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Exploring the Economics of Sustainable Energy

A Comparative Analysis of LCOE and System Costs for Nuclear and Offshore Wind Projects in Norway

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Abstract

This study explores the impact of input factor variability and the scope of analysis on profitability calculations for nuclear and offshore wind power in the Norwegian power market. The research employs several data sources and combines LCOE calculations and Monte Carlo simulations to assess the impact of uncertain factors on profitability estimations. Additionally, regression analyses assess the relationship between the share of the different power technologies and balancing volumes in a system. Additionally, a comprehensive discussion on system costs is included to encompass the system cost concept fully.

The study's main findings include that the LCOE of offshore wind projects primarily relies on the discount rate and capacity factor. On the other hand, a potential SMR project would be impacted mainly by CAPEX and OPEX. Additionally, we find that LCOE has two significant limitations. First, the metric fails to account for the value of longevity in power production, which contradicts long-term supply and environmental objectives. Secondly, it does not count for system costs occurring beyond the scope of the project. This makes the validity and significance of the LCOE metric vary among different stakeholder groups.

Another important finding is a significant but low correlation between the penetration of the different power sources and balancing volumes. While an increase in wind power penetration level is associated with an increase in imbalance volumes, the opposite effect is observed when studying the relationship with nuclear power. This could have important implications for the total costs of electricity production and suggests that a holistic approach is essential for informed decision-making regarding the future Norwegian energy mix.

***Keywords**:* Integration of Renewable Energy Sources, Nuclear Power, SMR, Offshore Wind, LCOE, System Costs, Norwegian Electricity Market, Hydropower

Contents

List of Figures

List of Tables

Applied Exchange Rates

USD/NOK	10,00	**SEK/NOK**	1,00

List of Abbreviations

ACER	Agency for the Cooperation of Energy Regulators
aFRR	automatic Frequency Regulation Reserves
ARIS	Advanced Reactor Information System
BRP	Balance Responsible Party
BWR	Boiling Water Reactor
BWRX-300	Boiling Water Reactor SMR concept by GE Hitachi
CAPEX	Capital Expenditures
EU	European Union
FCR	Frequency Containment Reserves
FRR	Fast Frequency Reserves
GEN III	Third Generation Nuclear Reactors
GW	Gigawatt
HVDC	High Voltage Direct Current
IAEA	International Atomic Energy Agency
ICT	Information and Communication Technology
IEA	International Energy Agency
IFE	The Norwegian Institute of Energy and Engineering
KWh	Kilowatt hours
LCOE	Levelized Cost of Energy
mFRR	manual Frequency Restoration Reserves
MW	Megawatt
NDE	Non-Delivered Energy
NEA	Nuclear Energy Agency
NREL	US National Renewable Energy Laboratory
NVE	The Norwegian Water Resources and Energy Directorate
O&M	Operations and Maintenance
OLS	Ordinary Least Squares
OPEX	Operational Expenditures
PWR	Pressurized Water Reactor
SMR	Small Modular Reactor
TSO	Transmission System Operator
TWh	Terawatt hours
VRE	Variable Renewable Energy

1. INTRODUCTION

The Norwegian power market has undergone radical changes since its deregulation in 1991. From an isolated market offering regional, fixed prices to its consumers, it has gradually evolved into a spot price market, increasingly connected to Europe and the European Union (EU) (Bye & Hope, 2005). The connection to Europe culminated with the endorsement of the EU energy bureau ACER and the opening of the interconnection cables NordLink and North Sea Link in 2021. The EU aims to become carbon-neutral by 2050, and Norway has agreed to support this transition towards net zero by aiming for a 55 % reduction in emissions by 2030 (Regjeringen, 2022).

In addition to the challenge of reducing emissions, the Norwegian power demand is estimated to grow from 140 TWh/year in 2020 to 234 TWh/year in 2050 (DNV, 2021). Considering this predicted increase in demand, Statnett estimates that Norway may experience a national deficit in electricity in 2027 (Statnett, 2022a). These estimates imply a severe need to upgrade and expand the current production capacity to secure sufficient security of supply. Hence, Norway is in a challenging position needing to expand its electricity generation capacities while reducing greenhouse gas emissions.

To achieve the goals of reduced emissions and increased production capacity simultaneously, the strategy of the EU has relied mainly on promoting *Variable Renewable Energy* (VRE) (The European Union, 2018). Examples of such sources are solar, onshore- and offshore wind power. These VRE sources share characteristics such as zero direct emissions during production, intermittency, and low marginal production costs. VRE power generation depends on weather conditions rather than demand, but ramping up production when circumstances allow it is cheap. However, due to its inherent intermittency, there is a significant need for backup power generation when conditions prohibit VRE production (Ueckerdt, Hirth, Luderer, & Edenhofer, 2013). This poses new challenges to the energy system and increases its complexity.

Due to the more stable winds, less direct impacts on the natural environment, and the major offshore engineering industry, Norwegian policymakers and the private sector have been eager to grasp offshore wind opportunities. Politicians and industry actors have been vocal about their ambition to become world-leading in the sector (Ministry of Trade, Industry and Fisheries, 2022a). As a result, several projects are currently in progress. The two projects that have advanced the furthest are *Utsira Nord* and *Sørlige Nordsjø II.* The first phase of these projects is expected to be rewarded to qualified private actors by 2023. Utsira Nord is a floating project off the coast of Haugesund. In contrast, Sørlige Nordsjø II is fixed offshore wind situated far from land in the North Sea (Ministry of Petroleum and Energy, 2022a).

Implementing nuclear power production is another effective approach to simultaneously increase capacity and reduce emissions. France and Sweden are examples of how this can be a powerful national strategy to attain both goals (Millot, Krook-Riekkola, & Maïzi, 2020). Despite causing no direct emissions from power production, nuclear power is not regarded as a renewable energy source as it relies on the limited resource of Uranium as fuel. However, nuclear power has been labelled as sustainable in the EU sustainable finance taxonomy from 2023 (Abnett, 2022), meaning that investments in these sources can be categorized as green. Regardless, the characteristics of nuclear power production differ vastly from those of VRE. The production is relatively constant, independent of external conditions and requires limited to zero backup generation. In addition, nuclear plants produce at a marginal price decided mainly by variable production costs. Norway has no ongoing nuclear power projects, but the topic has recently gotten increased public interest. This is partly due to elevated energy prices, but some interest can be attributed to the emerging technology of *Small Modular Reactors* (SMR). This smaller and standardized category of nuclear power plants reduces a project's investment expenditures and construction time compared to traditional technology (IEA, 2020).

Because of the different characteristics of nuclear and offshore wind power, it can be challenging to perform accurate and legitimate profitability calculations comparing the two. A frequently used and often misused measure for comparing the profitability of power generation is the *Levelized Cost of Energy* (LCOE). The assumptions for different input variables in LCOE estimations can often prove decisive in the outcome. Moreover, the measure only considers the cost side, and not the production value (Valeri, 2019). This is important as electricity generation occurs in systems with fluctuating demand and complex supporting infrastructures. Consequently, the scope of the analysis and how one incorporates integration costs that may appear on a system level rather than a project level can severely impact a profitability estimate (IEA, 2020).

This thesis aims to investigate how the LCOE calculations of nuclear- and offshore wind power rely on its input variables and how variations affect the estimated electricity cost. In addition, it aims to highlight how the scope of analysis impacts the cost estimations and how this may affect different stakeholders. Hence, the following research question will be investigated:

"How can the variability of input variables and scope of analysis impact the results of profitability calculations for nuclear and offshore wind power in the Norwegian power market?"

To answer the abovementioned research question, we will construct an LCOE calculation based on data from reliable sources. Thereafter, we will perform a Monte Carlo simulation to implement uncertainty to each input factor and run regressions on the variables for a hypothetical SMR project in Norway, the Utsira Nord and Sørlige Nordsjø II project. These investigations aim to make understandable and realistic LCOE estimations and view how the result varies with fluctuations in the input assumptions. In addition, system costs for the energy sources will be addressed. First, balancing costs will be analysed by performing regression analyses on the share of each electricity source in a system and the balancing volume. Thereafter, grid and adequacy costs will be qualitatively discussed based on reliable sources and reports due to the limited data material suited for quantitative analysis. This will highlight how the scope of research affects profitability estimations.

1.1 Delimitations and Assumptions

This paper excludes other low-emission energy sources like solar and onshore wind. Onshore wind projects usually meet heavy opposition, which has led to a complete stop in issuing concessions (DNV, 2021). Moreover, due to Norway's location and irradiation, solar energy has limited industrial potential (DNV, 2021). In addition, this thesis does not consider the expansion of hydropower with new projects or upgrading existing plants. The reason for this delimitation is a significant public reluctance to new hydropower due to the major interventions with nature, similar to the unwillingness towards onshore wind. The potential gain from upgrading existing plants is estimated to be 6-8 TWh, which only brings a minor potential contribution to meet future demand (Henriksen & Østenby, 2020). Hence, nuclear power and offshore wind come off as the two energy sources with the most potential to bring additional large quantities of electricity to the system without adding significant emissions.

1.2 Motivation and Structure

There are several reasons why this topic is of significance. First, debates about new power projects are a heated topic in the Norwegian media, where various stakeholders representing different interests or companies often display their views. Unfortunately, these can be coloured by who the various actors represent and thus be biased, which may lead to sub-optimal decisions regarding Norwegian electricity production. Hence, there is a need in the Norwegian debate for independent and unbiased research on the future energy mix. This thesis aims to be a contribution in that direction.

In the following chapters, the research question will be investigated. Chapter 2 will present the context of this thesis by introducing background information on LCOE, system costs, and the Norwegian power market. In Chapter 3, nuclear and offshore wind technologies and their historical development will be presented to enhance the readers' understanding of the fields. Chapter 4 will review the literature on cost drivers for nuclear and offshore wind power and the relationship between the technologies and system costs. Thereafter, Chapter 5 will lay out our chosen methodology to address our research question, before we present our results in Chapter 6. Consequently, Chapter 7 will discuss the implications of our results. Lastly, we present our conclusion in Chapter 8 and discuss the thesis's limitations and implications.

2. ECONOMIC BACKGROUND

Expanding production as economically efficient as possible will be essential in increasing capacity while reducing emissions. This chapter aims to equip the reader with a thorough understanding of the terms LCOE and system costs. In addition, the mechanism behind the electricity price for end-users will be presented.

To fully grasp the research presented in this paper, it is vital to recognize the distinctions between electricity as a commodity and other types of goods. Firstly, electricity is a homogenous product. This implies no qualitative differences between different electricity units in a given market. Secondly, the storage of electricity in large commercial units of significant capacity does not appear economically viable in the foreseeable future. Therefore, the market must always be in an equilibrium between supply and demand.

2.1 Levelized Cost of Energy

The economic evaluation of different generation technologies has historically relied on the Levelized Cost of Energy or LCOE (Joskow, 2011; Byrom et al., 2021). This metric measures the average price of producing one unit of electricity over the power plant's lifetime. Hence, it calculates all the expected and discounted expenses for a plant's construction, operation, and deconstruction, divided by its expected lifetime production (Energiforsk, 2021).

Thus, LCOE can be calculated as the following (Byrom et al. 2021):

$$LCOE = \frac{\sum_{t=1}^{n} \frac{CAPEX_t + OPEX_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

$CAPEX_t$ = *Capital Expenditures for year t.*

$OPEX_t$ = *Operating Expenses costs in year t.*

r = *The discount rate.*

n = *The expected economic life of the installation.*

E_t = *Electricity generation in year t.*

The underlying assumptions are that the income is solely generated from energy production, and the timing and location of energy delivery are irrelevant. Additionally, costs associated with connecting or supporting the technology are not considered (Byrom et al. 2021).

CAPEX refers to capital expenditures. An investor spends these funds to construct, acquire or upgrade long-term assets. These expenses typically have a long-term impact on the company's operations. An example of CAPEX could be the investment costs for constructing a new power plant.

OPEX is operating expenses. These are short-term costs incurred by a company to maintain its regular business operations. These expenses are vital to running the business but do not involve acquiring or improving long-term assets. For example, for a power plant, typical OPEX could include fuel costs, insurance, and O&M costs like staffing.

Energy production is capital-intensive due to a project's significant upfront investment costs. The weighted average cost of capital is represented by the discount rate (r). This rate reflects several financial aspects, like an investment's risk and alternative value. Equity holders will, for instance, demand a return consisting of several factors. First, a perceived risk-free rate equal to the return that can be earned by investing in a risk-free security. Second, an equity risk premium or the extra yield above the risk-free rate that can be earned in the general market. Additionally, investors may want compensation for the project's risk relative to other projects.

On the other hand, debt holders will require an average return on their lender capital and often compensation for the tax benefit they provide by reducing the project's taxable result through debt payments. The structure of the capital costs varies depending on the chosen financing model. Projects with high risks and alternative values generally yield high capital costs and vice versa.

The expected economic life of a project (n) is another essential input. However, it is important to note that in an LCOE calculation, production costs occurring early in the life of a project will be more influential than those occurring later. This is due to the constant discount rate applied in the metric, which emphasizes the time value of resources (Hagen, 2011).

Electricity generation (E_T) consist of the production capacity multiplied by the *capacity factor*. The capacity factor is the ratio of actually produced energy by a generating unit, in a period, compared to the level that could have been produced if the plant was operating at full effect continuously (U.S. Energy Information Administration, 2023).

It can be argued that LCOE is not a reliable metric for measuring economic efficiency or competitiveness because it only considers the costs and not the income. Hence, it overlooks the importance of how the electricity price varies over time (Ueckerdt et al. 2013). This is essential as energy storage is too expensive to implement. In addition, it cannot be used to assess a project's effect on the consumer bill (Byrom et al. 2021).

Despite its limitations, LCOE has maintained its appeal in a rapidly evolving energy sector as it remains a straightforward and uncomplicated measure. However, the need to complement it with additional information on system contribution under different constellations is becoming increasingly important (IEA, 2020). One way to achieve this is to complement the LCOE estimation with an additional system cost analysis.

2.2 System Costs

System costs are defined as the total costs accumulated beyond the perimeter of a power plant to supply electricity (NEA, 2012). This implies that the costs of generating electricity exceed the direct expenses of the project itself, and that the total sum also includes the costs of integrating a specific source into a power system (NEA, 2012). Exploring the issue in greater detail, the IEA (2011) published a comprehensive study on system costs, where the term was disaggregated into three main components: balancing costs, adequacy costs and grid costs. These cost components are also frequently utilized in other system cost studies (Holttinen, et al., 2013; G.E Energy, 2010; Sims, et al., 2011; Holttinen, et al., 2011).

2.2.1 Balancing costs

A critical aspect of power systems is maintaining balance. This means that the sum of production and imports must always equal the sum of consumption, exports, and losses (Statnett, 2023). Balancing costs refer to short-term operational costs due to output variability and uncertainty (IEA, 2011).

The Norwegian grid is primarily balanced by Statnett, a state-owned *Transmission System Operator* (TSO), responsible for ensuring that the frequency in the power grid remains stable between 49,9 and 50,1 Hz. The TSO maintains the balance between electricity supply and demand in real-time by incentivizing electricity producers and particular major consumers to adjust their electricity generation and consumption in response to changes in frequency. These actors are referred to as *Balance Responsible Parties* (BRP). Incentives include penalties and fees charged to BRPs for deviations from the planned production or consumption. This mechanism helps to ensure the stability and reliability of the grid.

In 2018, the Nordic TSOs agreed to collaborate on developing a joint Nordic balancing model. This decision was made to recognise the increasing need for a more flexible and efficient regional power system. This was due to the ongoing transformation with more renewable energy in an increasingly integrated and harmonized Nordic market (Statnett, Fingrid, Energinet, & Kraftnet, 2019). The aim was to create a common balancing market enabling balancing electricity supply and demand in a more coordinated manner. This joint effort is expected to bring numerous benefits, including cost savings, improved security of supply, and a more sustainable energy system for the Nordic region (Statnett, Fingrid, Energinet, & Kraftnet, 2019).

In 2021, the Nordics also implemented the single-price model, introducing a uniform price for all imbalances. Consequently, instead of having two separate fees for production and consumption imbalance, the Nordics now operates with a single imbalance fee regardless of positive or negative deviations. The technical implementation of the single price model is done in the joint Nordic imbalance settlement service, eSett.

2.2.2 Adequacy costs

System adequacy is defined as sufficient facilities within a power system to meet the load requirements without violating steady-state limits (Almutairi et al., 2015). Historically, resource adequacy focused on peak demand times for a given region and is associated with the reliability assessment of system planning over extended periods (Zhou et al., 2018; Sánches et al., 2021; Almutairi et al., 2015). Hence, adequacy costs are the costs of providing long-term security of supply.

Statnett carries the primary responsibility regarding the security of the electricity supply in Norway. Therefore, they are equipped to manage a variety of unexpected failures. As part of their role as TSO, Statnett also oversees the maintenance and upgrades of the grid, scaling of power stations and the ICT infrastructure to ensure the security of supply (Statnett, 2019a).

Power planners have employed various methods to guarantee an acceptable level of electricity adequacy, such as establishing targets for reserve margin (Söder, et al., 2020). Hence, to assess the adequacy, it is also necessary to consider the capacity factor of the energy sources within the power system (IEA, 2021b). This is because the measure accounts for various factors influencing a generator's performance, such as planned or forced outages, seasonal ratings, and temporally limited energy supply (Söder, et al., 2020). The adequacy challenges in Norway generally occur on a regional level. Due to constraints in the transmission grid, certain districts can encounter insufficient capacity margin when experiencing a significant load increase (Söder, et al., 2020). However, power availability is generally very high; for 2021, it was 99,99 % (Statnett, 2019a), while the average since 1998 is 99,83 % (Söder, et al., 2020).

2.2.3 Grid costs

The final cost component associated with system costs is grid costs. Grid costs refer to the cost of linking sources of supply to sources of demand (World Nuclear Association, 2021a). This might include the cost of building transmission lines, additional infrastructure and costs associated with reinforcements within the existing grid (IEA, 2011).

Notably, the most significant driver of grid costs is the physical separation between the power plant and the corresponding demand centre it is intended to supply (IEA, 2011). In addition, the cost of connecting to the grid varies based on several factors, including terrain, voltage level, infrastructure availability, and compliance with national regulations (Weißensteiner, Haas, & Auer, 2011). The cost of building transmission lines to integrate distant sites or interconnect existing networks to improve grid strength varies significantly by region.

Determining the grid costs involved in power source integration can be challenging. While estimating the cost of new transmission lines is rather uncomplicated, additional reinforcement may be needed within the existing grid to accommodate the additional capacity. It is challenging to attribute the cost of an asset that benefits the broader power system to a single cause for constructing it (Müller, et al., 2018). Statnett manages the Norwegian grid and the interconnections to the Nordic and European grids. In addition, they are assigned to ensure a thorough and well-planned offshore grid by the Norwegian government (Ministry of Petroleum and Energy, 2022b).

2.3 The Pricing Mechanism of Electricity

The Norwegian power market is connected to Europe through various interconnectors. In addition, Norway has a common synchronous area with Denmark, Sweden, and Finland, which operates on the Nord Pool power exchange (NVE, 2023a). Nord Pool, the market clearing agency, administers production and demand bids to the lowest possible production price. Hence, they use a marginal price setting (Nord Pool, 2023). The thought behind marginal electricity pricing is to avoid inefficiencies in consumption and production, which had been prevalent in regulated markets and achieve a more socio-economically optimal energy distribution (Friedman, 2011).

However, not all energy generation costs are covered by the marginal production costs. The electricity projects also include sunk costs of investments made in the past. Therefore, the sunk costs are not balanced just by charging the marginal cost of production. To solve this problem, Norway uses a method called the “two-part tariff” (Friedman, 2011; Econ, 2008). This approach sells the power to the marginal production costs via Nord Pool, and the residual costs in the energy system are spread out to the system users at a fixed fee called the grid tariff charged by the TSO.

VRE resources incur the vast majority of their costs upfront, with no fuel costs to produce electricity. Hence, the marginal costs of production are close to zero. In marginal cost markets, increasing VRE shares can push down wholesale prices when conditions allow them to produce, especially if receiving a per-unit subsidy. This places financial pressure on conventional resources that do incur marginal costs like fuel. Final consumers, however, do not pay the wholesale prices. Instead, they pay the total price of delivering electricity, which is rarely equal to the marginal cost of production (Friedman, 2011; Murray, 2019).

In 2020, the power price only contributed 15 % of the end-user prices in Norway. On the other hand, the grid tariff added 39 %. The remaining costs consisted of taxes, certificates, and the fee for the Enova fund (EnergiFacts Norway, 2022).

3. TECHNICAL BACKGROUND

Offshore wind power and nuclear power are two technologies that are predicted to play a significant role in meeting society's future energy demand. This chapter aims to provide a comprehensive overview of these two technologies, including their historical evolution, current trends, and position in the Norwegian political landscape. Lastly, the chapter outlines scientific research on how the two technologies couple with the dominant source of electricity in Norway today, hydropower.

3.1 An Introduction to Wind Power

Wind power exploitation dates to ancient civilizations, where wind-powered boats were utilized for transportation and windmills for grinding grain (Fanchi, 2005; Nesesian, 2010). The modern era of wind power started in the 1970s when the oil crisis sparked greater interest in alternative energy sources and rekindled the utilization of wind for power production (Nesesian, 2010). In the following decades, wind power technology saw significant advancements, and the industry grew rapidly, particularly in northern Europfe (Nesesian, 2010).

Modern, commercial, grid-connected wind turbines have evolved from small, simple machines to large, highly sophisticated devices (Edenhofer, et al., 2011). Modern wind turbines harness wind energy and convert it into electrical power by utilizing the aerodynamic force produced by rotor blades. The rotor blades are attached to a hub and main shaft, from which energy is transferred to a generator. The result of this conversion process is the generation of electrical power.

In recent years, the costs associated with wind power have experienced a significant decline, and advances in technology have rendered wind turbines more efficient and durable (Statkraft, n.d.). As a result, onshore wind power has become cost-competitive with fossil-based generation and emerged as one of the most rapidly expanding sources of renewable energy (Statkraft, n.d; Shukla, et al., 2022). Globally, installed wind capacity has increased by 70 % from 2015 to 2019. The increment in wind capacity and generation is presumed to be driven by policy, societal pressure to limit fossil generation, low-interest rates, and cost reductions (Shukla, et al., 2022).

3.1.1 Offshore wind power

In recent years, offshore wind has emerged as a promising area of growth in the electricity sector, with significant technological advancements being made. As a result, Europe's investments in offshore wind energy reached an all-time high in 2020, with €26,3bn committed to constructing 7,1 GW of new offshore wind farms. This investment followed the completion of 2,9 GW of offshore wind energy in Europe in the previous year, indicating an ongoing growth trend in this sector (Ramírez, Fraile, & Brindley, 2021). As a result, Europe's total offshore wind capacity reached 30

GW in 2022 (Hutchinson & Zhao, 2023), and the EU has set an ambitious goal of increasing this capacity to 300 GW by 2050 (European Commission, 2020).

Offshore wind turbines take advantage of the stronger and more consistent winds found at sea. Moreover, the size of commercial-scale offshore wind turbines has increased significantly, allowing for higher energy output and improved efficiency (Statkraft, n.d). Historically, offshore wind has required high investment costs, making the cost difference between offshore and onshore wind farms significant (Statnett, 2020). However, offshore wind has made considerable strides in terms of cost reduction, deployment scale-up, and improved performance (Shukla, et al., 2022).

There are two main types of offshore wind turbines, bottom-fixed and floating. Bottom-fixed turbines are anchored to the sea floor and are the most common type of offshore wind turbine in use today. Floating turbines, on the other hand, are designed to float attached to a buoyant structure. This design allows for greater location and water depth flexibility, making them suitable for deep-water environments. The different anchoring concepts are illustrated below in Figure 1.

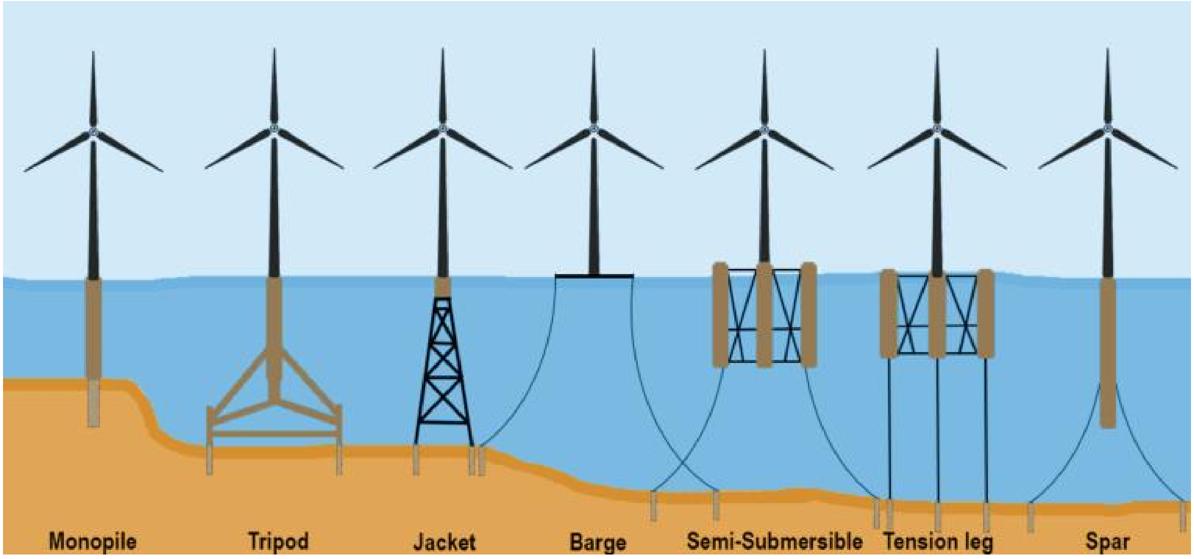

Figure 1 - Fixed and Floating Offshore Wind Turbines Concepts (Edenhofer, et al., 2011)

Since the first offshore wind farm was established in 1991 in Denmark, the development of offshore wind power has experienced significant growth, with the number of installed offshore wind turbines increasing globally. Advancements in offshore wind turbine technologies, such as floating turbines, are expected to increase the potential for large-scale energy production from offshore wind power. The cost of offshore wind energy exceeds that of onshore wind energy due, in part, to higher O&M costs and more expensive installation and support structures (Edenhofer et al., 2011). However, offshore wind power's predicted improved cost competitiveness is expected to increase the worldwide use of the technology.

3.1.2 Offshore wind power in Norway

Norway opened Sørlige Nordsjø II and Utsira Nord for offshore wind development in 2020. These projects could have the capacity to generate 3 GW and 1,5 GW of wind power, respectively, resulting in a combined potential of 4,5 GW (Ministry of Petroleum and Energy, 2022c; Statnett, 2022b). Utsira Nord, located west of Haugesund, is a 1,010 km^2 area suitable for implementing floating wind power. The second area, Sørlige Nordsjø II, spans 2,591 km^2 and borders the Danish sector in the North Sea. This region features depths that allow for the development of bottom-fixed wind projects. The location of the areas is illustrated in Figure 2.

The Norwegian government has established an ambitious target of commissioning up to 30 GW offshore wind capacity by 2040. To contextualize, the installed capacity in Norway for 2022 amounted to 39,4 GW. This indicates that the target for offshore wind commissioning almost equals 75 % of the total electricity capacity currently installed in Norway (Ministry of Petroleum and Energy, 2022c).

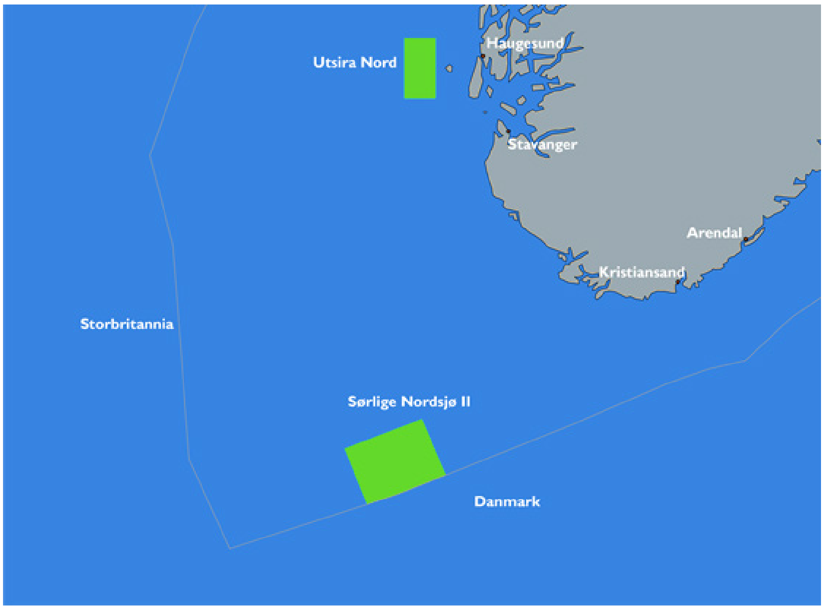

Figure 2 - Map Sørlige Nordsjø II and Utsira Nord (Norwegian Ministry of Petroleum and Energy)

The commissioning of the first phase of Sørlige Nordsjø II and Utsira Nord is planned for 2023, with a subsequent allocation of the areas during the year. The development of phase one of Sørlige Nordsjø II is planned to be allocated through auctions. For the Utsira Nord area, the government has proposed a departure from the traditional auction-based allocation model, opting for a qualitative criteria-based allocation process. The current Minister of Oil and Energy, Terje Aasland, emphasized that this approach will encourage innovation and technological progress in floating offshore wind, thereby reducing costs for the industry. Moreover, actors in the offshore wind industry consider the traditional auction model as an inadequate method for assigning areas for floating offshore wind projects, due to the high levels of uncertainty and the risks associated with technology and costs (Ministry of Petroleum and Energy, 2022b).

According to Oslo Economics (2022), a broad political agreement exists to invest in developing floating offshore wind in Norway. Floating offshore wind turbines are not limited by water depth, making them a more viable option for Norway's deep-water coastlines. However, the technology is still in its early stages and lacks established supply chains. Currently, the focus is on refining ideas and concepts and bringing them to the market, with an emphasis on learning and gaining experience through other projects. To achieve success, initial efforts must be directed towards technology development, innovation, and scaling to reduce costs and enhance competence within the supply chains (Ministry of Trade, Industry and Fisheries, 2022b).

The qualitative criteria-based allocation process coincides with an ambitious national strategy for offshore wind power. This strategy emphasizes the support of the Norwegian supplier industry, the implementation of an efficient legal framework, and the advancement of grid infrastructure on the Norwegian continental shelf (Ministry of Petroleum and Energy, 2022c). Notably, the planned 30 GW from offshore wind is too much for the Norwegian electricity grid to accommodate. Therefore, a significant portion of this power must be sold to other countries (Ministry of Petroleum and Energy, 2022c).

3.2 An Introduction to Nuclear Power

Nuclear power generates electricity using nuclear reactions, typically fission (Fanchi, 2005). Nuclear fission is a process by which the unstable nucleus of an atom is split into two or more smaller nuclei, releasing a large amount of energy in the form of light, heat, and kinetic energy (Fanchi, 2005). In traditional nuclear power plants, the heat generated from nuclear fission is utilized to heat water and create steam. This steam drives large turbines, producing electricity (Eidemüller, 2021).

The field of atomic charge, radiation and nuclear fission underwent significant developments from 1895 to 1945 and experienced a noticeable acceleration in the final six years, during which the primary objective was to produce the atomic bomb. After the end of World War II, greater attention was directed towards harnessing the energy of nuclear fission in a controlled manner for applications such as heating, transportation, and electricity generation (Eidemüller, 2021). In 1953, the Atoms for Peace Program foretold a future where commercial nuclear energy would be a clean, abundant, cheap, and safe energy source. Since the mid-1950s, the primary focus has been on the technological evolution of reliable and safe nuclear power plants (Fanchi, 2005; Nesesian, 2010).

From the late 1970s to the early 2000s, the nuclear power industry experienced a period of stagnation and decline. This decline could be attributed to the catastrophic events of the Three Mile Island Meltdown in 1979 and the Chernobyl Disaster in 1986. These incidents generated widespread public fear and scepticism towards the safety and security of nuclear energy, leading to decreased investments and development of the industry (Eidemüller, 2021; Nesesian, 2010). However, commissioning the first Generation III (GEN III) reactors in the late 1990s signalled the beginning of a global recovery in the industry. The graph in Figure 3 visualizes the number of nuclear reactors under construction from the 1950s to 2020.

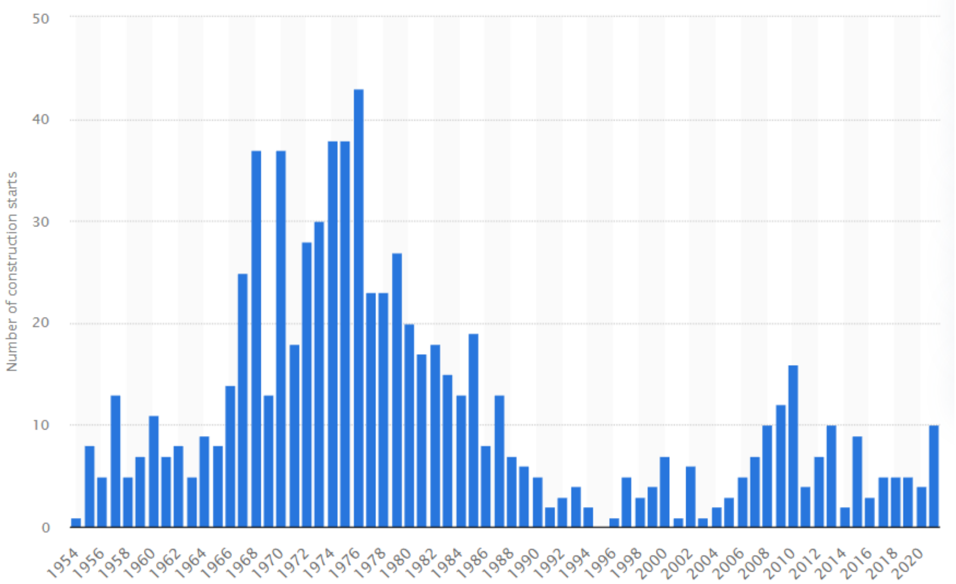

Figure 3 - Nuclear reactors under construction year by year (Statista, 2023)

Despite substantial technological advancements, most nuclear electricity comes from two types of reactors developed in the 1950s, the *Pressurised Water Reactor* (PWR) and *Boiling Water Reactor* (BWR). PWRs make up most of the nuclear electricity generation today. This type of reactor operates by maintaining water under pressure at over 300° C. The pressure ensures that the water is heated but does not boil. The heat from nuclear fission is used to produce steam in a secondary circuit, which drives the turbines to generate electricity (United States Nuclear Regulatory Commission, 2023 a). The BWR generates steam directly from the reactor (Nesesian, 2010). In this design, the steam from boiling the water drives the turbine, generating electricity (Nesesian, 2010; United States Nuclear Regulatory Commission,). The higher temperatures possible with the PWR design make it more thermally efficient than a BWR.

The operating temperatures of nuclear power bring a noteworthy potential to generate additional revenue by utilizing the excess thermal energy from their production process for heating purposes. This remarkable capability arises because it is impossible to transform 100 % of the power generated from the nuclear process into electricity (IAEA, 2002; Ma et al., 2019). By capturing and utilizing the excess energy produced, nuclear plants can provide low-carbon thermal energy for various heating needs, such as district heating systems, industrial processes, and desalination plants. This potential for utilization of residual energy not only enhances the overall applicability of nuclear power but also offers an opportunity to generate an additional revenue stream.

3.2.1 Third-generation reactors and SMRs

The advanced or GEN III reactors represent a considerable improvement to prior nuclear power designs. These modern reactors' more straightforward and robust design is less susceptible to operational disruptions and displays a lower risk of core meltdown incidents. Another noteworthy feature of GEN III reactors is a higher burn-up rate, which enables more efficient fuel utilization and a reduction of generated waste (World Nuclear Association, 2021b). Furthermore, this evolution of the nuclear power industry has led to the development of SMRs, which represent a departure from the traditional large-scale reactors in size and flexibility.

SMRs embody the latest advancements in reactor design, incorporating the simplicity, fuel efficiency, and safety features of GEN III reactors. SMRs typically have a power output capacity between 10 MW and 300 MW per unit and are designed to be manufactured in a factory and transported to the site for assembly (IEA, 2020). This modular approach could yield higher predictability and productivity rates, as well as reduced construction times and lower CAPEX (IEA, 2020).

In terms of dimensions, an SMR could be accommodated within the confines of a European football stadium (TWI, n.d.) and have the ability to be deployed in a variety of settings, including remote locations away from large grid systems (IEA, 2020). This feature expands the role of nuclear energy in decarbonizing the energy mix. It is especially relevant in power-intensive, inflexible industries and where low-carbon alternatives are scarce (IEA, 2020).

Despite notable advancements in validating initial designs, numerous obstacles remain. The successful completion of the prototypes in the late 2020s will therefore play a crucial role in showcasing the anticipated advantages of SMRs (IEA, 2020).

3.2.2 Nuclear power in Norway

The Norwegian government has, since the 1970s, decided not to pursue nuclear energy and has never had commercial power plants in operation. However, the Institute of Atomic Energy, now the *Institute of Energy Engineering* (IFE), was established in 1948 to research the peaceful utilization of nuclear energy (Hofstad, 2022). The nuclear research program has included the operation of several research reactors over the years. The IFE has planned, built, and operated four research reactors in collaboration with the Norwegian industry.

The first research reactor was operational in 1951. At that time, only Canada, the USA, the Soviet Union, Great Britain, and France had built reactors (Hofstad, 2022). In 1958, the Halden reactor was put into operation. This reactor was run as an international collaborative project, with assignments mainly related to the safety and certification of reactor facilities. These activities have contributed to building considerable Norwegian expertise in nuclear power technology (Hofstad, 2022; Energi21, 2022). However, the last Norwegian reactor was shut down in 2018, and the longstanding policy against the construction of commercial nuclear power plants remains unchanged, citing concerns about nuclear safety, waste management, and the proliferation of nuclear weapons.

However, SMRs have recently garnered heightened interest as a potential solution to the rising demand for clean, dependable, and cost-effective energy. This trend has also been observed in Norway, despite the country's historic negative political and public stance on nuclear power. A recent survey by Opinion[1] found that 51 % of respondents support developing nuclear power in Norway. On the other hand, 37 % of respondents disagreed with the idea, while the remaining participants were unsure or had no opinion on the matter (Opinion, 2023).

The interest has resulted in a public debate centred around the advantages and disadvantages of this technology and its role in the energy sector moving forward. Proponents cite its potential as a reliable energy source that can help meet the world's growing demand for electricity while reducing greenhouse gas emissions. However, opponents argue that nuclear power poses significant safety and environmental risks, including problems with waste management and a lack of expertise. They also argue that more sustainable and economically viable alternatives, such as offshore wind power, are available.

3.3 Coupling with Hydropower

As this thesis addresses offshore wind and nuclear power in a Norwegian context, discussing how these sources may couple with the existing system is essential. The Norwegian power system primarily relies on reservoir hydropower, resulting in a system that is more constrained by seasonality and annual variations rather than capacity limitations. Therefore, the capacity margin has traditionally been high (Söder, et al., 2020). The different characteristics of nuclear and offshore wind power diverge the suggested interplay between them and a hydropower-dominated system.

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[1] The survey was carried out in Opinion's community monitor, in a nationally representative sample of the population of 1,003 people in January 2023

The main benefit of adding wind power to a system is that it can reduce fuel costs and emissions as wind replaces fossil sources (Holttinen, et al., 2011). If not considering imports and exports, this is less relevant in Norway, which relies on 90 % hydro and 10 % wind. However, using flexible hydro systems with large water reservoirs for storage is likely the most efficient way to balance energy systems with higher shares of wind energy (Holttinen, et al., 2011). Furthermore, as energy security relies on reservoir inflow, wind power proves an additional energy source during dry spells. Moreover, wind speeds in Norway are highest during the winter, when influx may be problematic due to ice and snow (Söder, et al., 2020). Hence, wind power can reduce the need to spend reservoir water when this resource is limited. Thus, it can enhance supply security and the capacity margin in certain regions. However, due to variability, wind power also increases the need for regulating backup power from the national reserve market (Söder, et al., 2020).

In Finland, France, and the UK, enhancing national energy security while reducing emissions has been essential arguments to support the nation's development of the nuclear power industry (Teravainen, Lehtonen, & Martiskainen, 2011). Norwegian energy security is currently regarded as strong (Söder, et al., 2020). However, due to the increased electrification and growth in demand, Statnett estimates that Norway may be dependent upon electricity imports by 2027 (Statnett, 2022a). This implies that nuclear power may be a suited component of the future Norwegian energy mix.

Qvist Consulting (2022) simulated Sweden's optimal energy mix and found that 1/3 nuclear, 1/3 hydro and 1/3 wind power would achieve fossil-free production with the lowest total costs. However, when they considered a scenario of 100 % VRE, wind power was found to be the cheapest energy source. Nevertheless, this scenario was also the most variable one, requiring a significantly volatile balancing by hydropower. This balancing was discovered to be cheaper and more manageable if combined with nuclear power. Because nuclear power could cover some of the baseload, freeing the hydropower from dramatic shifts in production.

Current nuclear power practice revolves around operating the plants at baseload mode, delivering maximum capacity whenever online. However, GEN III reactors are designed for more flexible operation. Therefore, unlike traditional nuclear technology, all nuclear plants under construction in Europe from 2018 have flexible capabilities (Jenkins, et al., 2018). This is an essential trait for deployment in systems with high shares of VRE. Jenkins et al. (2018) found that in these systems, flexible nuclear power could lower the total system operating costs, significantly reduce the curtailment of VRE and increase revenues for nuclear plant owners compared to traditional operation practices. Furthermore, given the limited potential to develop the national hydropower industry, flexible nuclear power could be a viable zero-emission option if the share of VRE increases significantly.

4. LITERATURE REVIEW

The following chapter provides a comprehensive review of the existing literature on the topics addressed in this thesis. First, this chapter will outline the latest findings concerning the key cost drivers influencing the LCOE of offshore wind- and nuclear power. Secondly, it presents the literature exploring the energy sources' contributions to overall system costs, providing a comprehensive overview of the existing body of knowledge in this field.

4.1 LCOE Drivers

4.1.1 Offshore wind power

Lerch et al. (2018) explored the most critical drivers of the LCOE for different floating offshore wind farm concepts in France, Scotland, and the US. They found the six most influential factors to be: the discount rate, turbine costs, energy production, electrical losses in turbines, availability losses, and O&M costs (Lerch et al., 2018). This is consistent with the findings of Aldersey-Williams et al. (2019). They studied audited company data from UK wind farms and found that the discount rate significantly influenced LCOE (Aldersey-Williams et al., 2019). In a study examining different offshore wind concepts, Myhr et al. (2014) also found that the discount rate was most influential to the LCOE. They also found the capacity factor and the steel price to be the most important (Myhr et al. 2014).

Notably, Lerch et al. (2018) found that OPEX and turbine costs are the most influential variables of the LCOE that do not mediate the production output. The importance of OPEX is in accordance with the US *National Renewable Energy Laboratory* (NREL), which states that O&M costs, an essential component of total OPEX, generally contribute around 30 % of the LCOE for offshore wind plants (Maples et al. 2013).

Lerch et al. (2018) and Myhr et al. (2014) found that the economic life of offshore wind projects has only a minor influence on the LCOE. Both studies assume an economic life of 25 years and observe that extending this parameter to respectively 30 and 28 years only brings small reductions in the LCOE. One suggested reason behind the marginal improvement is that extending the lifetime would imply increased investments and OPEX (Aldersey-Williams et al., 2019). In addition, it prolongs the period the plant is exposed to damaging weather conditions, which may increase material deterioration (Myhr et al. 2014).

Summarized, there seems to be scientific agreement that discount rates are most crucial for the LCOE outcome. Additionally, components describing the production output, like availability losses, rate of degradation and capacity factor, seem important.

4.1.2 Nuclear power

Uncertain investment costs have been the leading cause behind the relatively small expansion of the nuclear energy industry in the last decade (MIT, 2018). The first-of-a-kind projects for conventional nuclear plants in Europe and the US have, on average, used twice the original estimates for construction costs and time (Stewart & Shirvan, 2022). One potential solution to the issue of unpredictability regarding construction is the implementation of SMRs. These smaller plants may experience a loss of economies of scale compared to traditional technologies, potentially leading to increased capital costs (Stewart & Shirvan, 2022). However, the benefits of minor constructions and standardization through modularization are expected to drive upfront costs down and offset the lack of scale (Testoni et al., 2021).

Asuega et al. (2023) performed a comparative economic analysis of different nuclear power concepts. Based on the American NuScale light water SMR, they found that the CAPEX was the most critical cost driver. Similar to those of conventional nuclear technology, contributing 37 % of the total LCOE. Financing costs were the second most important parameter, comparable to traditional technology, accounting for 25 % of the total LCOE (Asuega, Braden, & Quinn, 2023). These findings are in accordance with the literature review on SMRs by Testoni et al. (2021). Who investigated several microreactor designs and found that reactor size and capital costs were the most influential parameters on the LCOE (Testoni et al., 2021). Interestingly, Testoni (2021) also found that extending the economic life of nuclear plants reduced the LCOE significantly. However, the reduction was most prominent from 0 to 30 years. From 30 to 60 years, the average LCOE were almost constant with varying lifetimes (Testoni et al., 2021). This is likely due to the constant discount rate (Hagen, 2011), which considers the time value.

Fuel costs are one key factor distinguishing nuclear from wind power. In addition, costs related to safe storage and disposal of toxic waste must be considered. Evaluations of how much these expenditures affect the LCOE vary among different sources. For example, NVE estimates that a nuclear plant in Norway would achieve an LCOE of 65,58 ø/kWh and that fuel costs would make up 13 % of the costs (NVE, 2019). On the other hand, Energiforsk assumes that fuel costs in Sweden vary between 7,1 and 5,5 % of the total LCOE (Energiforsk, 2021). These moderate contributions to the LCOE are in accordance with the findings of Testoni et al. (2021). Whereas IEA suggests fuel costs equalling 35 and 31 % of the total LCOE in Sweden (IEA, 2020). Energiforsk also estimates the storage costs for used fuel to vary between 6,7, and 5,2 %.

In summary, the literature suggests that upfront investment and financing costs are the most important cost drivers for the LCOE. At the same time, economic life seems to be significant to a certain point. However, obtaining relevant studies on the field was hard, as SMR technology is not yet operating commercially on a large scale, and these hypotheses remain untested.

4.2 System Costs

The concept of system costs in the context of power system analysis has been around for several decades. However, it gained significant attention and recognition in the early 2010s when a wave of studies and reports introduced and conceptualized the concept (IEA 2011; NEA 2012; Hirth, Ueckerdt, & Edenhofer, 2015; MIT 2018; NEA 2019).

Literature and reports on system cost in the context of VRE integration are rather plentiful. These studies often compare costs under different VRE penetration levels. Contrary to the LCOE metric, system costs are heavily affected by the energy mix in as system. For instance, when the penetration rate of VRE rises, the project LCOE remains unchanged. However, the system costs in the grid are expected to experience an increase. (Idel, 2022). On the other hand, literature on system costs associated with integrating nuclear power into the grid is scarce. Due to this shortage, we intend to draw upon more general literature in our subsequent efforts to discuss the system costs of nuclear power technologies in Chapter 6.

4.2.1 Balancing costs

Balancing costs and wind power

Relevant studies on the impact of offshore wind on balancing costs are hard to obtain. This thesis, therefore, assumes that integrating offshore wind power will yield similar results as general onshore wind power. This is because we expect the variability and intermittency associated with wind power to be equal, and this is an essential driver of balancing costs. Ueckerdt et al. (2013, p. 65) states, *"Balancing costs occur because VRE supply is uncertain. Day-ahead forecast errors and short-term variability of VRE cause intra-day adjustments of dispatchable power plants and require operating reserves that respond within minutes to seconds".*

Several studies[2] have analysed the costs of maintaining balance with increased penetration of VRE sources in general and wind power in particular. For example, Ueckerdt et al. (2013) compare balancing cost assessments from multiple sources covering different wind power penetration levels. Despite some variation in the results, a consistent pattern can be observed. As wind power penetration rises from 5 % to 30 %, balancing costs are estimated to increase from around 2 to 4 €/MWh (Ueckerdt et al. 2013). The findings are consistent with a study conducted by Holttinen et al. (2011). Their research examined the projected increase in balancing and operating costs caused by higher levels of wind power. The results indicated that when wind power accounted for up to 20 % of the

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[2] An overview of literature on balancing cost is listed in the Appendix A.

total supply the additional operating costs resulting from wind power's variability and unpredictability were between 1 and 4 €/MWh.

The UK Energy Research Centre published a report stating that at a 30 % renewable penetration level, balancing costs amounted to approximately £5/MWh. However, the existing number of studies is limited when considering a higher penetration level, and estimates vary more broadly. For instance, their data suggest that at a 50 % penetration rate, balancing costs range from £15 to £45/MWh. The lower values are based on integrating intermittent renewable sources into a flexible electricity system, while the higher values are due to assumptions of less flexible systems (Heptonstall, Gross, & Steiner, 2017).

Balancing costs and nuclear power

Wind power is not a power system's only source of variability and uncertainty. Fluctuations in demand, unscheduled equipment unavailability, environmental incidents, and weather phenomena will add their shares to the total aggregated variability (IEA, 2021b).

While GEN III nuclear power plants have a certain degree of flexibility in adjusting short-term output, their primary design objective remains to provide baseload power to the system (Teirilä, 2020). Nevertheless, SMRs are notably more flexible than traditional power plants (Chatzis, 2019) and can address fluctuations in the power system caused by intermittent energy sources (NEA, 2011). Keppler and Cometto (2020) argue that if nuclear power is introduced in a system with high VRE penetration, the nuclear plants will experience frequent episodes of steep ramping to balance grid fluctuations. This stresses technical structures, challenges system operations, and requires careful management and operations of nuclear plants, often resulting in higher operating costs (NEA, 2011). The costs associated with balancing nuclear power can differ significantly depending on the unique attributes of each nuclear facility and the electricity grid to which it is connected.

Using SMRs to balance fluctuations in the grid would require careful coordination and planning between nuclear and renewable energy sources and appropriate regulatory frameworks and market mechanisms to incentivize the provision of operating reserves. Even though it requires a complex and holistic approach, a market study conducted in 2014 found that integrating SMRs with other energy sources, particularly renewable sources, could potentially improve the stability and security of the power grid (Scully Capital Services Inc, 2014).

4.2.2 Adequacy costs

Adequacy costs and offshore wind power

As the proportion of variable renewable energy generation within the electrical grid increases, evaluating and ensuring the adequacy of electricity generation capacity becomes increasingly important and challenging (Almutairi, Ahmed, & Salama, 2015; Söder, et al., 2020).

Because offshore wind is an intermittent energy source depending on weather patterns, its contribution to overall system adequacy is less predictable than that of conventional energy sources. Wind power plants tend to have lower capacity factors compared to traditional power plants (Söder, et al., 2020), usually ranging from 30 to 54 % (IEA, 2020). Research conducted by Leahy and Foley (2012) suggests that the capacity factor of wind power is susceptible to the occurrence and frequency of extreme weather events, potentially affecting its overall performance. Moreover, Gilotte (2011) highlights that extended periods of low wind can significantly impact the capacity factor, posing a risk of power outages. These findings emphasize that depending solely on periods with high wind availability is inadequate for mitigating the increased risk of power outages during periods with low wind. This underscores the necessity for implementing additional measures to guarantee the stability and reliability of the electricity grid.

On the other hand, a study conducted by Tande and Korpås (2012) found that adding wind power to a hydro-based system could enhance system adequacy and contribute to the overall generation capacity. However, it is essential to highlight that the successful integration of wind power into an electricity grid also hinges upon factors such as interconnectivity and exchange capacity (Tande & Korpås, 2012). Denmark, which currently has the world's largest share of wind power, has increased the proportion of wind power in its power system without compromising the security of supply. In part due to its significant exchange capacity relative to consumption Söder et al. (2020).

Adequacy costs and nuclear power

Nuclear power plants are generally designed for long-term, continuous, and dependable operation, and under normal operating circumstances, they are anticipated to have a capacity factor surpassing 90 %. The capacity factor does not encompass planned outages (Jinyuan & Yong, 2016). Planned outages are scheduled shutdowns of nuclear reactors for routine maintenance, repair, and refuelling. These outages are typically scheduled well in advance to coincide with periods of low electricity demand to minimize the impact on the grid.

Nevertheless, planned outages can last several weeks or months, depending on the work required. The duration of the outage can have a significant impact on the availability and cost of electricity. Hence, the World Nuclear Association states that nuclear adequacy cost relates mainly to the need for reserve capacity to cover periodic outages, whether planned or unplanned (World Nuclear Association, 2022).

Researchers are also exploring more flexible SMRs, and the possible benefits of nuclear flexibility in power system operation with renewable energy (Jenkins, et al., 2018). As previously mentioned, SMRs can reduce and increase their output, providing frequency regulation and valuable operating reserves. This strategy could potentially reduce overall adequacy costs in the power system. In addition, the operating reserves provided by nuclear plants could help stabilize the variability of renewable energy sources and thus maintain grid stability during high-demand periods.

4.2.3 Grid costs

Grid costs and wind power

Up-to-date figures on transmission and grid reinforcement costs due to wind generation are limited. However, a rise in transmission congestion has been observed in regions of the United States with high VRE penetrations (Chakroun et al., 2021). This issue has resulted in elevated interconnection costs, leading to the abandonment of numerous renewable energy projects in the development pipeline (Chakroun et al. 2021). This observation is supported by findings by Holttinen et al. (2011), whose results are that grid-related costs increased when implementing a higher penetration of VRE. In addition, Ueckerdt et al. (2013) also assume a significant increase in grid costs with raising the VRE share.

Wind power development incurs substantially high grid costs because windy areas are frequently situated at a considerable distance from demand centres, characterized by weak or even non-existent grid infrastructure (Weißensteiner, Haas, & Auer, 2011; Hirth, Ueckerdt, & Edenhofer, 2015). This is particularly true for offshore wind, where offshore substations and export cables typically make up some 20-25 % of the total cost of energy (Ørsted, 2019). In addition, the distance from land, the sea depth, and the potential need for an offshore substation will affect the network facilities' costs and choice of technology (Nybø, Winsnes, & Ljønes, 2023).

Grid costs and nuclear power

Integrating nuclear power or SMRs into an existing grid will also incur costs related to the transmission and distribution infrastructure needed to transport the energy. Furthermore, additional expenses associated with upgrading the grid to accommodate the increased power supply from nuclear sources and ensuring the security of nuclear facilities might also be necessary.

However, SMRs may offer a more cost-effective solution than traditional large-scale nuclear plants, as they require less infrastructure due to the smaller scale of power generation. In addition, the SMR can be strategically located in areas where infrastructure limitations or spatial constraints prohibit the deployment of large-scale facilities (Scully Capital Services Inc, 2014). Therefore, SMRs are especially applicable in remote locations, smaller electrical markets, smaller grids, and scenarios with restrictions on acreage availability or specific industrial applications. In this manner, SMRs offer the possibility of bringing power generation closer to demand centres (Scully Capital Services Inc, 2014).

5. METHODOLOGY

This chapter will present the methodology used to address the research question:

"How can the variability of input variables and scope of analysis impact the results of profitability calculations for nuclear and offshore wind power in the Norwegian power market?"

The chapter will first state the research objective and discuss the choice of research subjects representing the different technologies. Consequently, it will provide an overview of the data collection process for the LCOE and balancing cost analyses, specifically emphasising the data processing and modelling approach.

5.1 Research Objective

Understanding the factors that affect profitability calculations is critical for decision-making in the energy sector. It can provide insights into the essential cost factors and the viability of different energy sources and is crucial information for investment decisions and policymakers. Hence, this study aims to be a contribution in that direction. Furthermore, the findings from this research could be useful in enhancing knowledge about the financial side of sustainable and profitable energy production. Finally, this research is particularly important because of the limited relevant literature on nuclear and offshore wind power in the Norwegian system.

5.2 Research Subjects

This thesis focuses on comparing offshore wind power and SMRs as potential sources of sustainable energy in Norway. In our study on offshore wind, we focused our investigation on Sørlige Nordsjø II and Utsira Nord. We selected these projects because they have progressed the most within bottom-fixed and floating wind. As a result, there is readily available data from trustworthy sources on the estimated costs.

For our research on nuclear power, we consulted Norwegian industry experts from Norsk Kjernekraft AS and NTNU. They advised us to focus our research on SMRs as this is a more likely concept for implementation in Norway than conventional nuclear technology. In addition, we were advised to use the BWRX-300 concept made by GE Hitachi[3] in our models, as this is one of the most mature SMR concepts on the market. This involves that there exist reputable cost estimations for the concept. Hence, it proves a suited modelling case.

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[3] Norsk Kjernekraft AS announced in March (2023a) that they have signed a non-binding agreement with Rolls Royce SMR Limited. This agreement explores potential projects for the deployment of Rolls-Royce's SMR.

The system cost analysis has explored imbalance volume data from Norway and Finland. In addition, Swedish data on activated frequency reserves have been used to broaden the study. Our research focuses on the relationship between the abovementioned variables and the penetration level of wind and nuclear power. Imbalance volumes and activated frequency reserves affect balancing costs because more extensive imbalances require added corrective actions to maintain the frequency between 49,9 and 50,1 Hz.

5.3 Data Collection and Processing

Data collection is critical to any research project, as it provides the raw material necessary for analysis and interpretation. This data collection process predominantly involved obtaining access to secondary data sources collected initially by third parties for other purposes (Saunders, Lewis, and Thornhill, 2015). Further, the availability of reports and other documentation related to the energy sector will supplement our research and enhance the overall validity of our findings. The following section will provide an overview of the data collection methods employed in this study and a detailed description of the data sources used.

5.3.1 LCOE

Access to cost component data was necessary for constructing the LCOE analysis for the projects. In the cases of offshore wind, NVE provided a dataset with essential information, including a detailed overview of the input data used to estimate the LCOE between 2021 and 2030. These estimates, updated in 2021, were crucial to the governmental report by the Ministry of Petroleum and Energy (The Royal Ministry of Petroleum and Energy, 2021). The dataset specified cost estimates for 2021 and projected estimates for 2030. As the evaluated projects lie in the future, our models used the 2030 cost-level estimations as the base case. The 2030 OPEX was also projected with two different discount rates of 4 and 6 % in the data. We based our model on the 4 % rate, as the government reports and NVE publications seem to be based on these figures.

In addition to cost, the data approximated 2030 project specifications like capacity factor, economic life, and construction time. These variables were also essential to our base case model. However, it is important to note that projections around offshore wind technology vary among different sources, especially concerning economic life and capacity factors. For instance, IEA estimates the capacity factor of offshore wind to range between 30 and 52 %, depending on location and other factors (IEA, 2020).

Notably, NVE also provides similar estimates for nuclear power (NVE, 2019). However, these rely on older input data for traditional large-scale nuclear technology. Hence, we decided to seek out other sources of information on this topic. Reliable cost estimations for OPEX were retrieved from a report on future needs for the Swedish energy industry by a consortium of different actors (Energiforsk, 2021). Due to Norway and Sweden's geographic and economic similarities, we assume these costs to represent a Norwegian context.

The OPEX data is based on conventional nuclear technologies and not SMRs. However, the costs are measured in SEK/MWh. Therefore, we assume that a reduction in produced MWhs due to the smaller capacity of an SMR corresponds to a similar decrease in yearly OPEX. Consequently, we assume that the OPEX from Energiforsk is viable input for our analysis of an SMR. We presume the O&M costs per MWh under the total OPEX to be 60 % higher than the estimates of Energiforsk. This is consistent with research by Asuega et al. (2023) which suggests that the lack of scale, compared to conventional plants, could lead to ca. 60 % higher O&M costs per MWh for SMRs.

Notably, the OPEX data for the nuclear project contains cost estimates for waste management and decommissioning. Waste management costs are related to the safe handling of the spent fuel. Decommissioning costs are associated with a secure deconstruction of the plant after its operating life, aiming to restore the area appropriately. We do not possess decommissioning costs for offshore wind. This weakness in our data and analysis is anticipated to be of marginal influence on the LCOE.

Appendix C illustrates that our cost data on offshore wind involves estimates for internal and external grid costs. These are related to the transportation of the produced electricity offshore to the energy grid onshore. This is particularly relevant for offshore wind situated far from the demand centres. Similar grid costs are not explicitly accounted for in our SMR estimations and could be a weakness in our study. However, due to the ability of SMRs to be placed closer to demand centres, these expenses would be significantly lower than those of offshore wind.

We found data on the CAPEX for the SMR project in the *Advanced Reactor Information System* (ARIS) database by *International Atomic Energy Agency* (IAEA). This database contains up-to-date information on all available nuclear power plant designs. IAEA reviews all the design descriptions to enhance quality and remove overly commercial statements. We also gathered project information like capacity factor, economic life, and construction time from ARIS. Notably, ARIS assumes CAPEX to be 1 billion USD for the first reactor, decreasing to 700 million USD when significant experience is gained. In this case, we consider an investment cost of 850 million USD. We find this reasonable, as Norway will likely not order the first reactor of its kind. However, cost levels are generally high in the country, meaning the lower ends of the cost interval also seem unlikely. We assume a 6 % discount rate for the SMR project, represented by a BWRX-300. The 6 % discount rate is proposed as the BWRX-300 is an early-stage technology and could pose a larger risk than the wind projects, especially fixed offshore wind.

To conduct the analysis, we have made several assumptions. Firstly, we assume an average yearly inflation of 3 % and an annual degradation rate of 2 %. Furthermore, regarding currencies relevant to the BWRX-300 estimations, we have assumed USD/NOK to be 10,00 and SEK/NOK to be 1,00. These assumptions exceed the 2013-2022 average of USD/NOK of 8,15 and SEK/NOK of 0,957 (DNB Markets, 2023). However, they are lower than April 2023 of USD/NOK 10,50 and SEK/NOK 101,71.

Lastly, we have made one assumption regarding construction time. We have added one year to the wind projects' construction time and one and a half years to the nuclear project. This is because the estimations in our data are very moderate, while the technologies are fairly new. Additionally, this simplification enables calculating with rounded numbers. In addition, we assumed all CAPEX to occur in year zero. This is a necessary simplification as we do not possess data on how these may be distributed throughout the construction time. Below in Table 1, the LCOE input data are summarized.

Table 1 - Base case project data for Sørlige Nordsjø II, Utsira Nord, and a BWRX-300

	Unit	**Sørlige Nordsjø II**	**Utsira Nord**	**BWRX-300**
Installed effect	MW	1400	1400	300
Capacity factor	%	56	51	95
Discount rate	%	4	4	6
Economic life	Years	30	30	60
Construction time	Years	4	4	4
Long-term avg. inflation	%	3	3	3
Yearly rate of degradation	%	0,2	0,2	0,2
Total OPEX	NOK/kW/year	707	1001	1840
Total CAPEX	NOK/kW	31 109	35 554	28 333

The total OPEX and CAPEX listed consist of several elements contributing to the total sum in Table 1. For the SMR, we only have data on the total CAPEX sum. However, we have data on the elements contributing to the total on the OPEX side. The different cost components contributing to the figures used in our calculations can be found in Appendix B and C.

5.3.2 Balancing costs

The balancing cost analysis is based primarily on data from two different sources. eSett supports a public data portal containing Nordic imbalance settlement data. Norwegian and Finnish data on imbalance purchase and sales volumes were derived from this source to study the relationships between grid imbalance and integrating different energy sources.

The imbalance purchase volume and imbalance sales volume data are utilized to capture the deviations between the scheduled and actual energy flows in the transmission system during a specific period. For example, when a BRP consumes and sells more electricity than it has produced and purchased, there is a deficit in the imbalance. In this case, BRPs can buy imbalance energy from the TSO to cover the deficit. On the other hand, if the BRP produces and purchases more electricity than it has consumed and sold, there is a surplus in the imbalance. BRPs can then sell the imbalance energy to the TSO to take care of the surplus.

Due to the absence of Swedish data on imbalance purchase and sales volumes[4], data on activated frequency reserves was collected through the Swedish platform Mimer. Mimer provides structure and settlement data for Swedish electricity market participants.

The reserve capacity is distinguished between primary-, secondary-, tertiary-, and fast reserves. Although they differ in purpose and characteristics, all the reserves aim to ensure a continuous balance of the power system (Statnett, 2023). In situations where the power system's frequency experiences a shift, the initial response is undertaken by fast reserves, commonly referred to as *Fast Frequency Reserves* (FFR). The FFR aim to slow down the frequency change. Subsequently, primary reserves, also known as *Frequency Containment Reserves* (FCR), intervene to arrest the frequency change and restore it to a stable level. The *automatic Frequency Restoration Reserves* (aFRR) then come into play to return the frequency to its normal range, following which manual *Frequency Restoration Reserves* (mFRR) are employed to maintain equilibrium in the system until a new balance is achieved in the power market (Statnett, 2023). The frequency reserve data used in the model consists of volumes of aFRR down/up, FCR down/up and FFR. The correction of imbalances using the different types of reserves is illustrated in Figure 4.

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[4] The reporting of Swedish data on balancing capacity settlement will be transferred to eSett in Q3/2023.

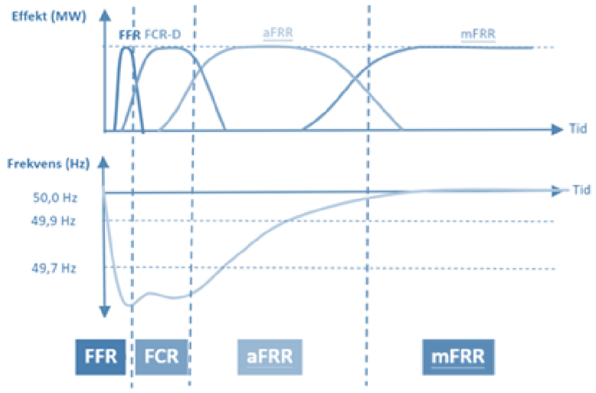

Figure 4 - Illustration of imbalance correction utilizing frequency reserves (Statnett, 2023)

Several assumptions and simplifications have been made during the data collection process. Firstly, it is assumed that the broader category of general wind production can represent the impact of offshore wind power. This assumption is founded on the fact that offshore and onshore wind power are forms of VRE. As we are studying relationships where the variability of an energy source is of particular interest, using general wind production data as a substitute for missing offshore wind data will provide valuable insights.

Secondly, we assume Swedish and Finnish data is transferable to Norwegian contexts. While there may be some differences between the regions' electricity grids, such as the types of power plants and the overall grid structure, the basic principles and occurrence of system cost are likely to be similar in the countries. Therefore, by utilizing Swedish and Finnish data, which is readily available, the analysis can provide valuable insights into the potential impact of nuclear power on system imbalance.

Pre-processing of data balancing costs analysis

The collected data were processed in the programming language Python. Various data pre-processing techniques, such as data cleaning and type transformation, were conducted to ensure accuracy and completeness. In addition, rows with missing values were removed to prevent errors in the mathematical computations and statistical modelling. Additionally, aggregations by bidding areas were made to allow the merging of datasets, and variables were rescaled through a normalization process. Rescaling the variables in a dataset is a technique that can be utilized when the independent variables have different measurement units and ranges, which can result in difficulties when interpreting the regression coefficients. Normalization allows for meaningful comparisons of the magnitudes of the coefficients, as the variables are established on the same scale.

Implementing a single price model in the Nordic countries in 2021 has led to a change in the reporting of imbalance volume data. Previously, the data was reported as four distinct values, including imbalance purchase and sales volumes for both consumption and production. However, due to the implementation of the single price model, eSett simply reports "*imbalance sales volume*" and "*imbalance purchase volume*". To extend the scope of the regressions, imbalance purchase volumes and imbalance sales volumes, both consumption and production, were combined to obtain total imbalance purchase and sales volume, allowing us to merge data from the periods before and after the change in pricing models. The activated frequency reserves data obtained from Mimer underwent a similar pre-processing to the abovementioned eSett data. As the goal was to obtain the total amount of activated reserves regardless of direction, the absolute value of the reserves was added together.

The final datasets for Norway, Finland and Sweden contain hourly imbalance data from 2020 to 2023, resulting in 28343 rows for each country. In addition, the dataset includes data on activated frequency reserves.

5.4 Data Analysis

This subchapter will describe the methodology employed for conducting data analyses. First, we investigate the LCOE for the chosen projects. This is done by initially calculating the metric using our base case input variables in **Error! Reference source not found.**Subsequently, uncertainties are p rescribed to the variables, and Monte Carlo simulations are performed on the calculation. This provides the opportunity to do a regression analysis on the variables, investigating which factors impact the LCOE outcome the most. Lastly, we explore how balancing costs are related to the different technologies in the projects. This is achieved through running several regression analyses on the relationship between the penetration rate of the different energy sources and imbalance metrics.

5.4.1 LCOE

Base case LCOE

To calculate our LCOE base case estimate for the different projects, we used Excel to produce a cash flow spreadsheet of the annual expenditures and production for the projects over their economic life. This was beneficial in measuring the impact of economic life and construction time. The spreadsheet format also allowed for easy local assessments of how altering one variable changed the LCOE output.

Monte Carlo simulation and regression analysis

This thesis aims to investigate how the input variables may affect the outcome of profitability calculations for power projects. To address this further, we performed sensitivity analyses through

Monte Carlo simulations. A sensitivity analysis is a crucial tool employed in decision-making and modelling, aimed at examining the impact of alterations to specific variables on the outcome of a particular model, simulation, or calculation. It comprehensively explores how modifications to one or more input variables affect the result. In this thesis, we have analysed how the LCOE depends on variations in the input variables: capacity factor, discount rate, economic life, construction time, CAPEX, annual OPEX, and yearly average degradation rate.

To examine how variations in the mentioned variables impact the LCOE, we ran Monte Carlo simulations on our LCOE models. A Monte Carlo simulation is a method to estimate the probability distribution of a process, in this case, the LCOE metric. This is achieved by prescribing a probability distribution to the different variables affecting the outcome and then performing many samples of the calculation. Repeating this process numerous times will attain data that can be further assessed for statistical purposes. A Monte Carlo simulation is a valuable supplement to an LCOE calculation with considerable uncertainty related to several input variables. The method allows for modelling this uncertainty and generating extensive data on the subject, facilitating deeper investigations and enhanced decision-making. This method's weakness is that the choice of the probability distribution for the different variables may affect the simulation results. Therefore, it is essential to select these with consideration. Despite the advantages of supplementing LCOE calculations with a Monte Carlo simulation, its use in literature is limited.

We have used qualitative assessments of each variable to prescribe probability distributions to the different inputs. For example, price fluctuations may affect CAPEX and OPEX significantly. As prices fluctuate positively or negatively, we have used a normal distribution for these costs, with a 20 % standard deviation. A normal distribution has also been used for the capacity factor of wind, where it seems likely that it could vary around a base case. However, other input factors do not seem likely to alter positively and negatively around a basis. Therefore, a triangular distribution is assigned to these variables. This allows setting a minimum and maximum value for variations to occur in between. One example of this is estimated construction time. For complex infrastructure like power plants, this estimate is often overrun and seldom underrun. Therefore, we have used the construction time from the raw data plus one year as our base case, with the original values as the minimum. For the maximum value, we have used twice the basis. Table 2 displays an overview of the variables and their probability distributions.

Table 2 – Overview of selected probability distributions for project data on offshore wind and a BWRX-300

	Probability distribution	**Minimum Value**	**Maximum Value**	**Standard deviation**
Capacity factor (wind)	Normal	-	-	4 percentage points
Capacity factor (nuclear)	Triangular	85 %	95 %	-
Discount rate (wind)	Triangular	3 %	8 %	-
Discount rate (nuclear)	Triangular	4 %	8 %	-
Economic life	Normal	-	-	1/6 of basis
Construction time	Triangular	3 years	7 years	-
Long-term avg. inflation	Constant	3 %	3 %	-
Yearly rate of degradation	Triangular	0,2 %	0,6 %	-
Total OPEX	Normal	-	-	20 % of basis
Total CAPEX	Normal	-	-	20 % of basis
Turbine costs	Normal	-	-	20 % of basis

After deciding on the above-listed distributions, we ran 10 000 simulations on the LCOE and the corresponding variables for the different projects. This was achieved using the built-in what-if analysis function in Excel. Furthermore, we standardized the variables as this allows studying the relative impact the variables have on the dependent LCOE outcome. Then, we used the data generated from these operations to run a multilinear regression analysis on the relationship between the LCOE output and the standardized variables. Again, this was accomplished using the regression function in the Excel Analysis Toolpak, which uses the *Ordinary Least Squares* (OLS) method to address how strongly each input affects the outcome.

An OLS regression is a statistical method that estimates the relationship between the dependent and independent variables by minimizing the sum of the squared differences between the observed and predicted values of the dependent variable, which is modelled as a straight line (Zdaniuk, 2014). By fitting the best possible line to the data, the OLS regression method provides a valuable tool for analysing the relationship between variables and identifying patterns in the data. The models' performances are evaluated using a variety of statistical metrics, such as adjusted R-squared and p-values. These metrics provide insight into how well the model fits the data and whether the independent variables are statistically significant. The results will be further discussed in Chapter 6.

5.4.2 Balancing Costs

To analyse balancing costs, we again used an OLS regression to model the relationship between the dependent variables, imbalance volume and activated frequency reserves, and independent variables of wind power and nuclear power penetration levels. This choice of methodology was motivated by its ability to uncover meaningful insights regarding the relationship between these variables. Furthermore, by leveraging data on both imbalance volume and activated frequency reserves, which reflect the balancing requirements of the system, we established a solid basis for the analysis. Data from Norway, Finland and Sweden are used in the analysis, and the multi-country approach enabled us to capture variations and similarities in the impact of wind power and nuclear power penetration on the balancing needs of different power systems. As a result, the approach yielded insights regarding the effects of wind power and nuclear power penetration on system balancing dynamics.

Furthermore, the thesis presents scatterplots with regression lines that illustrate the relationship between imbalance volume and wind power or nuclear power penetration levels. The use of visualizations is beneficial in presenting complex data in a concise and easily interpretable manner, which aids in identifying patterns and relationships between variables. We randomly sampled 140 data points for the visualisations to ensure a clear and representative view of the relationship between the variables. By reducing the number of data points, the visualizations become less cluttered and easier to interpret.

6. RESULTS

This chapter will first present and discuss the estimated baseline LCOE values for Sørlige Nordsjø II, Utsira Nord and a potential BWRX-300 project. Then, descriptive statistics of the Monte Carlo simulation results will be provided. Moreover, the regression results, which assess the influence of each variable on the LCOE outcome from the simulations, will be presented and discussed in alignment with the studies cited in Chapter 4. Lastly, the regression results on balancing costs will be presented and explored in light of the literature review. The regression analysis studies the relationship between wind- and nuclear power penetration levels, imbalance volumes, and activated frequency reserves. All regression result tables are found in Appendix D.

6.1 LCOE Analysis

6.1.1 Base case analysis

Running the LCOE calculations using our baseline data presented in Table 1 gives us the following LCOE values for the investigated energy projects.

Table 3 - Results of LCOE base case analysis

	Sørlige Nordsjø II	**Utsira Nord**	**BWRX-300**
LCOE øre/kWh	66,37	90,53	69,26

Table 3 shows a considerable price difference between the bottom fixed Sørlige Nordsjø II and the floating Utsira Nord project. Several factors could explain this difference. Firstly, the investment costs for Utsira Nord are higher for every cost component except the internal and external grid costs. The differences in these costs are due to the geographical location of the projects, where Sørlige Nordsjø II are notably more remote from existing infrastructure than Utsira Nord. For all other investment costs, Utsira Nord is more expensive. This is likely due to Utsira Nord being a pioneer project using relatively untested technology. This is also visible in its estimated yearly OPEX, where the operating costs for Utsira Nord again are extensively higher than those of Sørlige Nordsjø II. Lastly, the assumed capacity factor is higher for the Sørlige Nordsjø II, resulting in more production hours to account for the different project's costs.

Interestingly, the SMR project has an LCOE close to Sørlige Nordsjø II in the base case analysis. However, this project has a cost structure and delivery profile vastly different from the other two.

Therefore, the utility of using this as a comparison is limited. The installed effect of the project is modelled to be 300 MW, substantially lower than the other two of 1400 MW. However, the BWRX-300 is estimated to have a capacity factor of 95 %, meaning considerably more operating hours in a year.

Additionally, the SMR has twice the estimated economic life of wind projects. In isolation, this is of limited significance to the LCOE as the constant discount rate values the production output during the earlier years greater than those later. This is visible when conducting a local, isolated sensitivity analysis modifying only the economic life. Increasing this to 70 years only equals a 0,49 reduction in LCOE output to 68,67 øre/kWh. However, limiting the economic life to 50 years equals a smaller LCOE of 67,67 øre/kWh. Hence, the impact of economic life has a non-linear shape. This is likely due to the effects of OPEX and inflation. The OPEX relative to the production output is substantially higher for the SMR than for the wind projects. These expenditures will gradually elevate due to inflation throughout the project's lifetime.

Performing the same sensitivity analysis for wind power yields similar results. When the economic life is extended to 50 years while keeping all other variables constant, the LCOE for the wind projects experiences minimal changes. Specifically, Utsira Nord achieves a new LCOE of 89,43 øre/kWh, while Sørlige Nordsjø II gets a value of 64,14 øre/kWh. Thus, the impact of project lifespan on the LCOE is negligible also for offshore wind projects.

Given that the SMR has twice the economic life of the wind project, the inflation factor will impact the cost side of the equation considerably more than for the wind projects. However, increased OPEX due to inflation will likely coincide with elevated resale electricity prices. Therefore, the inflation effect on profitability is only nominal. Hence, inflation is held constant in the Monte Carlo simulations. Otherwise, results become hard to interpret. Lastly, it is essential to note that companies often secure against inflation by locking their prices for extended periods, which could affect profitability. However, obtaining this in longer terms, like 30 to 60 years, seems unrealistic and is therefore unaccounted for in our analysis.

6.1.2 Monte Carlo regression results

Running 10 000 simulations provides more extensive data on the uncertainties involved in the LCOE estimate. Table 4 displays a summary of descriptive statistics for each project's simulations. The table also illustrates the probability of achieving an LCOE above 66 øre/kWh with our assumed input and probability distributions. This is interesting as 66 øre/kWh is the electricity price that the Ministry of Petroleum and Energy suggests as the reservation price that the government guarantees to auction winners for the development of Sørlige Nordsjø II (Ministry of Petroleum and Energy, 2023). Our analysis indicates that it is unlikely for any of the explored projects to achieve LCOE values below this reservation price.

Notably, running 10 000 simulations makes Sørlige Nordsjø II and the SMR switch place in the ranked order of lowest LCOE. This seems to be due to a broader variability for Sørlige Nordsjø II, as this project has the lowest 5th and highest 95th percentile of the two.

Table 4 - Descriptive statistics Monte Carlo simulations results

	Sørlige Nordsjø II	**Utsira Nord**	**BWRX-300**
Mean LCOE (ø/kWh)	77,27	104,81	74,75
5th Percentile LCOE (ø/kWh)	58,75	79,86	60,45
95th Percentile LCOE (ø/kWh)	100,54	134,98	89,64
Probability of LCOE > 66 øre/kWh	81,55 %	99,87 %	84,24 %

To gain insights into what causes this effect, we have studied the regression results, measuring the impact of the variables on the LCOE outcome. The coefficient for each normalized variable is presented in Table 5, Table 6 and Table 7. These represent the impact of each variable relative to the others. The plus and minus signify if increasing the variable is linked to a higher or lower LCOE. All the variables were found to be significant on a 5 % level.

Regression results offshore wind

Table 5 - Regression coefficients Sørlige Nordsjø II ranked from most to least influential.

	Sørlige Nordsjø II	
Order	**Variable**	**Coefficient**
1.	Discount rate	7,74
2.	Capacity factor	(-5,53)
3.	CAPEX	5,03
4.	OPEX	4,79
5.	Economic life	(-2,95)
6.	Construction time	2,72
7.	Degradation rate	0,78

The regression analysis results for Sørlige Nordsjø II indicate that the LCOE is primarily affected by two key parameters: the discount rate and capacity factor. This seems natural as the discount rate influences all future costs. While enhancing the production hours and capacity factor by one unit intuitively should equal a corresponding increase in production. These findings align with Myhr et al. (2014), who identified these two variables as the most influential factors. Other studies, such as Williams et al. (2014) and Lerch et al. (2018), also found the discount rate to be the most crucial parameter for offshore wind project profitability. Lerch's (2018) study does not explicitly research the capacity factor, but several related measures are listed among the top contributors to LCOE, such as energy production and availability loss. The third most significant parameter studying Sørlige Nordsjø II was CAPEX, followed by OPEX. These results are consistent with previous research, where Myhr et al. (2014) identified steel prices as the third most influential parameter. Steel prices will, due to construction, be closely related to CAPEX.

Similarly, Lerch et al. (2018) found that turbines, an essential component of CAPEX, and O&M costs were among the four most significant cost drivers. Further, down the ranked list of influential parameters for Sørlige Nordsjø II, we find, in accordance with the findings of Lerch (2018) and Myhr (2014), that economic life is of relatively minor importance for the LCOE. Lastly, construction time and degradation rate are the two least significant variables, with degradation being the undoubtedly least important factor.

Table 6 - Regression coefficients Utsira Nord ranked from most to least influential.

Utsira Nord		
Order	**Variable**	**Coefficient**
1.	Discount rate	9,49
2.	Capacity factor	(-8,38)
3.	OPEX	7,48
4.	CAPEX	5,90
5.	Construction time	3,70
6.	Economic life	(-3,29)
7.	Degradation rate	1,09

The regression results in Table 6 for Utsira Nord are similar to those of Sørlige Nordsjø II. However, for this project, the results suggest that variability in OPEX is more critical for profitability than CAPEX. Furthermore, our data from NVE estimates higher OPEX for this project. This is likely due to the increased complexity of maintaining an installation not anchored with a fixed foundation. In addition, this technology is untested relative to bottom-fixed offshore wind. This implies increased costs both in terms of investments and maintenance. Notably, the government seems to acknowledge this in the concession program. Therefore, the Utsira Nord area will not be awarded solely based on economic measures but on a qualitative assessment of which actors may contribute most to innovation in floating offshore wind.

In contrast to Sørlige Nordsjø II, our research suggests that construction time is more influential than economic life for the Utsira Nord project. The reason for this seems to be the relatively higher costs for Utsira Nord than for Sørlige Nordsjø II. Furthermore, LCOE is a metric valuing early expenditures and production more than those incurring later. Therefore, the postponement of electricity generation due to construction delays may be more influential than gaining years at the tail of the project life to generate additional electricity and income.

In summary, our results suggest that the discount rate and capacity factor are the two most influential cost variables for offshore wind. Followed by CAPEX and OPEX, where OPEX seems more critical for the floating Utsira Nord projects than Sørlige Nordsjø II. Lastly, construction time and economic life seem relative to the other variables to be of minor significance for the LCOE outcome. The implications of these findings and how this knowledge may affect project planning will be discussed broader in the next chapter.

Regression results SMR

Table 7 - Regression coefficients BWRX-300 ranked from most to least influential.

BWRX-300		
Order	**Variable**	**Coefficient**
1.	CAPEX	5,81
2.	OPEX	5,32
3.	Construction time	2,69
4.	Discount rate	1,82
5.	Economic life	1,69
6.	Degradation rate	1,02
7.	Capacity factor	(-0,38)

Expectedly, the regression results displayed in Table 7 show a very different distribution of contributing factors for the SMR than those of wind. The results suggest CAPEX as this project's most influential variable for LCOE. This aligns with the research of Asuega et al. (2023). This study also finds CAPEX to be the most critical contributor to LCOE. On the other hand, Testoni et al. (2021) find reactor size the most influential variable. This will likely be strongly related to CAPEX as larger reactors will probably demand higher investment costs. However, a larger reactor size will also equal more production output which can reduce LCOE.

Our analysis suggests that OPEX is the second most influential variable. Asuega et al. (2023) imply that O&M costs are 60 % higher for SMRs than traditional nuclear technologies due to the relative scale loss. Our calculations account for this estimation, contributing to OPEX's significance as a cost driver.

Further, our analysis suggests that construction time and the discount rate are the third and fourth most influential parameters. This is notably different from the wind projects where discount rate proved the most significant factor. Additionally, our results differ from those of Asuega et al. (2023) and Testoni et al. (2021), who found capital costs to be the second most influential parameter. However, the study of Testoni was a literature study focusing on microreactors. This type of reactor has a smaller output and economic life than SMRs and is usually meant for industrial purposes isolated from the grid. Similarly, Asuega et al. (2023) reviewed multiple SMR concepts with different designs and production outputs. This may explain the contrasting results.

Economic life has a positive but relatively small coefficient. Hence, extending the economic life is related to a marginally increased LCOE. This is in accordance with our isolated local sensitivity analysis in the previous segment. The non-linear shape of this variable's influence seems to be the impact of yearly OPEX. This follows Aldersey-Williams et al. (2019) findings. They discover that increasing the lifetime of a project also increases investment costs and operational costs in ways that may not always be economically efficient.

In summary, our results suggest that CAPEX and OPEX are the two most significant cost drivers for a BWRX-300 SMR project in Norway. Additionally, construction time and the discount rate seem to be substantial. In the following chapter, we will elaborate and discuss the implications of these findings in regard to the utility of potential SMR projects in Norway.

6.2 Balancing Cost Analysis

6.2.1 Regression results

Wind power penetration level and imbalance purchase volumes in Norway

The regression analysis results indicate a significant, positive relationship between the imbalance purchase volume and the percentage of wind energy generation in a power system. The model has an F-statistic indicating that the regression model is significant at a 5 % level. The R-squared value suggests that the wind power penetration level in the Norwegian grid can explain 11,7 % of the variability in imbalance purchase volume.

The coefficient for the wind power penetration level is positive, indicating an increase in wind power penetration is associated with a rise in the imbalance in purchase volume, with all other variables held constant. The standard error of the coefficients is relatively small, suggesting that the estimates of the coefficients are precise. The p-value parameter also indicates that the coefficients are statistically significant. However, the low R-squared value suggests that other variables may impact the dependent variable, which is not included in the current model.

Figure 5 shows the relationship between the imbalance purchase volumes and both the penetration level of wind power and total wind power production. The slope of the regression line indicates a positive relationship between the variables. However, the fact that the dots are not precisely aligned with the regression line means that the relationship is not perfect and there is variation in the data. Nevertheless, this is coherent with the low value of the correlation coefficient.

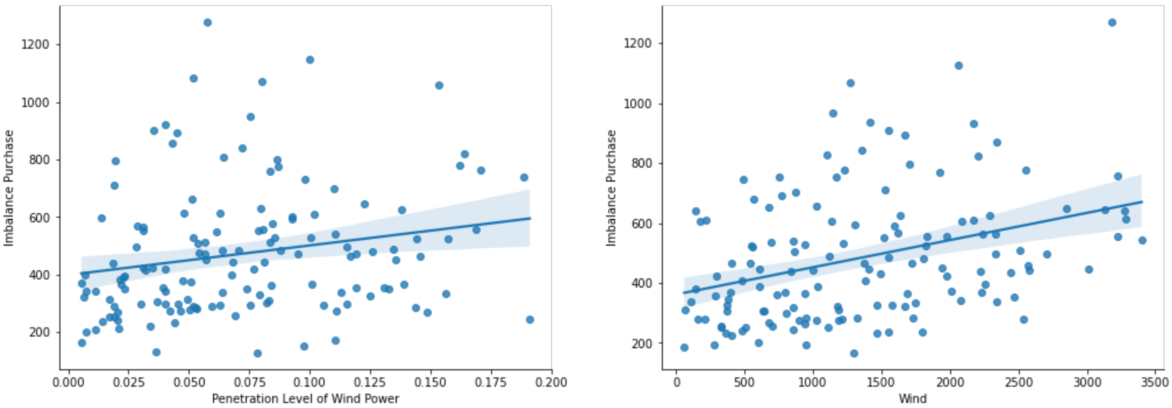

Figure 5 - Imbalance purchase volumes vs. wind power production and penetration level in Norway

Wind power penetration level and imbalance sales volumes in Norway

The regression analysis output suggests a significant relationship between the imbalance sales volume and the percentage of wind energy generation. The F-statistic indicates that the regression model is significant at a 5 % level. However, the R-squared value indicates that only 3,2 % of the variability in imbalance sales volume can be explained by the power system's share of wind energy generation. This suggests that the independent variable is a significant predictor of the dependent variable, even though it may not explain a considerable proportion of the variability in the dependent variable.

The coefficient related to the penetration level of wind power indicates that an increase in this variable is linked to a corresponding increase in the imbalance sales volume. The standard error of the coefficient suggests that the estimation is precise, while the p-value indicates that the results are statistically significant at a 5 % level.

Figure 6 illustrates the correlation between imbalance sales volumes and both the penetration level of wind power and total wind power production. The slope of the regression line indicates a positive relationship between the variables. However, the slight misalignment between the dots and the regression line suggests that the relationship is not entirely perfect, and the data has some variability. Overall, the results suggest a statistically significant but weak relationship between the imbalance sales volume and the percentage of wind energy generation.

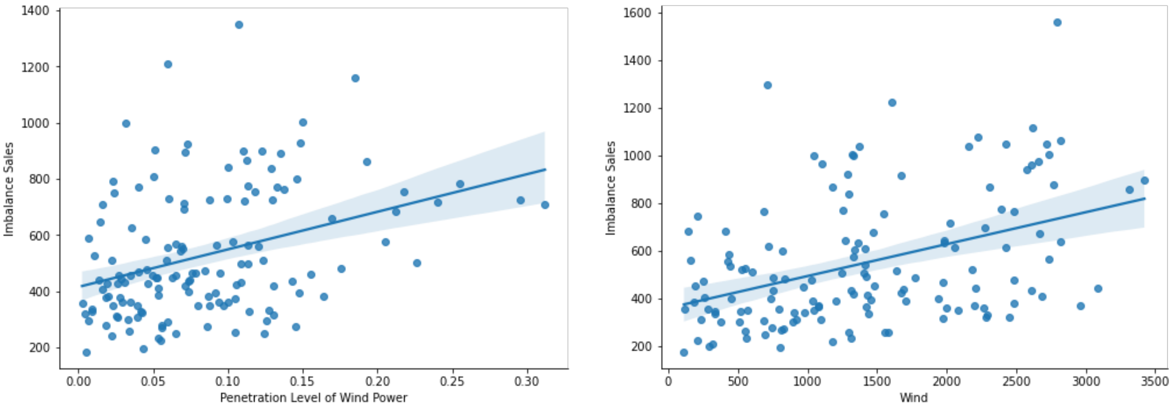

Figure 6 - Imbalance sales volumes vs. wind power production and penetration level Norway

Nuclear and wind power penetration level and activated frequency reserves Sweden

The regression studying the relationship between the penetration level of nuclear and wind power and the independent variable total activated frequency reserves volume has a low R-squared value of 1,6 %, which indicates that only a small proportion of the variation in the output variable is explained by the input variables. However, the F-statistic is significant at a 5 % level, which suggests that the model is statistically significant.

The coefficients for the share of nuclear and wind power indicate the direction and strength of their relationship with the output variable. The coefficient for wind is positive, which suggests that an increase in the percentage of wind energy is associated with an increase in the activated frequency reserves volume. Conversely, the coefficient for nuclear power penetration is negative, which suggests that an increase in the percentage of nuclear energy in the energy mix is associated with a decrease in the total activated frequency reserves volume. The standard errors for both coefficients are relatively small, which suggests that the estimates are reliable. In addition, both coefficients' p-values indicate that they are statistically significant on a 5 % level.

The regression results are visualized in Figure 7. The visualisations of the regression line and scatter plot for both independent variables indicate a weak relationship. However, the slopes of the regression lines clearly show a positive relationship between the dependent variable and wind penetration and a negative relationship with nuclear power penetration in the Swedish power system.

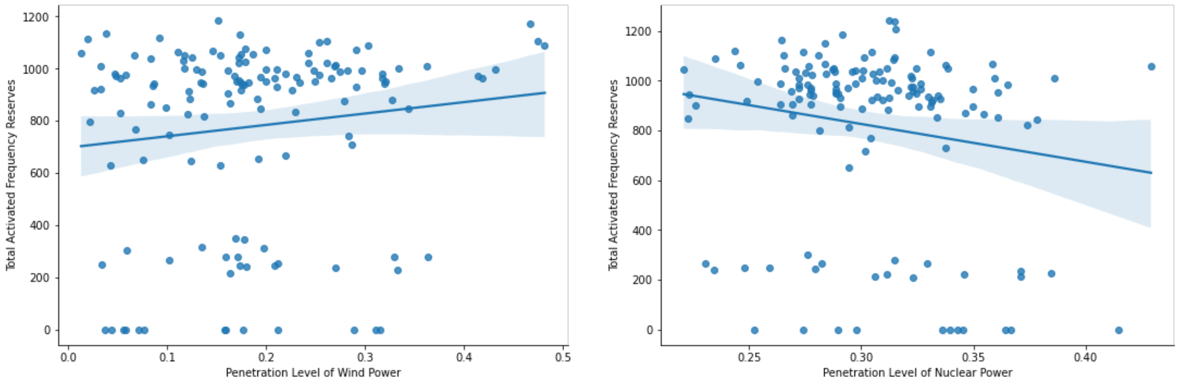

Figure 7 - Activated frequency reserves vs. wind- and nuclear power penetration level Sweden

Nuclear and wind power penetration level and imbalance sales volumes in Finland

The regression analysis investigates the relationship between Finish imbalance purchase and wind and nuclear energy percentage in the power grid. The regression model is significant at a 5 % level, indicated by its F-statistic. However, the R-squared value of the model is low, implying that only 1,3 % of the variance in imbalance purchase volume is accounted for by the predictor variables. Thus, it is likely that other factors not considered in the model contribute more to the variance in imbalance purchase.

The regression coefficients reveal that the percentage of wind energy in the grid positively relates to imbalance purchase. In contrast, the percentage of nuclear power in the grid is negatively associated with imbalance purchases. The p-value of coefficients indicates that they are statistically significant at a 5 % level.

The relationships between the imbalance purchase volume and the penetration level of wind power and nuclear power are displayed in Figure 8. This figure visualises the positive and negative relationship between Finnish imbalance sales volumes and the penetration level of wind and nuclear power, respectively.

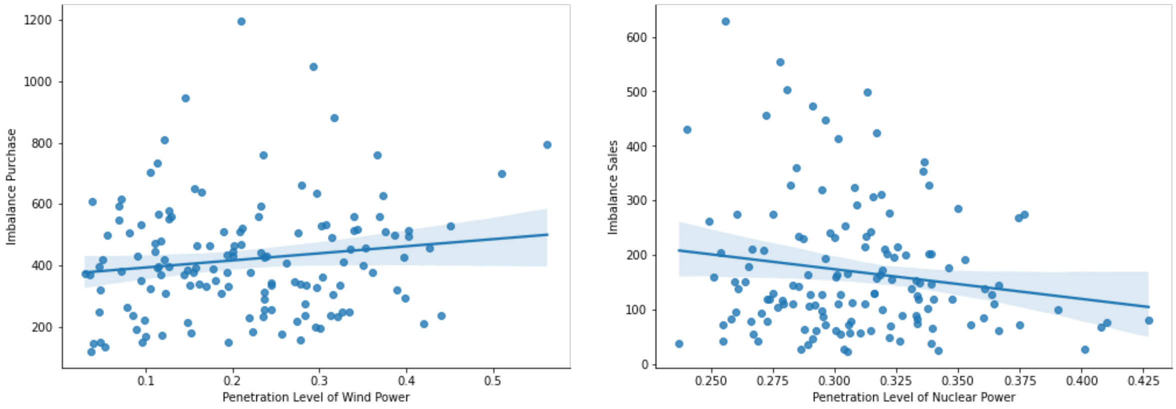

Figure 8 - Imbalance sales volumes vs. wind and nuclear power penetration level Finland

Nuclear and wind power penetration level and imbalance purchase volumes in Finland

The regression studying the relationship between the penetration level of nuclear and wind power and the independent variable imbalance purchase volumes has a low R-squared value of 2,5 %. The F-statistic is statistically significant at a 5 % level, meaning that the model as a whole is significant.

This model also displays a positive relationship between the dependent variable and the penetration level of wind power in the power system. Similarly, the coefficient for nuclear penetration level suggests a negative relationship. Both coefficients are statistically significant, as indicated by their respective p-values.

Overall, these results suggest that the amount of wind and nuclear power generation significantly affects imbalance sales. However, the model only explains a small portion of the variation in the dependent variable, indicating that other factors may influence imbalance sales beyond the two independent variables included in the model. The relationships are visualised in Figure 9.

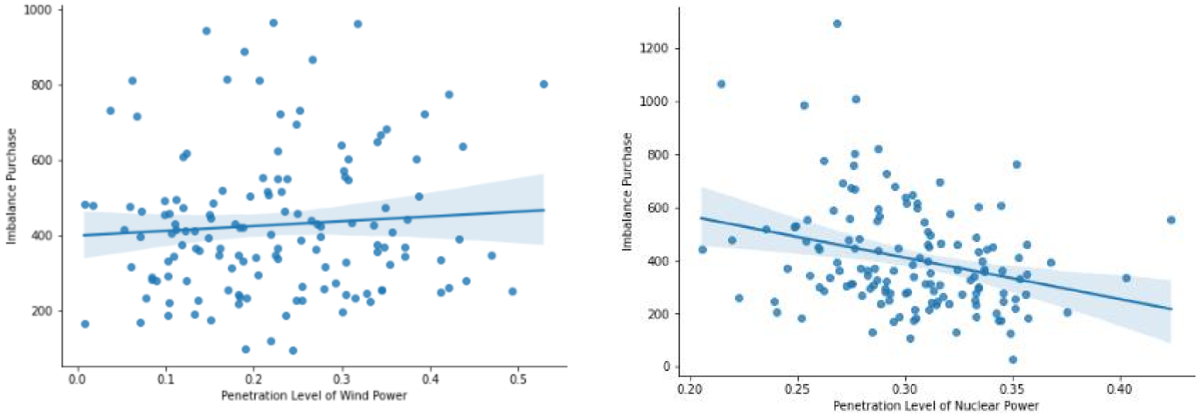

Figure 9 - Imbalance purchase volumes vs. wind and nuclear power penetration level Finland

Summary of regression analyses

The regression analyses investigated the relationship between wind and nuclear power penetration levels and imbalance purchase volume, imbalance sales volume, and activated frequency reserves. The results provide insights into the impact of the energy sources on grid imbalance.

The analysis of Norwegian data shows a significant positive relationship between the imbalance purchase volume, imbalance sales volume and the percentage of wind energy generation in a power system. These results indicate that incorporating more wind energy into the power grid may increase imbalance volumes and are coherent with existing literature on balancing costs and integrating variable renewable resources. Furthermore, the inherent variability in wind power can result in imbalances between supply and demand in the power grid. These results are also apparent when analysing the relationship between wind power penetration levels and imbalance volumes in Finland.

The Finnish data also provides insight into the relationship between the same dependent variables and nuclear power penetration percentage. The results show that the nuclear power penetration level has a significant negative relationship with both imbalance purchase and sales volumes. This can be interpreted as when the penetration level of nuclear power increases in a power system, the imbalance in purchase and sales volumes tends to decrease.

To support our findings, the analysis of data from Sweden suggests that higher levels of nuclear energy penetration correlate with lower total activated frequency reserves volume. This could be due to nuclear energy's increased stability and dependability, reducing the need for frequency reserves to manage power grid fluctuations. Additionally, the Swedish data indicates a positive relationship between the higher wind power penetration level and total activated frequency reserves volume. This implies that as the proportion of variable wind energy in the energy mix increases, so does the need for frequency reserves to manage the variability in wind energy production. This explanation is consistent with existing research, which has found that integrating renewable energy sources, like wind power, increases the need for grid flexibility and frequency regulation services.

In summary, the findings suggest that integrating greater amounts of wind energy into the power grid may raise imbalance volumes, while incorporating more nuclear energy may lower it. An increase in the imbalance volume can lead to higher balancing costs as it necessitates more corrective actions to maintain supply-demand equilibrium. These corrective actions tend to be more costly than the price of buying or generating energy under normal conditions. Consequently, an increase in the imbalance volume may have a notable effect on balancing costs and lead to a rise in the consumer bill. However, it is essential to note that all the regression coefficients, were low. This means that even though the share of wind and nuclear power explains some variation in imbalance volume, other factors account for the majority of the variation.

7. DISCUSSION

This chapter will first examine the implications of our findings from the analyses of LCOE and balancing costs in the previous chapter. Thereafter we will expand the scope further by including discussions on grid costs and adequacy costs. This is essential to attain a complete inclusion of the system costs term. Furthermore, the discussion of grid and adequacy costs is predominantly anchored in recent findings and reports conducted by governmental organisations like the Ministry of Petroleum and Energy, Statnett and NVE. Hence, we expect these reports to contribute valuable insights.

7.1 LCOE

Offshore wind

Our analysis from Chapter 6 suggests that the discount rate is the most critical cost variable for offshore wind projects. This implies that access to low-cost capital will be essential for offshore wind to be an efficient alternative for energy production. Currently, the industry is receiving financial support through various subsidies and tariffs (Oslo Economics, 2022). However, these are expected to be temporary contributions to establish the sector as a profitable and sustainable industry nationally. Therefore, our analysis suggests that access to low-cost capital is essential for similar projects to attain favourable LCOE estimates. This may seem obvious, knowing that these sizeable projects require substantial upfront investments that also significantly affect LCOE. Hence, CAPEX and the discount rate are closely linked. As a result, one particular threat to the profitability of offshore wind projects seems to be investment costs that overrun the initial estimates while being financed through sub-optimal solutions.

Additionally, the regression analysis suggests that the capacity factor is another factor that accounts for a considerable share of the variability in the LCOE. Interestingly, DNV estimates that the capacity factor for floating and bottom-fixed offshore wind will increase towards 2030, which implies a potential for increased profitability (DNV, 2021). However, the foundations of this assumption are ambiguous. There may be feasible technological improvements which can enhance the capacity factor of offshore wind in the coming decade, for instance, through larger turbines. However, one must note that offshore wind is not an entirely new technology. Instead, it is a new subset of components and subsystems combined with existing technologies like turbines and substations (Ørsted, 2020).

Therefore, it is essential to recognize that expecting an uninterrupted trajectory of progress at a consistent pace in terms of turbine size and capacity factor may be overly optimistic. Despite that the development has increased the cost-competitiveness and capacity factor for wind power in recent years. Additionally, there may be trade-offs for developers between incremental performance gains and higher investment costs of larger turbines. While capacity factors also depend on individual sites' wind speed (IEA, 2019).

These claims must also be viewed in light of floating offshore wind being a relatively untested technological concept. Therefore, it is unknown which implications it can have for the long-term capacity factor to generate power from an unfixed structure.

Lastly, our results suggest that the expected economic life of the plants is of relatively little significance for the LCOE for Sørlige Nordsjø II and Utsira Nord. This is an interesting finding as it may suggest that increasing the quality of the installations through more durable and expensive materials or increased maintenance expenses is of limited value, considering LCOE in isolation. This can be problematic as building wind turbines and the accompanying infrastructure requires significant resources and areas, which can negatively impact ecosystems and wildlife. Furthermore, the long-term effects of offshore wind on marine life are unconfirmed (Bergström, et al., 2014). When wind power projects have short economic lives, the need to quickly recoup costs and generate profits can increase pressure to site turbines in ecologically sensitive areas if wind conditions are beneficial. Hence, using LCOE in isolation could lead to increased interventions with nature.

Additionally, when wind turbines are decommissioned after a relatively short time, the ecological exploitation associated with the project may not be easily or fully reversible, leaving behind a legacy of environmental impacts that can persist for years. Therefore, ensuring the longevity of wind power projects and reducing replacements of wind turbines can be important not only for economic reasons but also for minimizing the environmental impacts of renewable energy development.

BWRX-300

The regression analysis in Chapter 6 suggests that CAPEX and construction time are essential variables that produce a significant share of the variability in the LCOE simulations. Interestingly, both factors could be influenced by modularisation and standardization of the construction process. The uncertainty regarding the investment costs has been the leading disadvantage to building and developing nuclear energy (MIT, 2018). SMRs are regarded as one potential solution to this problem (Stewart & Shirvan, 2022). However, considering the technology’s vulnerability to upfront investment cost overruns and delays, actors must conduct due diligence on the reliability of supply chains and the effectiveness of modularization and standardization before investing in an SMR project. Such measures are necessary to mitigate financial risks and uncertainties and ensure that investments are viable in the long run.

Additionally, locking the investment price in advance could be a viable option. By performing rigorous due diligence on the strength of supply chains, potential investors can assess the risks of delays, disruptions, and cost overruns associated with procuring essential components and materials. Similarly, evaluating the efficiency of modularization and standardization can help to identify potential sources of delays or inefficiencies in the construction and deployment of SMR units.

Ultimately, such efforts can help to increase the likelihood of project success and contribute to the long-term viability of SMR technology as a sustainable energy solution.

Our results also suggest that OPEX is a crucial SMR cost factor. As such, operating individual SMRs may not be the most optimal solution. Instead, running multiple SMRs at the same location may be a more advantageous approach. This can help to offset the loss of scale in O&M costs compared to conventional nuclear technology without sacrificing the gains in construction efficiency. This thesis focuses on a single 300 MW reactor from GE Hitachi. The limited geographic resources this concept requires may make operating several reactors in the same location a more cost-efficient solution. For instance, this could contribute to economies of scale in O&M costs by using the same staffing to oversee numerous reactors.

Additionally, the benefits of scale are likely to extend to construction costs and time. By constructing multiple reactors in the same location, improving construction time and efficiency through learning is possible. Therefore, optimizing the number and sites of SMRs can significantly impact the viability and profitability of SMR technology.

LCOE as a metric

After evaluating the importance of the different variables in the LCOE estimations, two main characteristics of the metric stand out. Firstly, the LCOE metric primarily focuses on cost components, thus excluding the consideration of revenue streams within the profitability assessment. This is problematic if using the metric for comparative measures. In this thesis, we have investigated offshore wind projects with capacity factors of around 50 % and an SMR project of 95 %. Hence, there is a vast difference in delivery profile for the energy sources. An SMR is anticipated to operate consistently, except for planned maintenance outages, when the supply in the system is sufficient.

On the contrary, offshore wind depends upon external conditions and will produce around half the time. The challenge is that it tends to be a substantial autocorrelation regarding wind speeds in the European offshore areas, particularly in the North Sea (NVE, ; Drivenes et al., 2010). With the proposed significant expansion of offshore wind capacity in Norway and Europe, the autocorrelation of wind speeds can exert a notable influence on electricity prices. In periods of high wind speeds, significant generating capacities will produce concurrently. Therefore, the electricity price will likely decline during these hours due to the elevated supply. In periods of low or no wind, the market will on the other hand, have a limited supply, and the price could increase.

These price effects could prove problematic for wind farms as this energy source will only be able to produce when electricity prices are low. The impact will depend on how much offshore wind is constructed and to which extent it is interconnected regionally. Therefore, the statements of NVE director Kjetil Lund regarding the profitability of offshore wind may be viable. He states that fixed offshore wind is unprofitable, while floating is far from profitable in Norway today (Larsen, 2023), despite wind projects achieving LCOE figures below the average resale price. SMRs will not incur this pricing problem as they can produce constantly, also when prices are high. Hence, SMRs could receive a higher average price for their production units. But this effect is unaccounted for in the LCOE metric, as it only considers the cost side.

Secondly, the results from both the offshore wind and the SMR projects value economic life minimally, in accordance with the cited studies (Lerch et al., 2018; Myhr et al., 2014; Testoni et al., 2021). For the SMR project, we also saw that decreasing the economic life to 50 years, rather than using the original estimates of 60 years, was beneficial to the LCOE output. Literature suggests that this effect is partly due to the constant discount rate and the time value of resources. Nevertheless, the insufficiency in valuing project longevity could be problematic because of the proximity to using LCOE as the guiding metric in public discussion and politics. As discussed above, this can be regarded at least partially as an incentive to construct short-lived energy projects and infrastructure. This will accelerate the exploitation of land, raw materials, natural resources, and financial resources.

For consumers and from a socio-economic perspective, constructing lasting power supplies and limiting the exploitation of nature may be of more value, even though this may imply an LCOE slightly above the alternatives. However, for investors, durable projects require more significant upfront investments and encounter extended payback times, making more temporary projects the preferred option. Nevertheless, this suggests that the LCOE metric's relevance is largely affected by which group of stakeholders one belongs to.

Lastly, it is essential to note that LCOE only accounts for electricity generation, not additional revenue streams. SMRs have significant potential to generate additional revenue by utilizing the excess energy from their production process for heating purposes. By capturing and utilizing the excess heat produced during electricity generation, SMRs can provide a valuable source of low-carbon thermal energy for various heating needs, such as district heating systems, industrial processes, and desalination plants. This potential source of income remains unaccounted for in the LCOE metric. Neglecting this additional revenue stream fails to capture the full economic potential of SMRs. As this thesis focuses on a hypothetical future SMR project in Norway, quantifying this additional revenue stream is impossible without a specific location. Nevertheless, it is crucial to be aware of this potential and how it is not accounted for in the LCOE figures.

7.2 System Costs

7.2.1 Balancing costs

Our regression analyses suggest that an increased share of wind power in an energy system is linked to a growth in balancing volumes. The intermittent nature of wind power as an energy source introduces fluctuations in electricity generation that necessitate ramping other energy reserves to maintain a balanced supply. This dynamic has significant implications for the overall energy mix within a system and can result in increased costs associated with balancing energy.

In contrast, the negative relationship between the share of nuclear power and balancing volumes suggests that nuclear power may decrease the need for balancing. Nuclear power is usually operated as a baseload energy source that runs continuously. Due to the reliability of delivery, nuclear power can make power planning less complicated and thus reduce the need for balancing actions. This is also reflected in our results regarding the relationship between Swedish activated frequency reserves and the penetration level of nuclear power.

Overall, the regression results suggest that wind power and nuclear power have different implications for the balancing needs of an electricity system. Wind power will likely increase the demand for balancing energy from reserve capacities, while nuclear power will reduce it. This can have important implications for the energy mix in a system and the associated costs of balancing energy.

Intuitively, it seems plausible that a higher production capacity in the system would lead to lower energy prices. However, this effect is countered by the fact that VRE significantly contributes to the system costs, not covered by the low marginal cost of production. For instance, to handle the intermittency of VRE, system operators need to activate balancing resources more frequently to meet demand. Increased deployment of these reserves can raise total system costs, which again will contribute to growth in consumer prices (Murray, 2019; Holttinen, et al., 2011; Hirth, Ueckerdt, & Edenhofer, 2015).

However, it is essential to note that the Norwegian power system has a significant proportion of hydropower. This source is well suited for balancing, as it is flexible and emission-free. Still, it is crucial to remember that increasing the use of hydropower as a balancing instrument will lead to more frequent ramping of hydro production. Resource managers believe limiting the ramping rate can reduce dam operation's negative impacts, such as habitat degradation and reduced downstream biodiversity (Sabater, 2008). Furthermore, findings in Sweden also suggest that frequent ramping is a costly and environmentally damaging way of operating hydro reserves (Qvist Consulting Ltd, 2022).

From a balancing perspective, one can argue that the Norwegian market will benefit from combining nuclear and offshore wind power to integrate into the existing hydropower-dominated system.

Integrating offshore wind can increase the generation capacity by introducing renewable energy, while SMR could limit the ramping rate of hydropower by providing stable baseload power into the system. This is beneficial, especially considering the environmental aspect beyond solely greenhouse gas emissions. Regardless, it is essential for policymakers and energy system operators to carefully balance the potential benefits and drawbacks of various sources of energy when planning and regulating the energy mix to ensure a sustainable and cost-effective energy system.

7.2.2 Adequacy costs

Norway's energy system is characterized by high energy security and self-sufficiency, with adequacy issues typically only arising at the regional level. This can be attributed to the significant hydro reservoir volumes and high exchange capacity with neighbouring countries. The following discussion will address how the expansion of offshore wind and nuclear power may impact flexibility, security of supply and adequacy costs.

Adequacy costs and offshore wind integration

Incorporating offshore wind power into Norway's energy system can significantly enhance the country's energy security and future self-sufficiency. As Norway faces the risk of a potential national electricity deficit as early as 2027 (Statnett, 2022a), adding offshore wind energy would increase energy production capacity and reduce the country's prospected reliance on imported electricity. In addition, integrating offshore wind energy into Norway's energy system could help address the anticipated increase in electricity demand in alignment with EU objectives and climate targets.

On the other hand, our regression analysis found a positive relationship between wind power penetration and imbalance volume and activated reserves. The results imply that when the penetration level of offshore wind and other VRE sources increases, so does the need for other sources of flexibility.

Encouraging and facilitating flexible demand is pivotal in maintaining supply security and the power system's flexibility. It allows the power system to dynamically match electricity consumption with the intermittent generation patterns of VRE, optimizing resource utilization and reducing supply-demand imbalances. Electrifying industries that exhibit high inflexibility in a power system reliant on VRE sources can present significant challenges to adequacy considerations. The inherent intermittency of VRE generation may not align with the rigid and non-adaptable energy demand patterns of inflexible industries, such as petroleum installations, leading to pronounced supply-demand imbalances and potentially undermining the stability and reliability of the power system.

Power trading with foreign markets enhances capacity and flexibility while strengthening Norway's energy security. Furthermore, incorporating offshore wind into the energy portfolio presents a unique opportunity to create a harmonized European offshore grid. While Norway is currently self-sufficient in energy, Europe relies heavily on Russian gas, which has been a contentious issue given Russia's inclination to use energy as a political tool. Therefore, integrating the suggested 300 GW of offshore wind into the energy portfolio by 2050 (European Commission, 2020) will provide the EU with significant advantages from an adequacy perspective. This makes it a compelling solution for mitigating some of Europe's dependence on imported gas and improving energy security. Furthermore, integrating offshore wind energy can help reduce the energy system's vulnerability to price volatility from supply disruptions in Europe.

While offshore wind can significantly increase energy production, security of supply must also be ensured during extended periods with minimum wind. This is particularly challenging if wind farms are located where wind conditions are not diversified, and wind speeds are consistently low over longer periods. In such cases, the total energy output from the wind farms may not be sufficient to meet the demand. This implies that additional reserves and capacity may need to be stored to ensure the security of supply during these periods. This has consequences for the adequacy costs of offshore wind integration, as it would require investments in additional backup capacity. Therefore, the cost of these technologies must be considered in the overall cost of offshore wind integration.

Adequacy costs and SMR integration

As the world shifts towards a more sustainable and renewable energy system, there is a united effort to reduce the reliance on fossil fuels. However, with this transition, ensuring a reliable baseload energy source that can provide a stable and consistent energy supply becomes a critical challenge. SMRs represent a promising solution to this challenge, offering a constant but scalable sustainable energy source.

Our regression results imply that imbalance volumes and activated frequency reserves are reduced when the penetration level of nuclear power increases, indicating improved system stability and reduced costs associated with managing the power system. SMRs could offer more stable and dependable power than other renewable energy sources. The consistent baseload supply and flexibility of SMRs make them a well-suited technology for reducing adequacy costs associated with balancing supply and demand.

Advanced nuclear reactor designs, such as GEN III reactors, are typically compatible with flexible load following and frequency control. This flexibility is crucial as the share of intermittent renewable energy sources continues to increase. With SMRs, balancing needs can be reduced, ultimately contributing to a more secure and cost-effective energy system. Moreover, SMRs can help address regional adequacy concerns by providing a localized source of power that reduces the need for long-distance transmission, leading to reduced transmission losses, and enhanced local grid stability.

SMR technology relies on fuel to produce electricity, making it vulnerable to potential geopolitical disturbances. The European nuclear industry's dependence on uranium from a handful of countries, such as Niger, Russia, and Kazakhstan, raises concerns about the security of supply. However, these concerns could be mitigated by research and development of alternative nuclear fuel cycles that rely less on uranium and can use alternative fuel sources, such as the more abundant thorium.

Another factor that may enhance concerns about the security of supply is the potential risk of incidents that could disrupt SMR operations, such as technical failures and the need for unplanned maintenance. In the event of unplanned maintenance or technical failures, there is a possibility for a sudden reduction or complete shutdown of power generation, leading to potential supply shortages. This was evident during the acute shutdown of two Swedish reactors in December 2022. The Swedish prime minister expressed his significant concerns regarding power shortages in southern Sweden and encouraged private households and industries to practice electricity conservation (Hjellen, 2022). Despite these potential risks, SMRs are designed to be safer and less exposed to such threats than conventional nuclear power plants. This could translate to improved security of supply, ensuring a more consistent and reliable source of electricity.

Summarized

Regardless of technology, there is a pressing need to expand and upgrade the present production capacity to guarantee adequate security of supply in the face of the anticipated increase in power demand. In addition, Statkraft's Low Emissions Scenario 2022 underscores that the escalating uncertainty in energy markets and Western nations' loss of trust in the Russian regime has made energy self-sufficiency and security of supply a top priority on the policy agenda (Statkraft, 2023).

Incorporating offshore wind power into Norway's energy system could help address the expected increase in electricity demand, in alignment with EU objectives and climate targets. However, the positive relationship between wind penetration and both imbalance volumes and activated reserves implies the need for flexibility from other sources such as generation, demand, and trade. Additional reserves and capacity may also need to be utilized to ensure the security of supply during longer periods with low wind speeds. The cost of these technologies must be considered in the overall cost of offshore wind integration.

SMRs represent a promising solution to ensuring a reliable source of baseload power to provide a stable and consistent energy supply in the transition towards a more sustainable and renewable energy system. SMRs offer a more stable and dependable source of electricity compared to other renewable energy sources, with improved system stability and reduced costs associated with managing the power system. There are, however, some concerns regarding the security of supply, like its fuel dependency and the risk of incidents that could disrupt SMR operations.

In discussing adequacy and security of supply, it is also essential to shed light on the energy source's complementary properties. For instance, the variability of offshore wind power can be balanced out by SMRs and hydropower, providing a more stable energy output. Integrating SMRs, offshore wind power and hydro can provide significant benefits in diversifying the energy mix and reducing the dependence on any single energy source. During planned and unplanned outages of SMRs, hydro and wind power can serve as backup power to maintain grid stability. Similarly, during long periods of low wind speeds, hydro and SMRs can provide the necessary power to meet our energy demands.

Coupling SMRs with hydropower can also relieve the pressure on hydropower to act as a base load power source, freeing up its capacity to provide flexibility. This flexibility is crucial for both balancing the grid short term and ensuring the long-term security of supply when integrating VRE into the power system. With the increasing demand for clean and reliable energy, exploring innovative solutions that leverage the strengths of different energy sources is crucial in ensuring the adequacy and security of the power system.

7.2.3 Grid costs

This subchapter will explore the factors influencing grid costs for integrating offshore wind power and SMRs. By analysing these factors, we can gain insights into the considerations and investment requirements of incorporating these energy sources into the grid.

Grid costs for offshore wind power integration

With a yearly total power production of 156 TWh and an installed capacity of 39 GW, Norway has set an ambitious goal to commission areas for offshore wind power production that will generate 30 GW of power capacity by 2040 (Ministry of Petroleum and Energy, 2022c). While Norway currently has a position as an energy exporter, the country must increase its installed capacity to meet future electricity demand, phase out fossil fuels and achieve climate goals through a transition to sustainable energy sources. The offshore wind capacity expected to be installed will require a substantial investment in grid infrastructure. These investments include the establishment of a harmonized offshore grid and general upgrades on the onshore grid to handle the considerable increase in electricity generation.

The distance to shore significantly influences the cost of developing offshore grids, as longer distances increase the cost of installing transmission cables. Additionally, wind farms located further away from the shore require high-voltage direct current (HVDC) transmission cables, which entail more expensive supporting infrastructure and converter stations than conventional alternating current (AC) cables (Csanyi, 2014). However, HVDC cables become more economically attractive when it is necessary to transmit electricity over long distances due to minimal transmission losses.

The Nordic countries have also agreed that the planned development of offshore wind farms may require the installation of offshore hybrid grids, which interconnect offshore wind farms with multiple countries. This implies that installing HVDC transmission cables to several connection points and over longer distances will be necessary, increasing grid costs. However, hybrid solutions also represent opportunities for the dual utilization of offshore grids. This dual purpose encompasses transporting the generated wind power and facilitating cross-border trade in low wind periods. As previously discussed, interconnections and power trade are essential sources of flexibility in the system.

Furthermore, by connecting offshore power grids between countries, the grid can be balanced on a larger scale, improving the stability and security of supply. Hybrid solutions represent not only a promising prospect for dual utilization of offshore grids, but Statnett's (2022b) report on offshore wind power also finds that these connections provide better resource utilization and socio-economically profitable power exchange. These results are coherent with findings from a new report from NVE (Arnesen, et al., 2023), where they consider both radial[5] and hybrid grid solutions for the second phase of Sørlige Nordsjø II.

The development of hybrid solutions and domestic grid reinforcements will account for a significant proportion of Norway's grid investments up to 2030. According to the 2021 Grid Development Plan (Statnett, 2021), Norway is expected to invest between 60-100 billion NOK in grid infrastructure development by 2030, which includes an estimated investment of 10 billion NOK in offshore grid infrastructure. The plan also anticipates further investments beyond 2030, with a higher average annual investment level until 2050.

The energy sector's forecasted grid investment costs have significantly changed from 2019 (Statnett, 2019b) to the most recent report published in 2021. In 2019, the estimates for future grid investments were conservative, with projections showing relatively modest growth up to 2040. However, in 2021, the outlook has shifted, with much higher estimates for grid investments up to 2050. In addition, according to Statnett, the investment level has been revised upward, reflecting an accelerated pace of grid development, integration of more renewable energy and major investments in offshore grid infrastructure. Figure 10 displays graphs with the projected grid investments from 2019 and 2021, respectively. Note that the charts are presented on different scales.

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[5] Radial solutions are power distribution systems with power flow in one direction to one connection point.

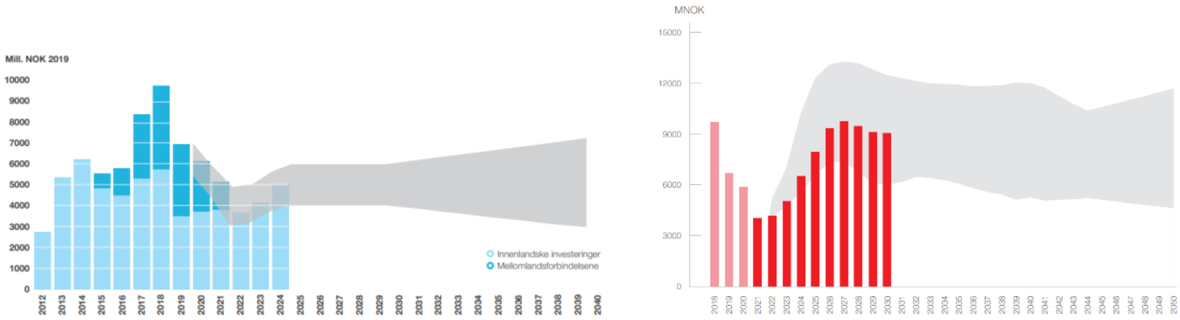

Figure 10 - Projected Grid Investments in Norway 2019 and 2021. Retrieved from their respective grid development reports.

Lastly, offshore wind farms are also envisioned to aid the prospected electrification of offshore petroleum installations. These off-grid wind farms expect lower grid costs due to shorter distances between the farm and the demand centre. Furthermore, this solution can simultaneously provide renewable energy to petroleum installations, mitigating some of the dependence on CO_2-emitting gas turbines. Therefore, this solution might be a good alternative for the shelf electrification project and has been explored through the collaborative initiative *Trollvind*. However, Equinor recently announced the indefinite postponement of the Trollvind offshore wind initiative. The decision was attributed to various challenges, including limited technology availability, escalating costs, and constraints in meeting the original project timeline (Equinor, 2023). This highlights the need for further advancements in technology to overcome the current obstacles and realize the full potential of offshore wind energy.

Grid costs for SMR integration

In Norway, integrating nuclear power into the grid remains a prospect for the future. There are no concrete plans for nuclear power, nor any references in reports and documents outlining the development of the Norwegian grid. However, Norsk Kjernekraft AS has recently released a press statement informing that they have entered into agreements with the municipalities of Aure, Heim, and Narvik to explore the possibilities of establishing one or several SMRs in their respective areas (Norsk Kjernekraft AS,).

The primary goal of this collaboration is to examine the potential of utilizing SMRs to secure sufficient power for the abovementioned communities. This effort is particularly important for municipalities in counties with a power deficit, where power shortages due to bottlenecks and transmission losses limit further industry development. In such situations, the integration of SMRs is perceived as a potential solution to address the existing power deficit and could provide opportunities for economic growth. However, it is essential to note that integrating SMRs into the grid is a complex process with varying costs, influenced by several factors. The main factors determining the price include the distance between the nuclear power plant and the grid, the capacity of the SMR, and the condition of the existing grid infrastructure.

The distance between the nuclear power plant and the grid will impact the construction cost of transmission lines and other necessary infrastructure. When the plant is located far from the grid, building transmission lines and other essential infrastructure becomes more expensive, increasing the cost of integration. Therefore, careful consideration of the location of the SMR concerning the grid is vital to ensure feasibility and cost-effectiveness. However, determining the location of SMRs demands careful consideration of various factors.

One aspect to consider is the availability of adequate land for the reactor, associated buildings, and access to cooling water. Environmental impacts must also be considered, as natural habitats and ecosystems may be vulnerable to disturbance. Another significant factor to consider is public acceptance of nuclear power, as concerns about the plant's proximity to the local population could arise. Engaging with the community is essential to understand their concerns and address any potential issues related to public acceptance, as it could impact the distance from the SMR to the grid.

When integrating any new energy source into the grid, the capacity of the source is an essential factor that can affect the cost of integration. SMRs might be more cost-effective to integrate into the grid due to their smaller size and lower capacity than traditional power plants. However, the increased system production capacity might pose challenges depending on the reliability and capacity of the existing grid. Upgrading and expanding the grid to accommodate a new nuclear power plant can be expensive, especially if the infrastructure is outdated or inadequate. Therefore, the cost of integrating a nuclear power plant into the grid will depend on the condition and capacity of the existing infrastructure.

However, SMRs also hold the potential to operate independently of a centralized power grid. Instead of being connected to traditional grid infrastructure, SMRs can be designed to be deployed directly at or near the demand centres they are intended to serve. As a result, transmission and distribution losses can be minimised by placing the SMR closer to the demand centres, improving overall system efficiency.

In conclusion, the cost of integrating nuclear power into the grid can vary depending on several factors, including the location and distance of the power plant from the grid, the capacity and size of the plant, and the existing grid infrastructure. Nevertheless, the recent agreements between Norsk Kjernekraft AS and the municipalities of Aure, Heim, and Narvik to explore the possibilities of establishing SMRs are an exciting development that could have significant implications for the future of nuclear power in Norway.

Summarized

Integrating offshore wind into the Norwegian power system will demand both the development of a new offshore grid and general upgrades to the onshore system. This will require significant investments and substantial grid costs. However, offshore wind can provide a dual benefit of producing clean energy, creating trade opportunities, and increasing supply security. Furthermore, hybrid solutions, where the offshore wind park is connected to two or several markets, can enable cross-country trade and increase potential socio-economic benefits.

SMRs have the potential to be especially important for local communities. SMRs can be directly connected to demand centres, providing a more localized source of energy that can help reduce the reliance on grid infrastructure. This can lead to reduced grid costs and transmission losses. Additionally, SMRs can provide a more reliable source of energy for remote communities, facilitating for development of industries and economic growth. Although the integration of SMRs in Norway is still in the exploration phase, it is a promising prospect that could benefit both the affected communities and the country's overall energy infrastructure.

To accommodate the increasing amount of renewable energy being produced and ensure efficient and reliable delivery of electricity to consumers, Statnett has stated that upgrading the onshore grid is strictly necessary. While these upgrades may require a significant investment upfront, they can also be seen as an inevitable cost, as infrastructure investments will be essential for meeting future energy demand regardless of sustainability.

8. CONCLUSION

This thesis aims to answer the following research question: *"How can the variability of input variables and scope of analysis impact the results of profitability calculations for nuclear and offshore wind power in the Norwegian power market?"*

To answer the research question, we have conducted a two-fold study. Firstly, we have investigated how variability in input variables in the commonly used LCOE metric impacts the evaluation and comparison of different energy sources. Secondly, we have investigated how LCOE may not accurately capture the complexities and costs related to system integration.

Our LCOE analysis identified the discount rate and capacity factor as the most influential cost drivers for offshore wind. Implying that access to low-cost capital and areas of steady wind conditions are crucial for the industry's profitability. However, for SMRs, we found CAPEX and OPEX to be the main drivers. This suggests that predictable investment costs are essential for the profitability of an SMR project. At the same time, pursuing measures to minimize OPEX is beneficial, like seeking economies of scale in O&M costs.

Additionally, the economic life of all the examined projects minimally impacted the LCOE. Implying that the metric fails to account for the value of long-term production. This raise concerns as it incentivises frequent exchange and construction of production units, which is not beneficial from a supply and environmental perspective. Moreover, LCOE fails to account for each project's delivery profile, revenue streams besides power production, and system costs.

Regarding the scope of analysis, power projects entail costs not considered in the LCOE metric. We find that the integration of wind power has a positive relationship with balancing costs, while the integration of nuclear power is negatively related. Our findings are statistically significant. However, the variables seem only to explain a minor part of the variation in balancing volumes. Regarding adequacy and grid costs, both energy sources involve factors that can affect the overall project viability, depending on the specific integration methods employed.

The inability of LCOE to incorporate costs beyond the project perimeter raises concerns, as specific projects may introduce substantial system costs to the grid despite having lower LCOE values. This can create a favourable perspective for investors, who prioritize low production expenses but may neglect the impact on other stakeholders. On the other hand, consumers may experience higher bills due to increased system costs, while entities like Statnett and the government responsible for ensuring the security of supply face challenges related to the hidden costs of balancing.

Lastly, our findings indicate that both offshore wind and nuclear power have the potential to be beneficial additions to the future Norwegian power mix. With its balancing capabilities, the Norwegian power system's hydropower backbone makes offshore wind a suitable supplement, adding generation capacity and contributing to a diversified energy portfolio. On the other hand, SMRs have the potential to cover baseload demand, prevent overexploitation of hydro resources, and enhance the overall reliability of power production.

In summary, this research contributes to understanding how input variable variability and the scope of analysis affect profitability calculations for nuclear and offshore wind power in the Norwegian power market. Furthermore, the findings highlight the importance of a holistic approach to assessing the economic viability of energy projects, considering long-term supply considerations, system costs, and the interests of various stakeholders. Such an approach is essential for informed decision-making in shaping Norway's future energy system.

8.1 Limitations

This section discusses the limitations of the research, acknowledging potential factors that may impact the accuracy and validity of the findings.

Firstly, it is essential to recognise that the estimates presented in this LCOE analysis could be subject to more variation than already accounted for. While we have made efforts to incorporate variability, unforeseen circumstances may inevitably arise in real-world scenarios that cannot be fully accounted for in our models. Therefore, the estimates should be interpreted cautiously, understanding that they represent predictions based on currently available information. Furthermore, SMRs and floating offshore wind technologies are still developing and do not yet exist on a large-scale commercial basis. Consequently, the data and information available for these technologies are limited, introducing inherent uncertainties in the analysis.

In terms of system costs, making accurate estimations is challenging due to the complex and interconnected nature of the factors involved. In this study, a simplified approach to regression analysis has been adopted, focusing only on selected variables. However, it is crucial to recognize that numerous other factors could influence balancing volumes that have not been explicitly considered in this study. Additionally, one limitation is the lack of data on offshore wind power generation. The substitution of offshore wind power with onshore wind power in our analysis introduces uncertainty regarding the applicability of the results. This is attributed to various factors, including the capacity factor and generation capacity, which can differ between offshore and onshore installations.

In conclusion, while this study provides valuable insights and analysis, it is crucial to acknowledge the limitations outlined above. These limitations highlight the need for further research and a comprehensive understanding of the complexities inherent in estimating system costs and projecting emerging technologies' impacts.

8.2 Further Research

Our finding implies that integrating floating offshore wind and SMRs into the Norwegian power system could benefit system costs due to their complementary nature. However, additional research is necessary to explore this topic further. Research should focus on simulating the optimal energy mix, considering various scenarios, and employing advanced modelling techniques. Moreover, studying the revenue aspects of the technologies by analysing delivery profiles, production timing, market dynamics, and pricing mechanisms would provide valuable insights into the economic viability of these projects. Finally, broader considerations, such as environmental impact, social acceptance, and policy implications, should also be addressed to ensure a comprehensive understanding of the feasibility and sustainability of integrating these technologies into the Norwegian energy mix.

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Appendix

Appendix A – Literature Overview Balancing Costs and VRE

Study	Context	Energy Penetration	Balancing Costs in €/MWh
Gross (2006)	Various countries, model	VRE up to 20 %	2.3 – 3.5
Heptonstall **(2017)**	Various countries, model	VRE up to 30 %	0 – 5
		VRE up to 50 % UK	15 – 45
Sijm (2014)	Various countries, model	VRE up to 30 %	1 – 6
Holttinen (2013)	In thermal systems, model	Wind up to 20 %	2 – 4
	In hydro systems, model	Wind up to 20 %	< 1
Pudjianto (2013)	Various EU countries, 2013, model	Solar 2 to 18 %	0.5 – 1
Hirth (2015)	Various countries, model	Wind to 40 %	0 – 6
	Various Countries, historic (market data)	Wind up to 17 %	0 – 13
	Historic (market data), 2015	Wind (8–10 % Germany)	1.7 – 2.5
Holttinen	Historic (market data), 2013	Wind (24 % Denmark)	1.4 – 2.6
		Wind (16 % Spain)	1.3 – 1.5
Holttinen **(2005)**	Historic (market data)	Wind (12 % Denmark)	2.8
Ueckerdt et al. (2013)	Various countries, model	Wind up to 30 %	2 - 4
Frade et al. (2019)	Historic (market data)	Wind (23 % Portugal)	2
Smith et al. (2007)		VRE up to 30 % the US	3 - 4.5
Mills et al. (2012)		VRE up to 30 % the US	2 - 4

Appendix B – Cost Components OPEX BWRX-300

OPEX BWRX-300 Cost Components	Cost in SEK/MWh
Minor Reinvestments	27
Major Modernization	11
Fuel	35
Waste management and decommissioning	33
Other O&M expenses	115
Total OPEX	*221*

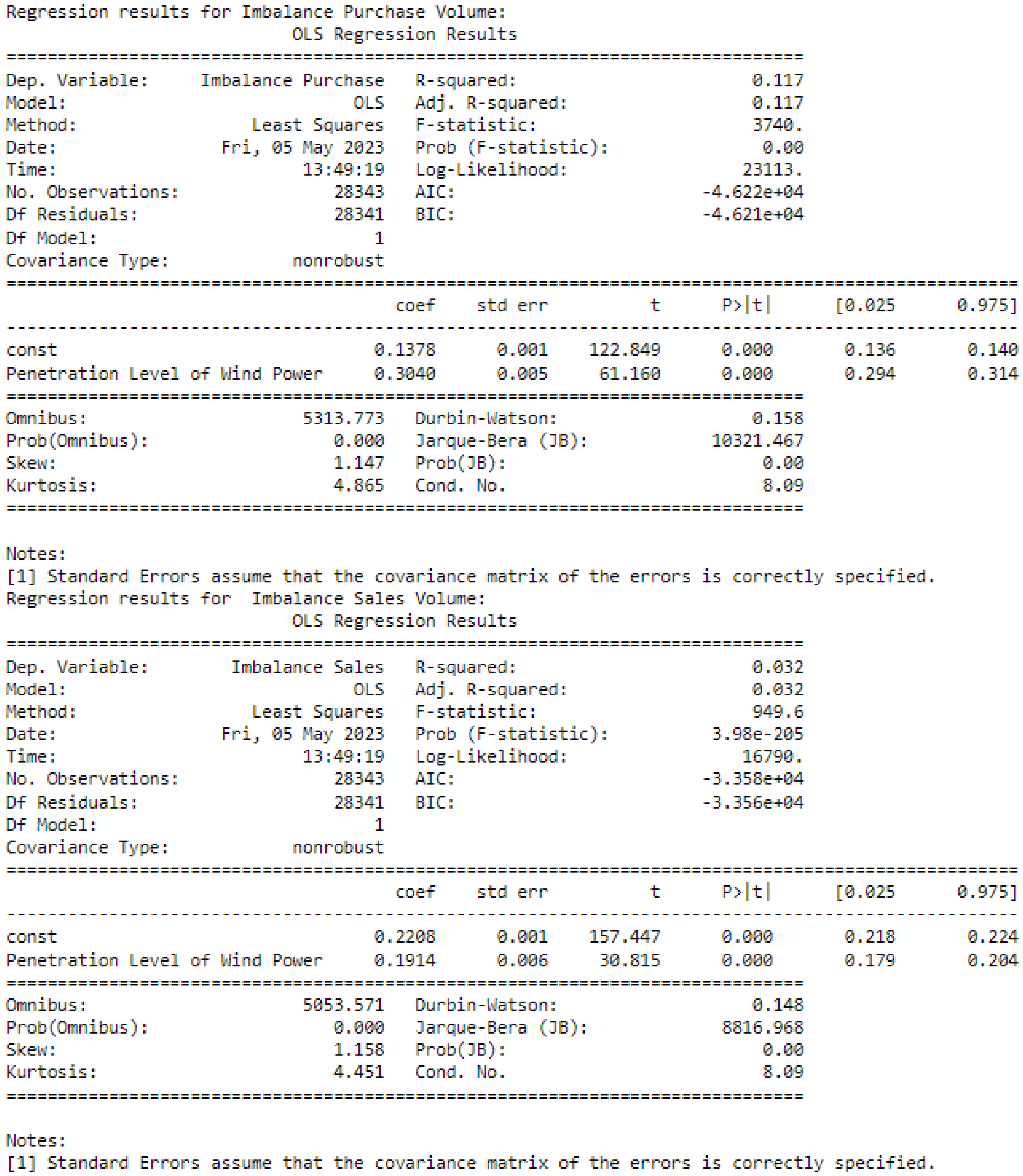
Appendix C – Cost Components CAPEX and OPEX Offshore Wind

Offshore wind cost components CAPEX (NVE)		
	Sørlige Nordsjø II	**Utsira Nord**
Investment costs offshore wind park		
Turbines	11 500 NOK/kW	12 000 NOK/kW
Substructure and foundation	3440 NOK/kW	6750 NOK/kW
Installation of substructure and foundation	1020 NOK/kW	3000 NOK/kW
Project development	1400 NOK/kW	2000 NOK/kW
Corporate level costs	4500 NOK/kW	5400 NOK/kW
SUM	***21 860 NOK/kW***	***29 150 NOK/kW***
Investment costs internal grid		
Array-cables	355 NOK/kW	480 NOK/kW
Installation of array-cables	1651 NOK/kW	1491 NOK/kW
Offshore substation	1314 NOK/kW	1287 NOK/kW
Installation of offshore substation	376 NOK/kW	376 NOK/kW
SUM	***3696 NOK/kW***	***3634 NOK/kW***
Investment costs external grid		
Export sea cable	2061 NOK/kW	1384 NOK/kW
Installation of export sea cable	1771 NOK/kW	520 NOK/kW
Export ground cable	96 NOK/kW	-
Installation of export ground cable	22 NOK/kW	-
Onshore substation	956 NOK/kW	568 NOK/kW
Installation of onshore substation	298 NOK/kW	298 NOK/kW
Switchgear	348 NOK/kW	-
SUM	***5552 NOK/kW***	***2770 NOK/kW***
Total CAPEX	***31 108 NOK/kW***	***35 554 NOK/kW***

Offshore wind cost components OPEX (NVE)		
	Sørlige Nordsjø II	**Utsira Nord**
Offshore OPEX		
O&M turbines and foundation	675 NOK/kW/year	975 NOK/kW/year
O&M offshore substation	23 NOK/kW/year	23 NOK/kW/year
SUM	***698 NOK/kW/year***	***998 NOK/kW/year***
Onshore OPEX		
O&M onshore substation	9 NOK/kW/year	3 NOK/kW/year
SUM	***9 NOK/kW/year***	***3 NOK/kW/year***
Total OPEX	***707 NOK/kW/year***	***1001 NOK/kW/year***

Appendix D – Regression Results of Balancing Costs

Regression results Norwegian data

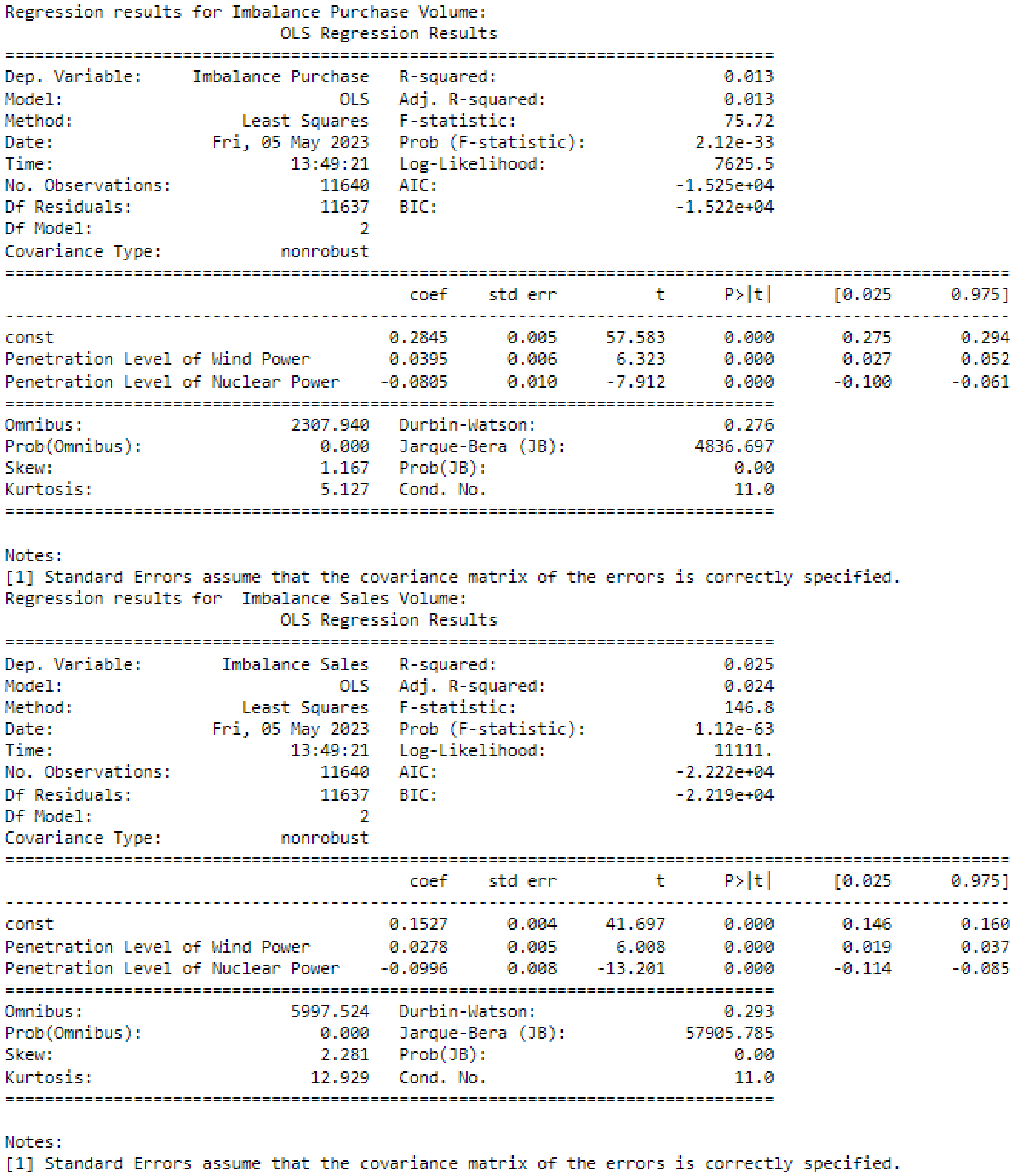


```
Regression results for Imbalance Purchase Volume:
                            OLS Regression Results
==============================================================================
Dep. Variable:     Imbalance Purchase   R-squared:                       0.117
Model:                            OLS   Adj. R-squared:                  0.117
Method:                 Least Squares   F-statistic:                     3740.
Date:                Fri, 05 May 2023   Prob (F-statistic):               0.00
Time:                        13:49:19   Log-Likelihood:                 23113.
No. Observations:               28343   AIC:                        -4.622e+04
Df Residuals:                   28341   BIC:                        -4.621e+04
Df Model:                           1
Covariance Type:            nonrobust
===================================================================================================
                                      coef    std err          t      P>|t|      [0.025      0.975]
---------------------------------------------------------------------------------------------------
const                               0.1378      0.001    122.849      0.000       0.136       0.140
Penetration Level of Wind Power     0.3040      0.005     61.160      0.000       0.294       0.314
==============================================================================
Omnibus:                     5313.773   Durbin-Watson:                   0.158
Prob(Omnibus):                  0.000   Jarque-Bera (JB):            10321.467
Skew:                           1.147   Prob(JB):                         0.00
Kurtosis:                       4.865   Cond. No.                         8.09
==============================================================================

Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.
Regression results for  Imbalance Sales Volume:
                            OLS Regression Results
==============================================================================
Dep. Variable:        Imbalance Sales   R-squared:                       0.032
Model:                            OLS   Adj. R-squared:                  0.032
Method:                 Least Squares   F-statistic:                     949.6
Date:                Fri, 05 May 2023   Prob (F-statistic):          3.98e-205
Time:                        13:49:19   Log-Likelihood:                 16790.
No. Observations:               28343   AIC:                        -3.358e+04
Df Residuals:                   28341   BIC:                        -3.356e+04
Df Model:                           1
Covariance Type:            nonrobust
===================================================================================================
                                      coef    std err          t      P>|t|      [0.025      0.975]
---------------------------------------------------------------------------------------------------
const                               0.2208      0.001    157.447      0.000       0.218       0.224
Penetration Level of Wind Power     0.1914      0.006     30.815      0.000       0.179       0.204
==============================================================================
Omnibus:                     5053.571   Durbin-Watson:                   0.148
Prob(Omnibus):                  0.000   Jarque-Bera (JB):             8816.968
Skew:                           1.158   Prob(JB):                         0.00
Kurtosis:                       4.451   Cond. No.                         8.09
==============================================================================

Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.
```

Regression results Finnish data

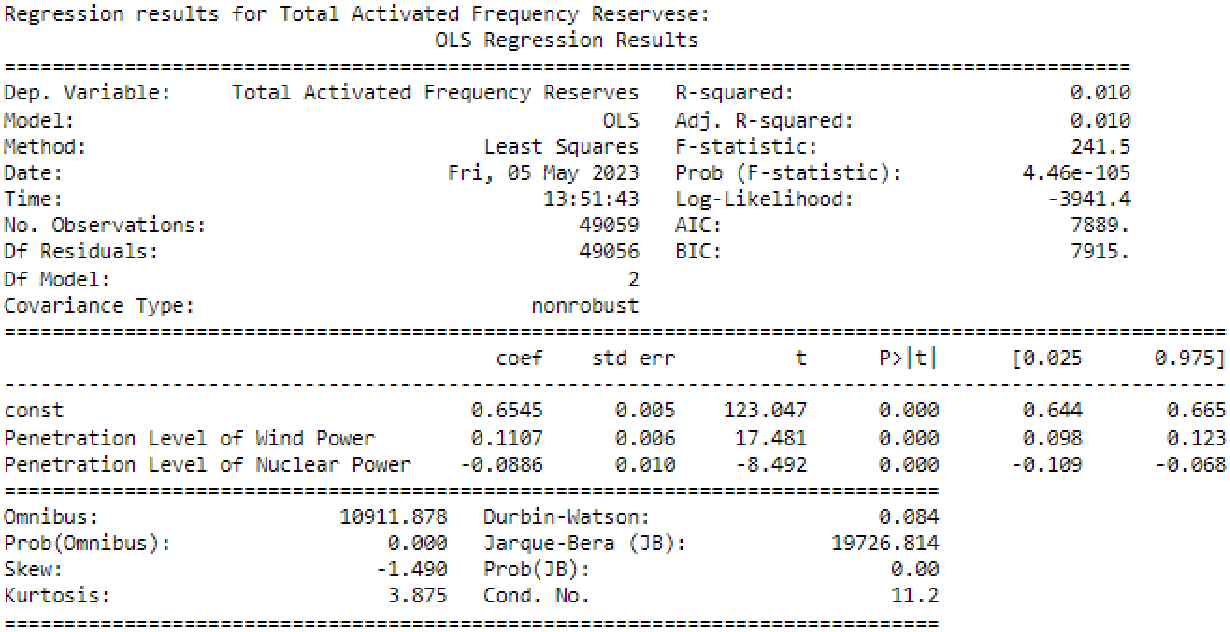


```
Regression results for Imbalance Purchase Volume:
                            OLS Regression Results
==============================================================================
Dep. Variable:     Imbalance Purchase   R-squared:                       0.013
Model:                            OLS   Adj. R-squared:                  0.013
Method:                 Least Squares   F-statistic:                     75.72
Date:                Fri, 05 May 2023   Prob (F-statistic):           2.12e-33
Time:                        13:49:21   Log-Likelihood:                 7625.5
No. Observations:               11640   AIC:                        -1.525e+04
Df Residuals:                   11637   BIC:                        -1.522e+04
Df Model:                           2
Covariance Type:            nonrobust
======================================================================================================
                                          coef    std err          t      P>|t|      [0.025      0.975]
------------------------------------------------------------------------------------------------------
const                                   0.2845      0.005     57.583      0.000       0.275       0.294
Penetration Level of Wind Power         0.0395      0.006      6.323      0.000       0.027       0.052
Penetration Level of Nuclear Power    -0.0805      0.010     -7.912      0.000      -0.100      -0.061
==============================================================================
Omnibus:                     2307.940   Durbin-Watson:                   0.276
Prob(Omnibus):                  0.000   Jarque-Bera (JB):             4836.697
Skew:                           1.167   Prob(JB):                         0.00
Kurtosis:                       5.127   Cond. No.                         11.0
==============================================================================

Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.
Regression results for  Imbalance Sales Volume:
                            OLS Regression Results
==============================================================================
Dep. Variable:        Imbalance Sales   R-squared:                       0.025
Model:                            OLS   Adj. R-squared:                  0.024
Method:                 Least Squares   F-statistic:                     146.8
Date:                Fri, 05 May 2023   Prob (F-statistic):           1.12e-63
Time:                        13:49:21   Log-Likelihood:                 11111.
No. Observations:               11640   AIC:                        -2.222e+04
Df Residuals:                   11637   BIC:                        -2.219e+04
Df Model:                           2
Covariance Type:            nonrobust
======================================================================================================
                                          coef    std err          t      P>|t|      [0.025      0.975]
------------------------------------------------------------------------------------------------------
const                                   0.1527      0.004     41.697      0.000       0.146       0.160
Penetration Level of Wind Power         0.0278      0.005      6.008      0.000       0.019       0.037
Penetration Level of Nuclear Power    -0.0996      0.008    -13.201      0.000      -0.114      -0.085
==============================================================================
Omnibus:                     5997.524   Durbin-Watson:                   0.293
Prob(Omnibus):                  0.000   Jarque-Bera (JB):            57905.785
Skew:                           2.281   Prob(JB):                         0.00
Kurtosis:                      12.929   Cond. No.                         11.0
==============================================================================

Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.
```

Regression results Swedish data



```
Regression results for Total Activated Frequency Reservese:
                                    OLS Regression Results
==============================================================================================
Dep. Variable:     Total Activated Frequency Reserves   R-squared:                      0.010
Model:                                            OLS   Adj. R-squared:                 0.010
Method:                                 Least Squares   F-statistic:                    241.5
Date:                                Fri, 05 May 2023   Prob (F-statistic):         4.46e-105
Time:                                        13:51:43   Log-Likelihood:               -3941.4
No. Observations:                               49059   AIC:                            7889.
Df Residuals:                                   49056   BIC:                            7915.
Df Model:                                           2
Covariance Type:                            nonrobust
======================================================================================================
                                       coef    std err          t      P>|t|      [0.025      0.975]
------------------------------------------------------------------------------------------------------
const                                0.6545      0.005    123.047      0.000       0.644       0.665
Penetration Level of Wind Power      0.1107      0.006     17.481      0.000       0.098       0.123
Penetration Level of Nuclear Power  -0.0886      0.010     -8.492      0.000      -0.109      -0.068
==============================================================================
Omnibus:                    10911.878   Durbin-Watson:                   0.084
Prob(Omnibus):                  0.000   Jarque-Bera (JB):            19726.814
Skew:                          -1.490   Prob(JB):                         0.00
Kurtosis:                       3.875   Cond. No.                         11.2
==============================================================================
```