and solar power. This stable nuclear energy could mean less need for large-scale energy storage and less need to overbuild the energy system when comparing to the renewables-only option. By producing power consistently due to their high capacity factor, SMRs improve grid stability and energy security, also largely reducing the need for imports. The expected LCOE of 72 €/MWh after the loan period points towards more stable and affordable electricity prices in the long run. This path allows Estonia to use the reliability and energy density of nuclear power while still developing renewables. The main challenges are managing the nuclear project costs effectively, finding long-term solutions for nuclear waste, and dealing with public opinion.

This thesis adds to the discussion on Estonia's energy future by summarizing relevant CBA definitions, gathering literature data on nuclear costs and benefits, showing Estonia's current energy situation and price issues, obtaining specific project data from Fermi Energia, performing calculations for operational costs and LCOE based on the data gathered, comparing these figures with published studies and illustrating potential future electricity price scenarios depending on financing and capital costs. However, there are limitations to acknowledge. The analysis depends heavily on cost estimates for SMR technology, which is novel and not yet used, creating uncertainty, especially regarding the costs of FOAK versus NOAK reactors. The financing details provided by Fermi Energia are crucial for the LCOE calculation and could change depending on market conditions or potential state support. Furthermore, this CBA focused mainly on economic aspects. While safety and waste were mentioned, a detailed plan for long-term waste management specifically for Estonia and a thorough study of public acceptance were outside the scope of this bachelor's thesis.

Future research should focus on getting more accurate cost estimates as more SMR projects are developed globally, particularly understanding the cost difference between FOAK and NOAK reactors relevant for Estonia. A detailed study of how potential state partnerships could affect financing costs is very important. Additionally, research is needed on practical long-term waste management solutions suitable for Estonia, as well as comprehensive studies on Estonian public opinion and acceptance of nuclear power. Comparing the total system costs and reliability of the renewables-only versus nuclear and renewables scenarios using detailed energy system models would also provide invaluable information towards concluding on a long-term energy solution for Estonia.

In conclusion, while recognizing the uncertainties related to costs and the importance of managing public concerns, this CBA indicates that, in case of favourable financing, developing SMRs could be a viable and economically reasonable long-term energy solution for Estonia. It offers a strong path towards achieving superior energy security, stable energy prices and meeting climate goals, especially when used together with renewable energy sources. However, the final decision must carefully weigh the identified economic factors alongside wider societal and environmental considerations, informed by continued research and open public discussion.

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Appendix A.

Participant consent form

Cost-Benefit analysis of developing a nuclear power plant in Estonia

Should you agree to participate in this study please read the statements below and if you agree to them, please sign the consent form.

- I have read and understood the participant information sheet.
- I understand what the thesis is about, and what the results will be used for.
- I understand that what the researchers find out in this study may be shared with others but that my name will not be given to anyone in any written material developed
- I am fully aware of what I will have to do, and of any risks and benefits of the study.
- I know that I am choosing to take part in the study and that I can stop taking part in the study at any stage without giving any reason to the researchers.
- I allow the interview to be recorded

I agree to the statements above and I consent to taking part in this research. ☐

Name:

Signature: ___________________________________ Date:

Investigator’s Signature ________________________ Date:

Appendix B.

Participant information sheet

Cost-Benefit analysis of developing a nuclear power plant in Estonia

What is the study about?

The final goal of all activities is to conclude whether developing a nuclear power plant in Estonia is a feasible long-term energy solution from the economic point of view.

What will I have to do?

I kindly ask you to participate in the bachelor thesis at the School of Economics and Business Administration by answering several interview questions that takes place in 10.03.2025 and 14.04.2025 at Fermi Energia office. To confirm your participation, you will be asked to sign a participant consent form.

What are the benefits?

The results of the thesis will potentially weigh in on the ongoing energy concerns in Estonia. The thesis hopes to shed light on an alternative long-term energy source, contrary to the current sources being publicly discussed by the government.

What are the risks?

The risks to participating in this study are minimal. The data provided will solely be used in writing the thesis and drawing conclusions. Should the interviewee be interested, the thesis will be provided in its final form.

What if I do not want to take part?

Participation in this research is voluntary and you can choose not to take part or to stop your involvement at any time.

What happens to the information?

The data that is collected will be kept private and stored securely. The computers are encrypted, and password protected. Your name will not appear on any information.

What happens at the end of the study?

At the end of the study, results will be analysed and the findings presented anonymously. No individual names will appear in any of the results.

What if I have more questions or do not understand something?

If you have any questions about the study, you may contact the researcher. It is important that you feel that all your questions have been answered.

What happens if I change my mind during the study?

At any stage should you feel that you want to stop taking part in the study, you are free to stop and take no further part. There are no consequences for changing your mind about being in the study.

Name and contact details of the investigator: Fred-Erik Penu, penufred@gmail.com

Resümee

EESTISSE TUUMAJAAMA ARENDAMISE TASUVUSANALÜÜS

Fred-Erik Penu

Käesolev bakalaureusetöö hindas tasuvusanalüüsi (CBA) abil tuumaelektrijaama, täpsemalt väikeste moodulreaktorite (SMR), arendamist Eestis. Teoreetiline osa määratles CBA raamistiku ja kirjanduse ülevaade tõi välja tuumaenergia peamised kulud - kapitali-, O&M-, kütuse-, dekomisjoneerimiskulud - ning kasud - vähese CO2 heitega elekter, energiajulgeolek, stabiilne hind, töökohad. Eesti praegune energiasektor sõltub endiselt põlevkivist, mis põhjustab kõrgeid heitgaase ja energiahindade volatiilsust, olles kõrgemad kui tuumavõimekusega naaberriikides. Taastuvenergiaallikate ilmastikust sõltuvus tekitab probleeme võrgu stabiilsusele, rõhutades vajadust stabiilse energiaallika järele.

Empiiriline analüüs, tuginedes Fermi Energia intervjuule ja teistele allikatele, näitas, et kahe 300MW SMR-i kapitalikulu oleks umbes 1,5 miljardit eurot reaktori kohta, mis mahub varasemate uuringute hinnavahemikku. Oluline on mainida ebakindlust seoses esimese (FOAK) ja järgmiste (NOAK) jaamade kuludega. Tegevuskulud ja finantseerimiskulud viivad esialgse LCOE hinnanguni 82,6 €/MWh, mis pärast laenu tasumist langeks konkurentsivõimelisemale 72 €/MWh tasemele, eeldusel et kapitalikulud ja finantseerimistingimused püsivad soodsad.

Tuumaenergia peamine kasu on stabiilne elektritootmine, koormustegur 0,9, tootes 2,36 TWh aastas ühe tehase kohta. See võib viia elektrihindadeni 60–70 €/MWh, mis on oluliselt madalam Eesti 2024. aasta keskmisest, 87 €/MWh. Muudeks kasudeks on kliimaeesmärkide täitmine, energiajulgeoleku parandamine ja uute töökohtade loomine.

Tasuvusanalüüsi tulemused näitavad, et SMR-ide arendamine Eestis võib olla pikaajaline energialahendus, pakkudes stabiilset ja konkurentsivõimelist elektrit. Selle eelduseks on suurte esialgsete kapitalikulude edukas haldamine ja soodsa finantseerimise tagamine, kus riigi partnerlus võib olla määrav. SMR-id suudavad pakkuda Eesti energiasüsteemile vajalikku baastootlikkust, täiendades taastuvenergiaallikaid.

Töö piirangutena tuleb arvestada SMR-tehnoloogia uudsusest tulenevat kulude ebakindlust ja finantseerimisdetailide võimalikku muutumist. Jäätmekäitluse ja avaliku arvamuse detailne analüüs jäeti antud töö raamest välja. Tulevased uuringud peaksid keskenduma täpsematele kuluhinnangutele, riiklike partnerluste mõjule, tuumajäätmete käsitlusele ja avaliku arvamuse uurimisele.

Kokkuvõttes näitab tasuvusanalüüs, et soodsate finantseerimistingimuste korral võib SMR-ide arendamine olla Eestile majanduslikult mõistlik pikaajaline lahendus, mis tagab

energiajulgeoleku, stabiilsed hinnad ja aitab saavutada kliimaeesmärke, eriti koostöös taastuvenergiaga.

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