Pre-study for SMR and nuclear establishment in Norway

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Nomenclature

Abbreviations

DSA The Directorate for Radiation Protection

GIS Geographic Information System

IAEA International Atomic Energy Agency

IFE Institute of Energy Technology

LCOE Levelized Cost of Energy

LMA Long-term Market Analyses

LWR Light Water Reactors

MCDA Multi-criteria Decision Analysis

MoU Memorandum of Understanding

NND Norwegian Nuclear Decommissioning

NVE The Norwegian Governmental Energy Commission

SMR Small Modular Reactors

Abstract

Norway has Europe's highest share of renewable electricity production and the lowest power sector emissions. Thanks to the country's stable power production, Norway has affordable and stable access to electricity, leading to industries choosing to relocate to the country. To keep this industry, the country needs to meet the increasing electricity demand and ensure it is still competitively priced. Forecasts of the electricity needs in the future to 2050 indicate that electricity demand can increase by 50 TWh in the lowest scenario and up to 160 TWh in the highest scenario. To meet these needs, the forecasts indicate that new wind power will meet half the demands and the rest by increased solar and hydropower [1]. However, wind power on land has recently been controversial over the last few years in Norway due to land disputes. The uncertainty of new investments in production, the European energy market being affected by the war in Europe, and the reduced gas supply has led to higher electricity prices in Norway and the risk of having a power deficit by 2027. It has also led Norway to rethink its energy investments to keep up with the green shift. New nuclear technologies, such as small modular reactors (SMRs), are therefore gaining more focus and being investigated.

With help from nuclear consultants from WSP, the focus of this thesis project has been to establish a process for evaluating geographical considerations and different counties' energy needs in Norway for a site selection for SMRs. By doing and reviewing an energy mapping of Norway's county's energy production, consumption, and energy balance for 2021, different operators of interest were chosen for further investigation for a siting. After selecting a county, a fully geographical information system (GIS) SMR siting was performed. The county was subjected to a multi-criteria decision analysis based on specific criteria drawn from IAEA regulation documents and from nuclear consultants from WSP. Criteria weights were assigned concerning the chosen county's geographical and infrastructure advantages and disadvantages. The three cases, Open, Normal and Restrictive, were conducted to assign spatial suitability advantages for all the criteria. Models were then created in a ArcGIS to identify possible candidate sites.

Four different geographical maps were constructed showing suitable sites for SMRs, ranging from very suitable to unsuitable. The first map without any restrictions offers more potential than the other cases due to no restrictions being introduced. The Open case provides the most potential among the three cases with restrictions due to the low geographical distances considered for the restriction criteria. The Restrictive case offers the most minor suitable area than the other due to the high geographical distance considered for all the criteria. The Normal case falls between the Open and Restrictive.

Chapter 1.

Introduction

1.1. Problem description

Energy demand is currently high and forecasted to increase in the coming decades. Norway has the highest share of renewable electricity production and the lowest power sector emissions. Norway has primarily relied on hydropower, with a share of about 91.5% of the country's total production in 2021 [2], with wind power being in second place with a share of 7.5% [3]. Thanks to its stable power production and the country's affordable and stable access to electricity, many industries have chosen to relocate to Norway. To keep this industry, the country needs to meet the increasing electricity demand and ensure it is still competitively priced [4].

The forecasts of the electricity needs in the future to 2050 indicate that electricity demand can increase by 50 TWh in the lowest scenario and up to 160 TWh in the highest scenario. To meet these needs, the forecasts indicate that new wind power will meet half the demands and the rest by increased solar and hydropower [1]. Recently, however, a significant increase in wind and solar power has been introduced into the system, which has caused concerns for the stability of the electricity system due to its intermittent characteristics. Also, wind power on land has been controversial over the last few years in Norway due to land disputes, which led to the licensing for new projects being halted in 2019 and began again in 2022. Offshore wind power has thereby been Norway's new focus, but due to high investment costs and limited technology, it will only take off after 2030, which requires technological development and a cost reduction to become a reality [4].

The uncertainty of new national investments in energy production, in combination with the rapidly changing and unpredictable energy market, has led to higher electricity prices in Norway and the risk of having a power deficit by 2027. It has also led to Norway's need to rethink its energy investments to keep up with the green shift, and new technologies in nuclear, such as small modular reactors (SMRs), are gaining focus. Enabling the implementation of new fossil-free energy sources such as SMR in Norway is therefore of high interest, and complementing the energy mix with other energy sources could strengthen national and industrial competitiveness. Therefore, studying how the implementation of SMR could be performed nationally would provide valuable information on potential future key power generation projects in Norway [5].

To better understand where new energy production should be constructed and where it will benefit the Norwegian energy system the most, energy mapping over the country is required. This will result in locating the counties with the largest consumption and production, thereby locating counties with power deficits. It will also help in understanding what category has the highest consumption within the county, thereby, an evaluation of whether SMRs will benefit the county can be drawn.

Furthermore, SMRs require different geographic and infrastructure requirements than hydropower and wind power, a siting is therefore required in a selected area to understand the location's advantages and disadvantages.

1.2. Company description

This master's thesis has been carried out in collaboration with WSP. WSP is a global analytic and technology consulting firm providing design services to clients in the environment, transportation, infrastructure, building, power, energy, water, and resource sectors. The company originates from Canada with approximately 65 000 employees situated all over the world.

WSP Sweden has about 4000 employees who operate from around 30 offices around the country. It is in partnership with WSP Sweden and more specifically within the systems division of energy and the sector and team of Nuclear Power Advisory that this research has been carried out [6].

The Nuclear Power Advisory team at WSP works with a focus on security, efficiency, and sustainability. They offer services within management, nuclear safety, nuclear waste, testing and commissioning, construction and calculation, technical documentation, and decommissioning of nuclear operations [7].

The results are intended to be used internally at WSP to provide added value to projects and investigations within the energy sector and to contribute to the overall research of Norway's energy system.

1.3. Aim of the research

The aim of this research is to investigate and create insights into a hypothetical future development of where an SMR could be constructed in Norway. The research also aims to provide insights into the Norwegian energy system and locate where the majority of energy is consumed and where it is produced. It also investigates what types of energy sources are used today, which are predicted to be used in the future, and where they should be placed.

Norway's future energy production is a debated topic with close connections to political agendas, and many of the current investigations and reports on the topic are, therefore, often more or less biased. Due to different complications with investments in wind and hydropower and the fact that new technologies within nuclear, such as SMR, have made a breakthrough, investing in nuclear power has become an active topic in the country. The aim is to investigate if building SMR in the country is possible and where it may be suited. The aim is to conduct an energy mapping over the country to find which county has an energy deficit and requires new energy production. It aims to see if the methodology works in practice and is suitable for assessing where new energy production should be constructed.

1.4. Research questions

Two main research questions with coherent subquestions have been developed to answer the aim of the thesis:

1. Research Question 1: Where and why should new energy production be constructed in Norway?
    a) How much energy is produced and where is it produced?
    b) What energy source is used for production?
    c) How much energy is consumed in the country and where is it consumed?
    d) Which county has the highest energy deficit?
    e) What category has the highest consumption in the counties with the highest energy deficits?
    f) Based on the results from the questions above, which county needs new energy production and should be chosen for an SMR siting?
2. Research Question 2: Through an SMR siting, how suitable is it to deploy an SMR in the chosen county?
    a) What parameters/criteria should be chosen for geographical and infrastructure evaluation?
    b) What restrictions should be evaluated for geographical and infrastructure evaluation?
    c) Based on the criteria and restrictions evaluation, what are the county's geographical and infrastructure advantages and disadvantages?

d) Based on the results, where is it suitable to construct an SMR?

e) How should the result be presented to get a clear view of where the construction of SMR is suitable?

Research question 1 addresses how Norway's energy system is constructed in 2021. It investigates the country's energy production, consumption, and energy balance. With an energy mapping over the country, the aim is to find the counties with the lowest energy balance and, therefore, need new energy production. From the counties with the lowest energy balance, a specific county can be selected to be evaluated in research question 2.

Research question 2 evaluates the chosen county's geographical and infrastructure advantages and disadvantages. The aim is to find different evaluation and restriction parameters concerning IAEA regulations, WSP nuclear consultans, and the county's geography and infrastructure. How the evaluation and restriction parameters should be combined and presented to establish a precise overview of the county on where it's possible to construct an SMR is also investigated.

1.5. Delimitations

Norway's existing electricity system is composed of a diverse array of power sources, each possessing unique attributes. To understand how SMRs can contribute to the power system, it is essential to have a comprehensive understanding of all these power sources. On what type of fuel they use, where they can be constructed, and how they generate energy. In this report, however, the focus is not on how each power source works, it is instead only covered to the degree needed to provide a basis and context on how they support Norway's energy production today and how they may look in the future. To receive the best data to compare each energy source, 2021 was set as the newest and best data quality. Therefore, all data analyzed in the energy mapping are from that year, even though some energy sources may have updated production numbers from 2022 and forward. Two future forecasts are however compared from 2021 and 2022 to get the most updated understanding of how the future may look like.

The policies, regulatory aspects, and social views of this research are currently limited to a general level. A more comprehensive exploration would overly expand the research scope. It's important to note that new information regarding these topics continues to evolve throughout the course of this study. Therefore, the latest social views, policies, and regulatory aspects may not be up to date at this moment.

The study did not include factors such as economic aspects and cultural issues, disposal of radioactive waste, or the public opinion of constructing an SMR in the chosen study area to any significant extent. However, some aspects of the economy are brought up when it is considered necessary but simplified to an accessible level.

Only one county and operator of interest is chosen for an SMR siting as the research otherwise would be too extensive. Parameters and criteria are, therefore, only adapted to that location and would be different if another site were to be studied. A precise location for the construction of SMR is not evaluated; thus, it would need another more detailed and accurate siting of a smaller site. Instead, a broader overview of siting is given over a whole county, with recommendations for smaller areas where a more precise siting could be done.

Chapter 2.

Theory

This chapter covers why new energy construction is being investigated in the country and why SMRs are a possible solution. It briefly introduces Norway's current energy system and its future prognosis. A brief introduction to SMR technology, an overview of Norway's history with nuclear power, and the country's different social and political views of nuclear are introduced. Furthermore, Norway's regulatory situation for implementing SMR is introduced. The chapter also aims to describe where Norway stands with introducing nuclear power into its energy mix, what previous knowledge the country has, and why SMRs could benefit the energy system. It also presents the reasons for evaluating different sites through screening, pre-studies, and site-specific studies, and an introduction to siting is presented.

2.1. Introduction to Norway's energy system

Norway leads Europe in the highest share of renewable electricity production and has the lowest emissions from the power sector because of its large amount of hydropower. After 2021 the country had around 40 000 MW of installed capacity and set a production record of 157.1 TWh, which is about 11 TWh more than the average over the last five years [2]. This was driven by good reservoir water levels and increased wind power capacity. Norway is currently investing heavily in renewable energy production, with wind power accounting for 12.5% of capacity and dominating new investments [8].

Hydropower is Norway's primary source of electricity, and its production depends on annual precipitation, unlike the rest of Europe, which relies on thermal power plants with fuels available in the energy markets. Norway has half of Europe's reservoir storage capacity, and its large storage allows for flexible production that can rapidly increase or decrease at a low cost to balance the supply and demand at all times in the power system. As intermittent production technologies such as wind and solar become more prevalent, flexibility in the rest of the power system becomes increasingly important [8].

Norway deregulated its power market in 1991, providing long-term investment signals through electricity prices and enabling short-term balancing of supply, demand, and transmission. Renewable power plants are located where resources are available, resulting in uneven distribution of production capacity between different regions of Norway. Therefore, a well-developed power grid must transmit electricity to consumers nationwide [8].

Thanks to the hydropower plants, Norway has a more decentralized transmission network than Sweden. They are also ahead of Sweden as the largest investments in the transmission network have been made in the last ten years, which makes it technically easier to continue the expansion of transmission lines [4].

Norway's power system is closely integrated with other Nordic systems through market integration and physical terms. In turn, the Nordic electricity market is integrated with the rest of Europe through cross-border interconnectors to the Netherlands, Germany, the Baltic states, Poland, and Russia. This integration, combined with the characteristics of hydropower production, makes Norway's power supply system highly flexible and reduces vulnerability to fluctuations in output between seasons and years [8].

In 2021 the gross electricity consumption in Norway was 139.5 TWh, about 5 TWh more than the average five years [2]. This was driven by the industry and transport sector's electrification [4]. This means that Norway had a positive electricity balance of 18 TWh and was a net exporter of electricity in 2021 [9].

Due to Norway's affordable and stable access to electricity, industries have chosen to relocate to Norway. To keep this industry, the country needs to meet the increasing electricity demand and ensure it is still competitively priced [4]. The increased demand is estimated to come from new industries such as data centers, battery factories, electrification of oil extraction in the North Sea, hydrogen for industry and transport, and electric vehicles [4].

Two different governmental and state-owned enterprises have given the future prediction for Norway's energy production and consumption. The first one is given by Statnett, a state enterprise owned by the Norwegian state and the system operator in the Norwegian energy system [10]. The other one is given by the Norwegian governmental energy commission (NVE).

In the prognosis by Statnett, the energy demand for 2050 will be much higher than expected, and the enterprise gives three scenarios from 2022 to 2050. The consumption will increase by 50 TWh in the lowest scenario and up to 160 in the highest scenario. In the standard scenario the consumption will increase by 80 TWh, half of this demand is primarily being met by 40 TWh of new offshore wind power, the rest will be met by increased solar, hydropower and, onshore wind power [1].

In the prognosis by NVE, the new energy demand from 2021 to 2040 will be higher than the newly constructed power production during that period. The consumption for 2040 will increase by about 36 TWh and the production by about 28 TWh. The increase in production is divided into two periods: the first period from 2021 to 2030, where solar and hydropower will increase the most, and the second from 2030 to 2040, where investments in wind power will dominate. The power surplus of 17 TWh from 2021 falls to 9 TWh in 2040 [11].

Both the reports from Statnett and NVE show that wind power will have a significant role in the future. However, wind power on land has been controversial over the last few years in Norway [12]. The subject has started a lot of debates over the years and is facing negative social acceptance. This resistance is why Norway is considering offshore wind power. Due to its high price and limited technology, offshore wind power will only take off after 2030, which requires technological development and a cost reduction to become a reality [4].

The uncertainty of new investments in production, the European energy market being affected by the war in Europe, and the reduced gas supply has led to higher electricity prices in Norway and the risk of having a power deficit by 2027 [5]. This has also led to Norway's need to rethink its energy investments to keep up with the green shift, and some municipalities are shifting their focus towards modern nuclear power, such as SMR [13].

2.2. Small modular reactors

SMRs are small-scale nuclear reactors that produce 300 MW or less. They are designed with modern technology for serial factory construction to gain economies of scale, short construction time, and reduced siting cost [14].

SMRs have a passive safety system in the event of a malfunction, making them operate without continuous manual monitoring or external safety systems [15]. Many reactors are designed to be placed below ground level, generating a lower risk for terrorist threats [14]. SMRs' small size implies that they generate less heat that needs to be removed by the safety system if an accident occurs. Heat cooling can arise passively to the surrounding compared to larger reactors, making SMRs naturally safe [16].

Except for the safety advantages, the increased interest in the technology is thanks to its small size and the possibility of being standardized and factory produced, lowering the investment and cost risk. Instead of constructing the reactor on-site with all associated costs that come with the necessary contractors, the reactors can be transported and installed at the site in a finished format [14].

After construction, SMRs are often united to comprise a large nuclear power plant. This is due to the modular design that allows them to operate in multi-module configurations where several reactor units can be installed together, making up a larger plant. This allows potential investors to gradually increase their investment in nuclear energy generation over time instead of investing in a large sum at once. An example in the use of SMRs standardization and modularity can be seen in figure 2.1.

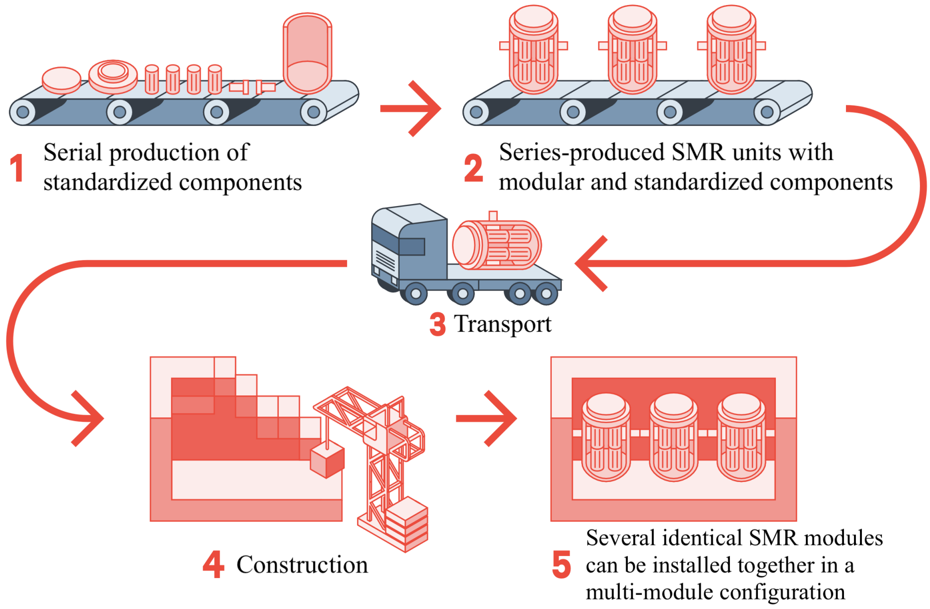


Figure 2.1.: Example of the use of SMRs standardization and modularity [15]

The smaller size enables construction on more remote sites than larger reactors due to more accessible access to coolant, less need for larger transports, and passive cooling, removing the need for water supply. It allows construction in places with small or non-existent electrical grids, as the reactors can be placed closer to the consumer. The possibility of producing high-temperature heat adjacent to the consumer opens up many possibilities beyond just power generation [15].

Flexible operation is another option with SMRs, and many reactors are expected to be able to regulate their power output within minutes. This could be useful in connection to intermittent energy production, such as wind power or solar cells, to compensate for the volatile production. Another application area is in an industrial process with varying energy demand [15].

The SMR concept is broad and can include many different types of reactors, types of coolants, construction methods, and usage. It is often categorized into two groups, conventional and advanced SMR.

Conventional SMR is based on Generation II and Generation III/+, which operate as light water reactors (LWRs). These reactors are most similar to operating power and naval reactors today, being cooled and moderated by ordinary water. They, therefore, have the lowest technological risk and a high degree of technical maturity. These reactors are estimated to be commercialized in the second half of the 2020s. They are mainly planned for use for energy production or district heating [17]. The use of conventional SMRs can be seen in figure 2.2.

Advanced SMR is based on Generation IV reactors and is a common name for future nuclear power systems. Another coolant than water, such as liquidized metal, gas, or molten salt, often cools these reactors. This allows the reactors to operate at higher temperatures than conventional LWRs, which makes them more suitable for hydrogen production or process heating for industries. They are also more fuel efficient and do not generate long-lived nuclear fuel waste; eventually, they can reuse spent nuclear fuel. This, however, requires a system of recycling and reprocessing used nuclear fuel. Generation IV reactors are designed with high safety, a significantly lower risk of severe accidents, and features that make it challenging to utilize fission products for nuclear weapon applications. Advanced SMRs are generally technologically and commercially less proven than LWRs [18] [19]. In Figure 2.2 examples are given of different user applications needing different temperatures.

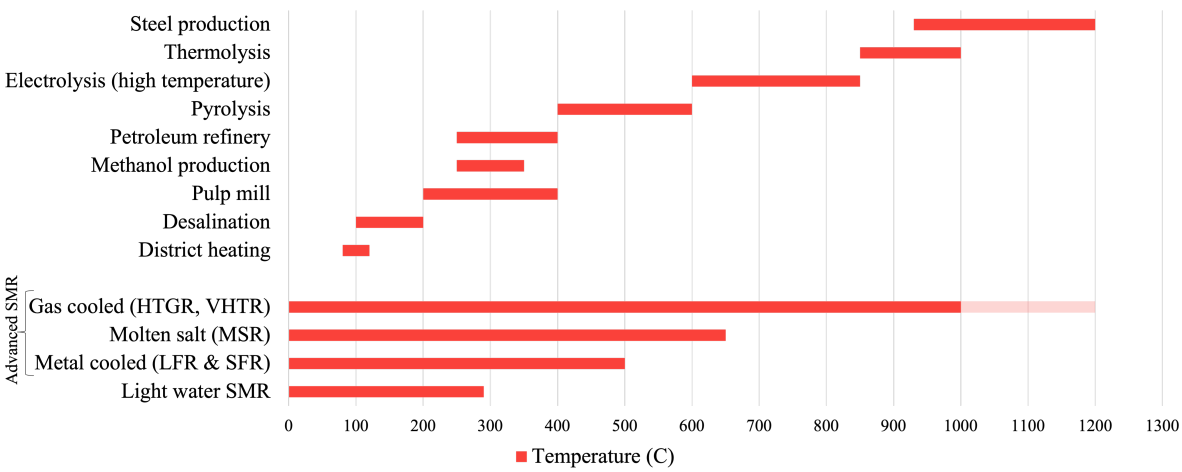
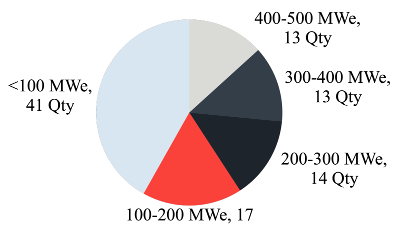


Figure 2.2.: Different heat applications for SMR-technologies [20]

Various designs and concepts exist worldwide today, with over 90 unique projects being developed in different stages. Some are already in use, and some are in the development phase. An overview of existing projects has been summarized and visualized in Figure 2.3. The reactors are established by nuclear companies and startups, and research institutions. Some of the biggest companies in the industry are the UK-based company Rolls Royce SMR and the American companies NuScale and GE Hitachi [14].

Technologies	Amount
Water-cooled reactors	28
Gas-cooled reactors	20
Fast neutron reactor	16
Molten salt reactor	13
Micro-SMR	8
Water-cooled (marine)	7
Water-cooled (heavy)	3

(a) Technologies



(b) Quantity & size

Project status	Amount
Early development	56
Advanced development	20
Under construction	3
Test facility operating	2
Operating	6

(c) Project status

Figure 2.3.: Different status, quantity of size and technologies in SMRs being used today [20]

The leading development of SMR technologies is in the same countries that have been historically large nuclear energy nations, such as the UK, US, China, Canada, and Russia. However, multiple nations that have not had atomic power before are now finding their interest in the technology, which can be related to the fact that the investment barrier for nuclear power has been lowered with SMR. This also brings new challenges regarding regulations and systems for managing nuclear waste, which must be built from the ground up [14].

2.3. Norway's history with nuclear

Nuclear power has never been a part of Norway's energy production. However, the subject area has been studied for decades, mainly through the operation of four research reactors that were operational between 1951 and 2019. In 1948 Institute for Energy Technology, IFE, was established in Norway and was a forerunner in international energy research and began to prepare for nuclear use in an early stage. IFE's mission was to research the peaceful utilization of nuclear energy [21]. In 1951 the first research reactor in Norway, known as JEEP 1, was put into operation in Kjeller with a thermal output of 400 kW [22]. This made Norway the fourth country in the world to have its own nuclear reactor. JEEP 1 reactor was later replaced sixteen years later by JEEP 2 [21]. JEEP 2 reactor had a thermal output of 2 MW and was used for fundamental research for medical and technical use as well as the doping of silicon with phosphorus in the production of semiconductors. In 1958 another reactor in Halden was put into operation with a thermal output of 25 MW. This reactor was mainly used for international collaborative research on safety for certification but also provided heat to a paper mill nearby. A fourth reactor was put into operation in Kjeller named NORA, which was, however, only operated from 1961 to 1968 [22].

In 2018 the Halden reactor was shut down for good, and in 2019 the JEEP 2 reactor was shut down. This ended the Norwegian nuclear program and began a new era of nuclear decommissioning [23]. After the decommissioning of the four reactors, about 16.5 tonnes of spent nuclear fuel is now needed to be disposed of in a safe way. The fuel is now stored in IFE facilities in Kjeller and Halden [24]. In 2018 the Norwegian Nuclear Decommissioning, NND, was established in Halden to dismantle Norway's historic nuclear research facilities in a safe and secure manner and take over the responsibility from IFE. As a part of that work, the agency must also find solutions for waste management. In addition, NND must also handle radioactive waste from other sectors such as industry, defense, medicine, and consumables [25]. The dismantling and clean-up work of the reactors are estimated to take around 20-25 years, and in 2045 the construction area will be free of all traces of nuclear activity and freed for other use. The final facility for storing radioactive waste is expected to be established in 2070 [24].

In March 2023, Norsk Kjernekraft, which is a technical energy company in the nuclear industry, signed a Memorandum of Understanding, MoU, with Rolls-Royce SMR Limited.

The parties want to work together to increase the acceptance of nuclear power in Norway and to establish future projects that could lead to the deployment of Rolls-Royce SMRs in Norway [26].

2.4. Political and social views of nuclear in Norway

In 1969 the Norwegian government discussed the possibility of constructing nuclear power plants due to the uncertainty of expanding hydropower. At that time, nuclear was seen as an economical supplement to hydropower. The same year the parliament approved a planning process, and in 1974 plans for constructing a nuclear power plant in the Oslofjord area were presented. In 1978 a committee recommended the development of nuclear power, provided that strict safety requirements were met, but one year later, the parliament chose to continue focusing on hydropower [21], partly due to the Tree Mile Island nuclear accident in the U.S [27]. The same conclusions were drawn after the Chernobyl accident in 1986, where high radiation levels started spreading in Scandinavia. 37 years later, radiation still remains a problem for farmers in Norway [28].

These two accidents generated a shift in public opinion against nuclear power, generating the decision to abandon the development of nuclear power in Norway. At that time, the concerns about environmental impact and safety were too high, and widespread protests were against its development [21].

Today public opinion is still mixed with some advocates for the use of nuclear power as a way to meet the future increased need for electricity in a more stable way and without destroying nature as much as wind power. However, many people remain skeptical about its safety and believe that hydropower and wind power are safer and more sustainable options [29].

In 2023 NVE allows for nuclear power in the future and states that the country must keep up with technological developments and be open to this technology in Norway's future energy production [30]. This conclusion from the energy commission is also supported by the latest strategy report for Energi21, which states that Norway should undertake research and commercialization activities in nuclear power. Energi21 is Norway's national research and innovation strategy for climate-friendly energy [31].

The subject is, however, still uncertain by most of the political parties in Norway, and so far, only two parties have come out and said that they are open to considering nuclear power in Norway. Most parties are skeptical about the safety and economic aspect of the technology and would like to focus on wind power and hydropower instead [29]. However, more and more parties are starting to open up the subject for discussion and are willing to invest in the technology SMR in the future when the concept is more mature [32].

Still, multiple municipalities and industrial companies with specific power and location needs have contacted Norsk Kjernekraft AS to investigate the possible deployment of SMR [33]. The people of Aure municipality have said no to building wind power, and the municipality is now forced to think differently and is currently involved in a project with Norsk Kjernekraft [29].

Nuclear power is an active subject being debated daily, both political and social, in Norway, with updates regarding political and social views constantly changing [32].

2.5. Regulatory situation for implementation of SMR in Norway

As mentioned, Norway's energy commission started allowing nuclear power in the future at the beginning of 2023, which is also supported by the latest energy strategy report in Energi21, which states that the country must keep up with technological developments and be open to this technology in Norway's future energy production.

It is not forbidden to build nuclear power in Norway, and the country has legislation that sets the framework for how nuclear power can be established. The atomic energy act states that establishing nuclear power requires a license, and the law states that the Norwegian parliament has to approve before a license can be granted under the atomic energy act [34]. The Directorate for Radiation Protection, DSA, must assess all applications for permits under the Atomic Energy Act and before a nuclear power plant is put into operation, the owner must obtain a permit from DSA. The owner is then responsible for assessing, documenting, and ensuring safety and security assessments must be verified by an independent party before being submitted to DSA. DSA can, at any time, demand access to the facility and must supervise operations. If necessary, they can impose measures or stop operations [35]. DSA conditions for a license are based on safety standards from the International Atomic Energy Agency, IAEA. The license requires that the design and safety assessments reflect the local conditions but with the general approval of the design as a ground [36]

The Norwegian Planning and Building Act, Pollution Act, and Impact assessment Regulations describe the process for the establishment of facilities that cause or may cause pollution, and these states that the process applies to nuclear power plants [37] [38] [39].

Initiating nuclear power plant establishment involves a planning process and a proposal for an investigation program. This proposal outlines details, including the power plant specifications, location, conditions that need investigation to ensure safety and environmental concerns are addressed, and the involvement of authorities and stakeholders throughout the project. The proposal undergoes a public consultation and is presented to relevant parties, including the municipality, DSA, and other responsible authorities. Following the consultation period, the responsible authorities determine the investigation program.

The impact assessment regulations establish that the DSA, the Ministry of Health and Care, the Ministry of Climate and Environment, the Norwegian Directorate of Water Resources and Energy, NVE, and the Ministry of Oil and Energy are responsible authorities when investigating nuclear power plants.

The investigation work in stages, with hearing and partial approval, may be necessary. Upon completion of the impact assessment, a license can be granted for construction. Before the plant is put into operation, DSA must grant an operating permit based on a safety report showing the plant has been built in line with the license [40].

The legislation in Norway makes it entirely possible to build nuclear power plants. Norway also has prerequisites such as basic nuclear competence from IFE which can be built on, and DSA is a competent supervisory authority with experience from supervision at IFE and international cooperations. Norway already has radioactive waste, which must be handled by NND and treated similarly to waste from nuclear power plants [40]. The country's geology is well suited for facilities for radioactive waste [41]. Norwegian industry also has a lot of experience with construction and operation of advanced technology. However, building nuclear power in Norway will be challenging, and significant political support and imported competence are needed to generate a project more extensive than the four test reactors [40].

2.6. Reasons for a comprehensive site assessment

Evaluating different sites through screening, pre-studies, and site-specific studies is essential for making informed decisions and achieving successful outcomes in various projects, especially those with critical or complex requirements such as SMRs. Some reasons are:

1. **Optimized resource allocation:** Conducting a preliminary siting allows you to identify sites that align with the project's goals while minimizing resources spent on unsuitable locations. This helps save time, effort, and funds on sites that may not meet the project's needs [42].

2. **Risk mitigation:** Early-stage siting helps identify potential risks and challenges for each site. Site-specific studies allow for a deeper analysis of these risks and the development of strategies to mitigate them effectively [43].

3. **Safety and Risk Assessment:** By assessing sites for safety factors, geological stability, natural disasters(landslides, flooding) and potential environmental impacts, and proximity to population centers, you can choose a location that ensures the safety of the project and surrounding areas [44].

4. **Regulatory Compliance:** Nuclear construction is subject to strict regulatory

standards and requirements. Screening helps identify regulatory considerations, ensuring the structure follows all necessary guidelines. This minimizes the risk of delays, legal challenges, and non-compliance issues [45].

5. **Infrastructure and Accessibility:** Nuclear facilities require specialized infrastructure, such as access roads, transportation for radioactive materials, and power supply. A screening assesses the existing infrastructure and identifies necessary upgrades or additions to support the facility's operation [46].

6. **Site Suitability:** Pre-studies help determine if a potential site is suitable for nuclear construction. Factors like geological stability, topography, transportation, and access to water are assessed to ensure the site can withstand the demands of nuclear facilities [47].

7. **Operational Efficiency:** Evaluating the local climate, available resources, and infrastructure helps optimize the operational efficiency of the nuclear facility. This includes factors such as cooling water sources, waste heat discharge, and access to transmission lines [48].

8. **Project Feasibility:** A pre-study assesses the overall feasibility of the nuclear construction project, taking into account technical, economic, regulatory, and environmental aspects. This assessment helps stakeholders make informed decisions about proceeding with the project [49].

2.7. Introduction to siting

The ability to value different sites through a multi-step approach helps eliminate unnecessary work. It gives a clear overview and options for a more detailed and in-depth analysis and siting.

Several studies, such as Geographical Considerations in Site Selection for Small Modular Reactors in Saskatchewan [50] and Small Modular Reactor (SMR) Siting in the State of Main [51] have focused on siting SMRs for specific power generation technology applications using appropriate site-screening criteria and a geographic information system (GIS) corresponding to the environmental factors identified. These studies have all used different criteria corresponding to the chosen location and based on different laws, nature, applications, etc.

Location analysis determines how tangible assets such as land and buildings can objectively support an activity's performance to the suppliers, clients, and other facilities it interfaces with. The decision process of location analysis emphasizes the systems approach to distribution is a complicated process that requires many trade-offs. The location analysis and selection method should follow the steps: Identifying the dominant factor in a location, developing alternatives, and evaluating the alternatives to the site

[52].

Several methodologies are available during location analysis, including a load-distance model that analyzes location facilities based on proximity features. The factor rating method is an analysis method that involves identifying key factors responsible for the industry's success and giving those factors a weighted value, which is then used to calculate the factor rating responsible for the company's success. The transportation model is another technique that involves the movement of goods to different locations from where they are produced, and it is essential in finding the most efficient route for resource allocation [53]. With GIS and multi-criteria decision analysis (MCDA) an increase in the efficiency and accuracy of findings during site selection is given [54] and is therefore used in this research.

This research investigates the identification of suitable sites for SMRs across Norway, focusing on geographical factors. It demonstrates how an energy mapping can be made to determine what area to focus on for a possible SMR siting and how geographical siting activities fit into the phases of infrastructure development and identifies the factors likely to be used to determine appropriate sites based on safety, health, environmental and social parameters. The data used to inform the site selection process, implementation strategies for siting process, and methods for assessing the various siting factors are determined and described.

This study aimed to develop an objective, reproducible process for optimum SMR site selection. It was aimed to identify the essential spatial geographic factor in determining suitable sites for SMRs. The site suitability analysis was based on objective geographical factors. The study siting criteria did not include factors such as public perceptions, cultural resources issues, competition with other generation technologies, and cost or disposal of radioactive waste. All these factors must be considered by the chosen study areas governing bodies.

Chapter 3.

Methodology

This chapter describes the method used to answer the two research questions and their subquestions. The process toward the final answer to each question will be described and motivated.

3.1. Methodology energy mapping

This first part describes the method to answer the first research question, “Where and why should new energy production be constructed in Norway.”. This research was conducted through a combination of qualitative and quantitative research. Information and data were collected through several types of primary and secondary sources. Primary sources were, for example, different types of governmental reports. Secondary sources were, for example, scientific journal articles, technical reports from authorities and NGPs, and databases of various types. The method can be categorized into two groups: Energy mapping and Operators of interest. These groups and their subquestions are presented in Table 3.1.

Each group’s method and subquestions will be described and motivated. The method follows a flexible timeline since several steps were conducted and iterated in parallel. The sequence of sections follows the order of the research subquestions.

Table 3.1.: Different groups and their subquestions

Group	Subquestions
Energy mapping	• How much energy is produced in the country, and where is it produced? • What energy source is used for production? • How much energy is consumed in the country, and where is it consumed? • Which county has the highest energy deficit? • What category has the highest consumption in the counties with the highest energy deficits? • How does Norway's power grid system look like? • What do Norway's energy production and consumption forecasts look like based on consumer trends and future plans and investments?
Operators of interests	• Based on the results from the questions above, which county needs new energy production and should be chosen for an SMR siting?

3.1.1. Energy mapping

The mission of the first part of the research question was to collect data on Norway's energy production and consumption. Fortunately, this type of data could be collected from the same source, Statistics Norway, the National Statistical Institute of Norway, and the primary producer of official statistics. Different datasets were reviewed and combined, and conclusions led to the year 2021 having the most complete data and, therefore, set as the year to analyze each subquestion within this group. Furthermore, Norway's energy consumption and production forecasts were studied. The process consisted of conducting the literature review in terms of article search and screening, where different types of scientific forecast reports from primary sources were reviewed. The article search and screening process is described and illustrated in Table 3.2. Two main reports were found eligible and included in the research. One is from NVE, Norway's Directorate of Water Resources and Energy, and is a subordinate to the Ministry of Petroleum and Energy. The other one is from Statnett, which is a state enterprise owned by the Norwegian state and the system operator in the Norwegian energy system.

Table 3.2.: Search and screening process

Process	Description
Article Search	Articles identified through search with keywords such as "Future energy production and consumption Norway," "Norway's future energy prognoses," and "Energy production and consumption in Norway.".
Screening	Articles were screened through title and abstract and then excluded if they were found to be irrelevant.
Eligibility	Articles were then assessed for eligibility and excluded due to being outdated or irrelevant.
Included	The articles that made it through these steps were included for final review.

3.1.2. Operator of interests

The second part of the research question was to analyze the information and data collected from the previous groups to select a county in Norway to conduct an SMR siting on. The top three counties with the highest energy deficits were considered as potential operators of interest. A brief screening and eligibility check was performed on each county to investigate area size, population density, and geography. Future energy plans for the county were also considered. Because of time limitations, only one operator was then chosen for the actual SMR siting.

3.2. Methodology SMR siting

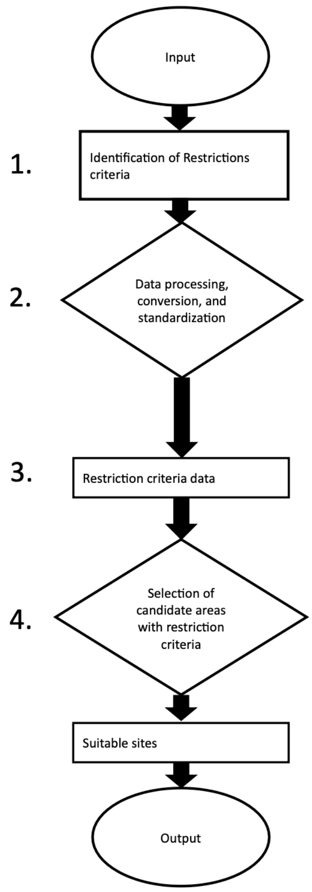
The second part describes the method to answer the second research question, "Through an SMR siting, how suitable is it to deploy an SMR in the chosen county?".

3.2.1. Flowchart and process

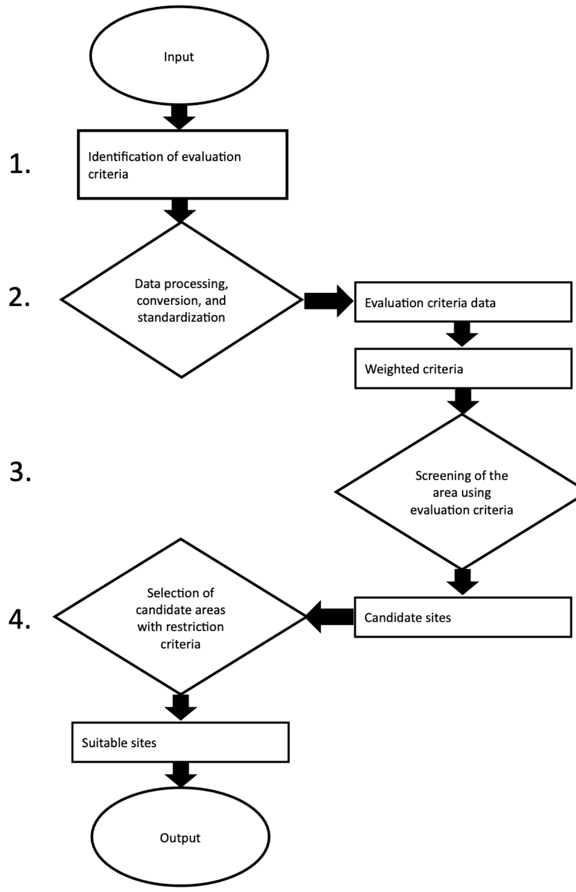
The process of identifying potential SMR sites in Møre og Romsdal took place in four steps:

1. Identifying the criteria and restrictions crucial for site selection
2. Assigning weight to the selected criteria to reflect their relative importance
3. Evaluating the methods by which the criteria are combined in a geospatial analysis
4. Spatial interpretation of the results

The research process is illustrated in the following flowchart 3.1. Figure 3.1a shows the process for identifying restriction criteria. Figure 3.1b shows the process for identifying evaluation criteria.



(a) Restriction criteria process



(b) Evaluation criteria process

Figure 3.1.: Study flowcharts for SMR siting

3.2.2. Identifying site selection criteria and data

Potential siting criteria for SMRs were identified from various resources, most from publications and research by IAEA: Nuclear Reactor Technology Assessment for Near Term Deployment [55], Milestones in the Development of a National Infrastructure for Nuclear Power [56]. Earlier sitings studies such as Geographical Considerations in Site Selection for Small Modular Reactors in Saskatchewan [50] and Small Modular Reactor (SMR) Siting in the State of Main [51] were also considered. Finally, meetings, discussions, and interviews with Nuclear consultants from WSP were considered in finalizing the criteria. The interviews included discussions about the chosen criteria, their thoughts and input, and their relevance to SMRs and Norway. They also gave input on criteria that were missing. The interviewing process can be seen in appendix A.1.

Criteria for siting included population distribution and density, surface water such as lakes and oceans, existing hydropower plants, protected land, airports, landslides, flooding, electricity infrastructure, large roads, topography, railroads, and industry. Other criteria were not used in this study as they were not specific to SMRs or did not apply to Norway or Møre og Romsdal environment, e.g., earthquakes, forest fires, volcanoes, and tornadoes. Although necessary, these factors impact constructing a reactor at a particular site more than selecting that site. For example, Møre og Romsdal has no volcanoes.

3.2.3. Identification of restriction and evaluation criteria

The selected criteria were refined by identifying site restrictions applicable for inter-site comparison evaluations. Site restrictions criteria excluded possible alternatives based on Boolean relations (true/false). The evaluation criteria could then be quantified according to the degree of suitability for all feasible options. The differences between the requirements and what criteria to use were determined according to the study goals, IAEA regulations, earlier sitings, and interviews with nuclear consultants from WSP. After reviewing the inputs from these sources and considering Møre og Romsdal, seven restrictions and five evaluation criteria were adopted to find suitable sites for SMRs. These were selected because of their relevance to smaller reactors and their applicability in Møre og Romsdal environment. These restriction and evaluation criteria are shown in Tables 3.3 and 3.4.

Table 3.3.: Restriction criteria for SMR site selection in Møre og Romsdal

Restriction Criteria	Description
Airports	Airport and land near airports. In case of a major aircraft incident. Helicopter platforms or airports are not included.
Flooding areas	Site assessment must consider surface water hydrology and instrumentally recorded data, such as water levels and flow rates. Flooding areas are land that have flood potential.
Protected areas	Include wildlife species, wildlife habitats, unique or ecologically sensitive areas, and national parks.
Industry	Land near large industries. In case of a large fire. This study considers only two large industries: Hydro Aluminum and Equinor gas terminals.
Landslides	Land that have landslide potential. Snow avalanches, slush avalanches, rock falls, landslides, and flood avalanches are included.
Population	Land with a population density of more than >100 inhabitants/200 m^2 is considered a population.
Hydropower plants	Proximity to large hydropower plants is considered due to, e.g., flooding risk.

Table 3.4.: Evaluation criteria for SMR site selection in Møre og Romsdal

Evaluation Criteria	Description
Roads	The SMR concept consists of manufacturing modules and then ship to the site for final assembly. Hence, more extensive land-based transport routes are of importance. Only Europe roads are considered in this study.
Railways	One of the advantages of an SMR is the ability to manufacture and ship the module to the site. Therefore, railways are preferred for siting SMRs, as rail transport is one of the essential means of equipment transport.
Cooling water	Combination of the ocean, streams, rivers, and lakes.
Transmission lines	Practical and strategic connections to the transmission grid to supply electricity to demand areas. The ability of the grid system to accept power in feed at a site location without requiring costly and time-consuming reinforcement is critical. Only the central power line is considered in this study.
Topography	Møre og Romsdal geography varies from a low-lying coastal landscape to high mountains above 1900 meters above the sea. For easier delivery, the county topography is considered.

3.2.4. Data finding, processing, and conversion

After the criteria were determined, matching datasets were found for each criterion. From Geonorge who is the national website for map data and other location-based information in Norway [57], different datasets could be collected. However, some datasets had different formatting, and various data formatting processes and conversions were implemented in preparation for weighting and combining data, such as scaling, resolution adjustment, and map extent selection. Some data were more complex and required a lot of work to process and were therefore excluded, e.g., slope data for the county. Therefore, a topography for the county in different intervals was considered instead for simplification. This, however, leads to the first step in the interval having a large gap between zero and 500 meters.

3.2.5. Data standardization

The data were measured on various enumeration scales and had to be standardized before being combined and weighted. The map layer data were converted into points depending on the suitability of that layer and area. In this case, the highest value was allocated to the very suitable areas, and the lowest value to the unsuitable areas. Table 3.5 describes the standardization values used.

The ranges in each criterion are used as examples and shown in Tables 3.6 and 3.7. They represented reasonable estimates of the importance of each criterion based on the observed ranges in the data and shared knowledge from the nuclear consultants from WSP. These criteria could be further fine-tuned with input from local domain

Table 3.5.: Standardization of scale of suitability classes.

Value	Description
1	Unsuitable
2	Less Suitable
3	Moderate Suitable
4	Very Suitable

experts. However, such expert knowledge would also be subjective, and experts could have provided different recommendations in the area.

In Figure 3.2, the geographic distances for the Restriction criteria zones used in this study were standardized into three cases. The three cases give three optional lengths from criteria to SMR. The open case has the least distance between SMR and Criteria, the Restrictive has the largest length and the Normal falls between Open and Restrictive.

- Open
- Normal
- Restrictive

The spatial distance between a reactor and its various restrictions and evaluation criteria features are necessary geographical measurements for SMR siting. There are no legislative or regulatory requirements for sizing the distance between SMRs and siting criteria, nor restrictions on minimum distances between SMRs and siting criteria. This is due to each unique case being an assessment question. In several countries such as Norway, Sweden, and Finland, you must present one or more reports demonstrating a safe "Safety case" for the facility and an "Environmental safety case.". This means that it is up to the "licensee" to prove that the facility can be located so close to a population, that the land is stable to build on, that it is located at an appropriate distance to a major airport, etc. After that, the country's radiation safety authority assesses the case and compiles a basis with its assessment to the government for final approval or rejection [46].

Consequently, three different case scenarios were created and would, in a real case, vary between different types of SMRs, governments, and vendors. In this study, the Open case, in which the reactor was placed near the siting criteria, contrasted with the Restrictive case, in which the SMR was placed more further away from the siting criteria.

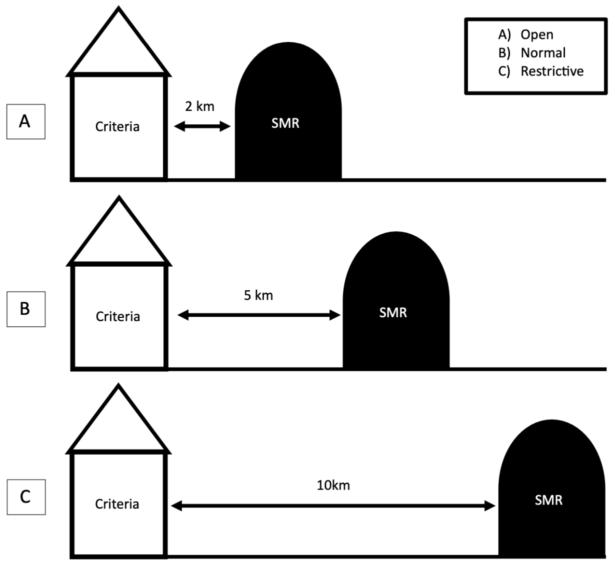


Figure 3.2.: Comparison of siting cases for SMRs

The distance values used for the restriction criteria and the three different cases are shown in Table 3.6. The distances were based on input from using documents from the IAEA, the Saskatchewan study, the Maine study, and with help from nuclear consultants at WSP. The ranges in each category are used for demonstration purposes as there are no real regulations or legislation for distances in Norway. They represent reasonable estimates of the importance of each criterion base on observed ranges in the data and shared knowledge. It is acknowledged, however, that they may benefit from additional fine-tuning from local experts. Even so, such input is somewhat subjective. All the restriction criteria were standardized on a binary scale: Either an SMR is permitted in this location, or it is totally excluded.

Table 3.6.: Restriction criteria standardization values.

Restriction Criteria	**Open**	**Normal**	**Restrictive**
Protected Areas	<3 km	<5 km	<10 km
Hydropower Plants	<2 km	<5 km	<10 km
Industry	<2 km	<5 km	<10 km
Airports	<2 km	<7 km	<10 km
Population	<5 km	<10 km	<20 km
Flooding Areas	<1 km	<2 km	<5 km
Landslides	<1 km	<2 km	<5 km

In Table 3.7, the ranges used in the evaluation criteria are demonstrated. These were set using the same documents, studies, and interviews as the restriction criteria. As the Restriction criteria, these ranges are used for demonstration purposes as there are no real regulations or legislation and could benefit from additional fine-tuning.

Table 3.7.: Evaluation criteria standardization values.

Evaluation Criteria	Unsuitable	Less Suitable	Moderate Suitable	Very Suitable
Roads	>15 km	10-15 km	5-10 km	0-5 km
Cooling Water	>15 km	10-15 km	5-10 km	0-5 km
Railways	>15 km	10-15 km	5-10 km	0-5 km
Transmission Lines	>15 km	10-15 km	5-10 km	0-5 km
Topography	>1500 m	1000-1500 m	500-1000 m	0-500 m

3.2.6. Assigning weights to the selected criteria

Weights and scores were assigned to the selected evaluation criteria with help from IAEA documents, the study from Saskatchewan, the study from Maine, nuclear consultants from WSP, and by considering the geography of Møre og Romsdal such as the dramatic topography and easy access to cooling water. Higher weightings were given to factors that have a potentially more substantial impact. The weighting of the Evaluation criteria and the reasoning behind it can be seen in Table 3.8.

Table 3.8.: Evaluation criteria weights priority and rankings.

Evaluation Criteria	Weight Priority	Description
Topography	1	The geography in Møre og Romsdal, with its high mountains and fjord environment, makes finding a flat surface at a low altitude a high priority to ensure easy transportation and construction.
Roads	2	Transporting the SMRs module to its site is a considerable challenge in the county. With tunnels, bridges, etc. Proximity to near roads is, therefore, a priority.
Cooling Water	3	Depending on the type of SMR technology, access to cooling water is less crucial than with regular nuclear power plants. The county's massive fjord network enables water access within a manageable distance. Cooling water is, therefore, a low priority in this study.
Transmission Lines	3	Depending on what the SMR will be used for, a close distance to transmission lines is preferred to enable less cost. However, this study sees it as less important than the roads and topography.
Railways	5	Delivering SMR modules via train is preferred. The railways in Møre og Romsdal are limited and significant upgrades are needed to support transport to different locations in the county.

Further, the weighting is compared to each other with topography as a reference and can be seen in Table 3.9. The comparison works in the way that, for example, roads are half as important as topography and railways only a fifth compared to topography.

Table 3.9.: Evaluation criteria weights compared to each other with topography as a reference.

Evaluation Criteria	Weight
Topography	1.0
Roads	0.5
Transmission Lines	0.4
Cooling Water	0.4
Railways	0.2

3.2.7. Assigning points to the selected evaluation criteria and set the combined points system

The maximum number of points in an area that is combined with all evaluation criteria was set to 50, and the lowest to zero points. The top points that a given criterion could get were set regarding the total value of 50 and the weighting of the different criteria. The number of points a criterion would receive depended on its range and was reduced evenly until it reached the range unsuitable, where it received zero points. The total points system is shown in Table 3.10, and each criterion points system is shown in Table 3.11.

Table 3.10.: Suitability scoring system.

Suitability	Points
Very Suitable	47-50
Suitable	43-46
Moderate Suitable	40-42
Low-Mod Suitable	37-39
Less Suitable	30-36
Exclusion Zone	<30

Table 3.11.: Points for each evaluation criteria.

Evaluation Criteria	Weight	Very Suitable	Moderate Suitable	Less Suitable	Unsuitable
Topography	1	20	15	10	0
Roads	0.5	10	7.5	5	0
Cooling Water	0.4	8	6	4	0
Transmission Lines	0.4	8	6	4	0
Railways	0.2	4	3	2	0

Chapter 4.

Results

4.1. Energy mapping

4.1.1. Production

Norway had an electricity production of 157 TWh and an installed capacity of 40 000 MW in 2021. Most of this production came from Hydropower, then wind, and then thermal power. An overview of Norways electricity production over the years and by power soucre has been summarized and visualized in Figure 4.1.

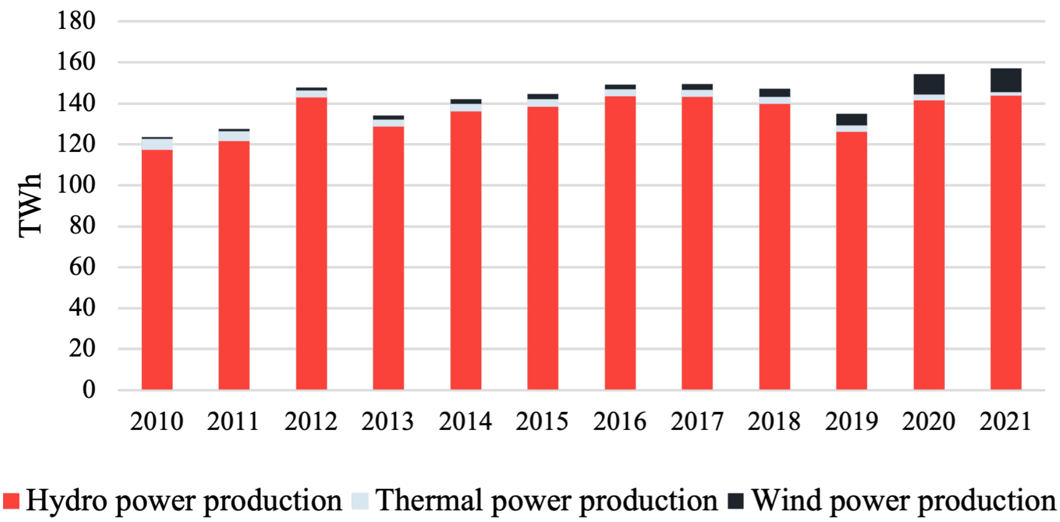


Figure 4.1.: Production of electricity by content and year [58]

Hydropower

After 2021 Hydropower stood for 144 TWh of the total production in Norway, which is a share of 91.5% [2]. This is an increase of 1.5% compared to 2020. A total of 1761 hydropower plants were in use with a total production capacity of 34 000 MW [59].

The production is determined by the water flow and installed capacity, the inflow varies during the year and from one year to another. Its highest in spring normally declines towards the end of summer but increases again during autumn. The inflow is generally very low during the winter months. During the period 1990-2019, the annual inflow to the hydropower plants varied by about 65 TWh [8].

Most of Norway's power plants have storage reservoirs, and production can be adjusted within the constraints set by the license and the watercourse. Hydropower is often seen as intermittent, but a number of the large run-of-river power plants in Norway lie downstream of storage hydropower plants in the same river system, influencing their production patterns and resulting in that 75% of Norway's production capacity being flexible.

The flexibility of reservoirs and power plants varies. Hydroplants with large reservoirs can store water for longer to produce winter electricity when consumption and prices are highest. Small hydropower plants with small reservoirs offer short-term flexibility and can transfer production from base to peak. The largest reservoir in Norway, called Blåsjø, has a capacity of 7.8 TWh and can hold three years of normal inflow. However, the reservoir could be emptied in 7-8 months when the hydropower plants work at full capacity. Much of Norway's reservoir capacity is concentrated in the mountains in the country's southern half and further north in Nordland [8].

An overview of where these hydropower plants are located can be seen in figure 4.2 [60].

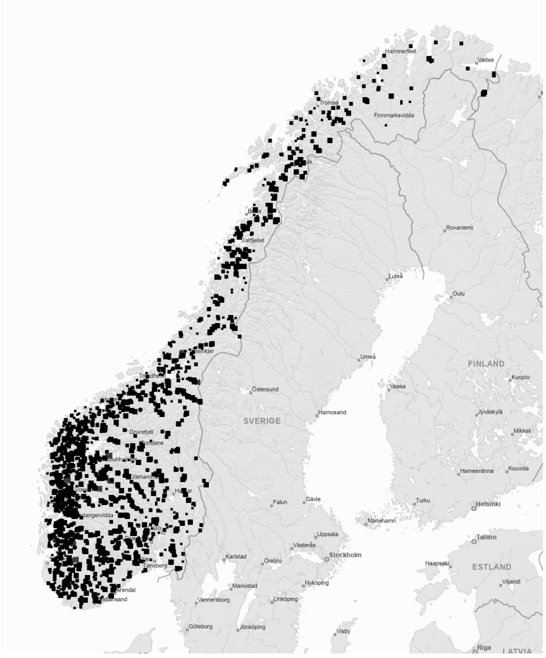


Figure 4.2.: Locations of hydropower plants in Norway [60]

Wind power

After 2021 there were 64 wind farms in Norway with an installed capacity of 5070 MW [61]. The production from those wind farms in 2021 was 11.8 TWh, which is a share of 7.5% [62]. That is an increase of 19% from the year before, despite the lower-than-normal wind resource availability. This was driven by favorable depreciation rules, decreasing levelized cost of energy (LCOE) of wind power projects, and the end of the electricity certificate scheme have driven the latest years the high-level deployment of wind power in Norway.

There is significant activity in the regulatory space for offshore and onshore wind power. Several processes are ongoing to improve the licensing scheme for onshore wind power. At the same time, the framework for offshore wind is under development. Neither of these processes was completed in 2021 [3].

An overview of where these wind farms are located and plants under construction can be seen in figure 4.3 [63].

Figure 4.3.: Locations of wind farms in Norway. Dark green represent constructed wind farms and light green wind farms under construction [63]

Solar power

After 2021 around 8800 photovoltaic systems were installed in Norway, with a production of 186 MW. This is an increase of 45 MW of new solar power compared to 2020.

An overview of where these systems are placed and the production over the last years has been summarized and visualized in Figures 4.4 and 4.5 [64].

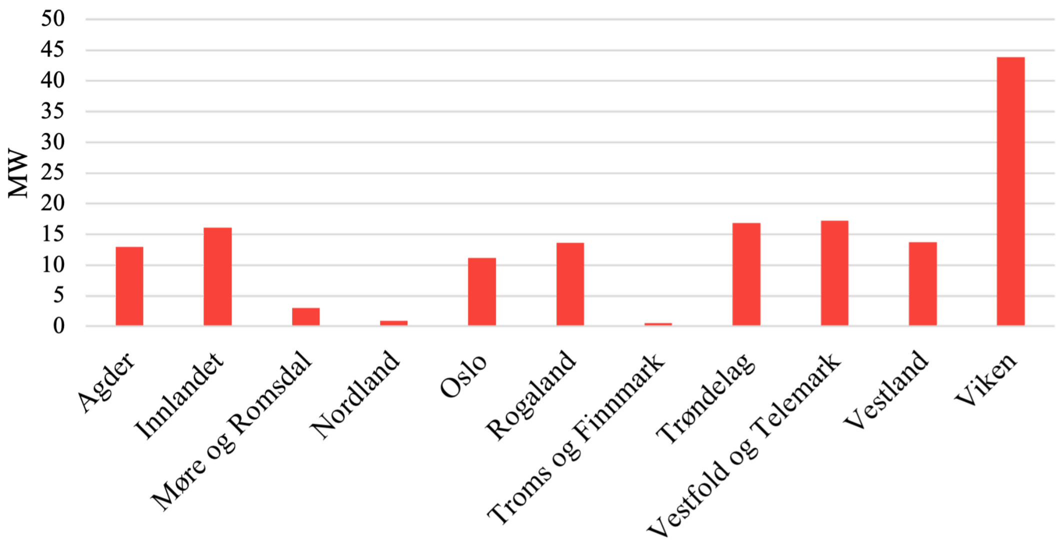


Figure 4.4.: Installed effect of solar power and location in Norway 2021 [64]

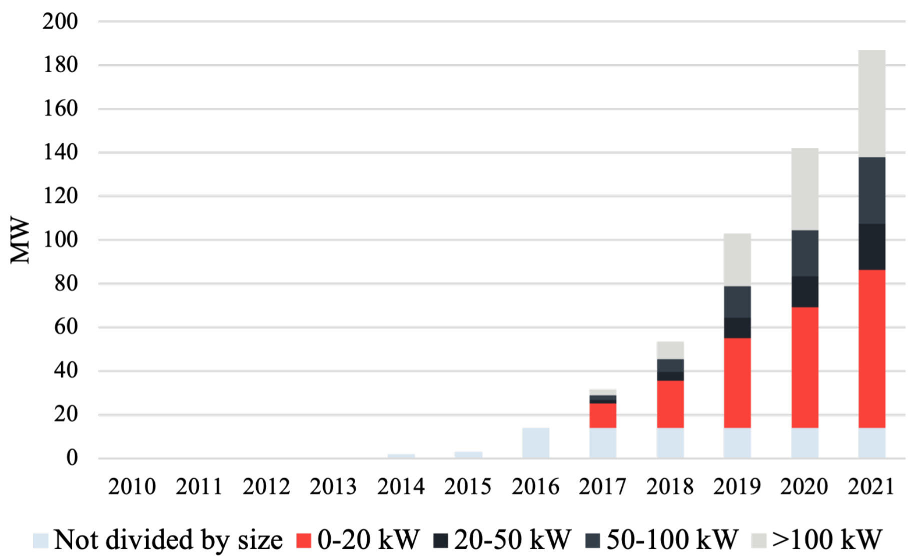


Figure 4.5.: Development of installed power in grid-connected solar power plants in Norway - broken down by plant size [64]

Thermal power

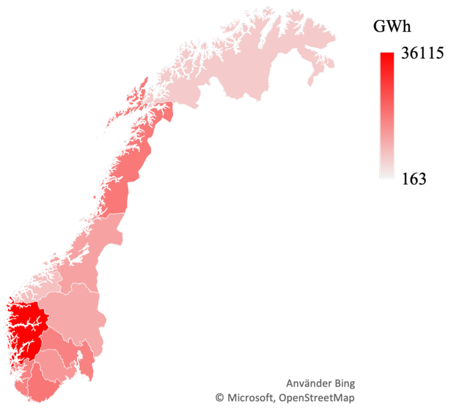
After 2021 thermal power had a production of 1.6 TWh, which is a share of 1%. This is a decrease of 39% from 2020 [2]. Many of Norway's thermal power plants are located in large industrial installations using the electricity generated. Production, therefore, depends on the electricity needs of the industry. These power plants use a variety of energy sources, such as municipal waste, industrial waste, surplus heat, oil, natural gas, and coal [8].

Mapping production

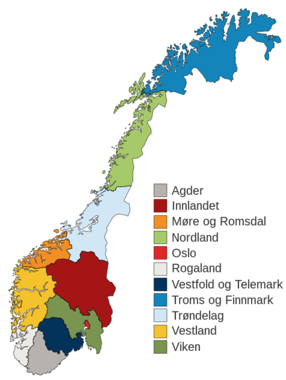
With the data from Statistics Norway, an energy mapping could be done on Norway's 12 different regions to see where and how much electricity was produced in the different regions. The result has been summarized and visualized in Figures 4.6a and 4.6b. From the data, it can also be retrieved that the regions with the biggest production are Vestland, Agder, and Nordland [58].

Production	
State	**GWh**
Vestland	36115
Agder	18510
Nordland	18066
Rogaland	16896
Viken	16743
Vestfold og Telemark	13742
Trøndelag	12044
Innlandet	11066
Møre og Romsdal	7603
Troms og Finnmark	6125
Oslo	163

(a) Production in different regions in Norway



(b) Production overview of Norway



(c) Overview of regions in Norway

Figure 4.6.: Production in Norway [58]

4.1.2. Consumption

Mapping consumption

In 2021 Norway had a gross electricity consumption of 140 TWh, mostly from mining and manufacturing [2]. An overview of Norway's gross electricity consumption over the years has been summarized and visualized in Figure 4.7.

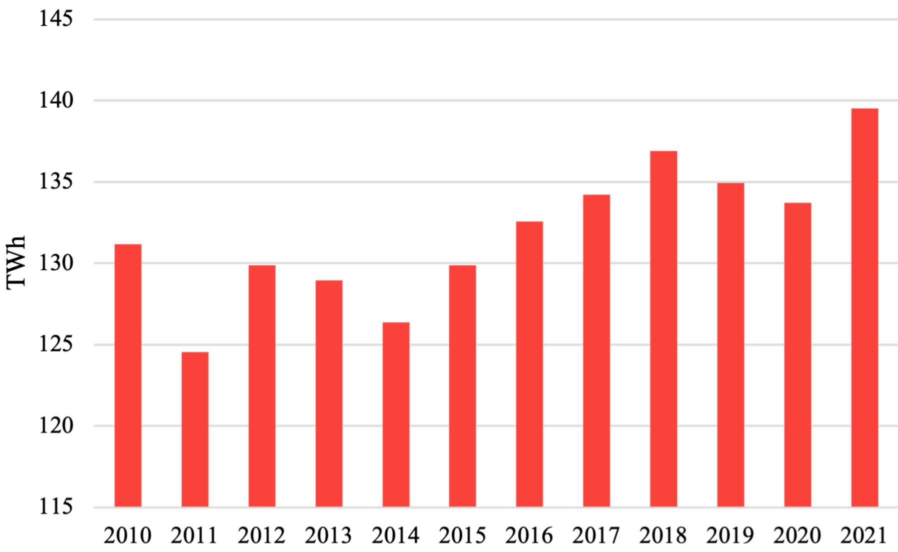
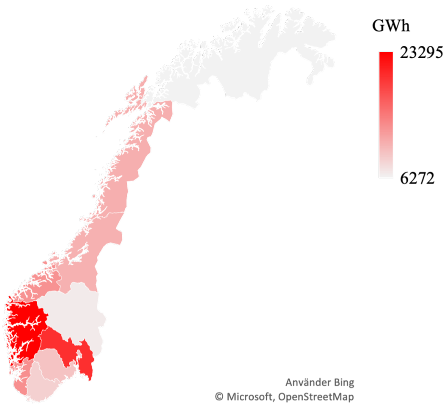


Figure 4.7.: Gross electricity consumption over the years in Norway [62]

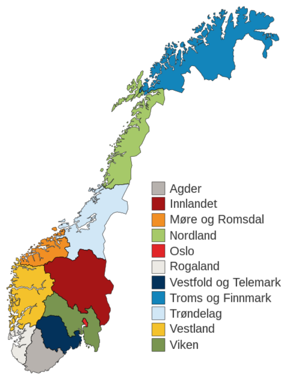
As with production data from Statistics Norway, an energy mapping could be done on Norway's 12 different regions to see how much electricity was consumed in the different regions. The result has been summarized and visualized in Figures 4.8a and 4.8b. From the data, it can also be retrieved that the regions with the biggest consumption are Vestland, Viken, and Rogaland.

Consumption	
State	**GWh**
Vestland	23295
Viken	20000
Rogaland	13245
Møre og Romsdal	13018
Nordland	11000
Trøndelag	10879
Vestfold og Telemark	9547
Oslo	9170
Agder	8652
Innlandet	6811
Troms og Finnmark	6272

(a) Consumption in different regions in Norway



(b) Consumption overview of Norway



(c) Overview of regions in Norway

Figure 4.8.: Consumption in Norway [58]

4.1.3. Energy balance

The energy balance expresses the relationship between production and consumption and indicates whether the Norwegian power system is a net exporter och importer in a particular year. Generally, production fluctuates with precipitation, water inflow, wind conditions, and consumption with temperature. An overview of Norway's total energy balance and its net balance over the years has been summarized and visualized in Figure 4.9.

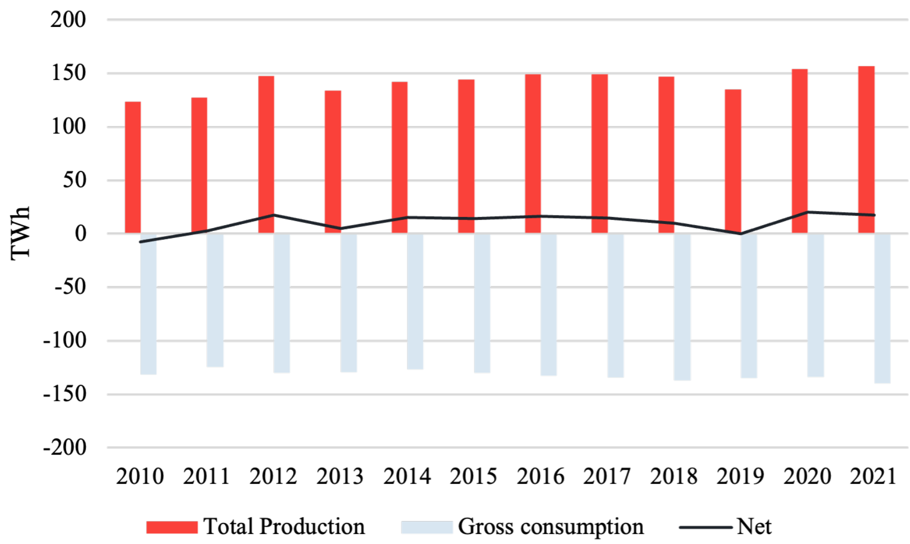
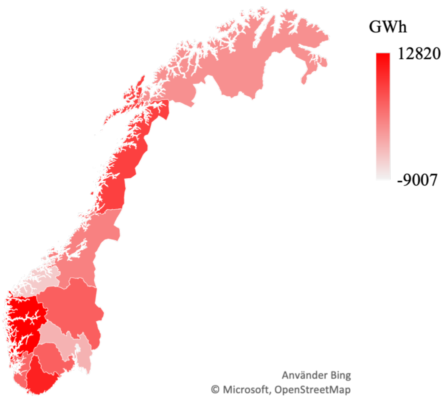


Figure 4.9.: Production, gross consumption and net energy balance in Norway [62]

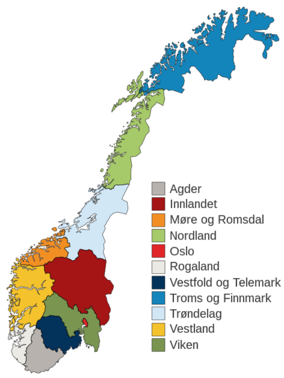
By comparing the data from production and consumption in Norway, an energy balance was made over the regions to see which regions have a negative or positive balance. The results has been summarized and visualized in Figures 4.10a and 4.10b. The data shows that the regions with the the highest energy deficits are Oslo, Møre og Romsdal, and Viken. These are the regions with higher consumption than production and regions that imports energy.

Energy balance	
State	**GWh**
Oslo	-9007
Møre og Romsdal	-5415
Viken	-3257
Troms og Finnmark	-147
Trøndelag	1165
Rogaland	3651
Vestfold og Telemark	4195
Innlandet	4255
Nordland	7066
Agder	9858
Vestland	12820

(a) Energy balance of different regions in Norway



(b) Energy balance overview of Norway



(c) Overview of regions in Norway

Figure 4.10.: Energy balance in Norway [58]

4.1.4. Power grid

Transmission and distribution

The only transmission system operator in Norway is Statnett which owns 98% of the transmission grid. The rest is owned by 13 regional grid companies and rented to Statnett. The company is in line with European Union regulations, and its revenues are regulated by the Norwegian Energy Authority, which also issues rules and regulations on connection duties and tariffs, quality of responsibility, and system responsibility.

Norway has over 11 000 km of transmission network due to the locations of its hydropower stations and its geographic length. It is divided into four subsystems, and since 2015 Norway has added 1065 km of high-voltage lines and has several ongoing projects to be finished by 2026.

Norway is divided into five bidding zones, and the need for transmission capacity from north to south results in significant price differences. Due to suitable international interconnections, prices in the south are linked to prices in continental Europe [65].

Interconnectors

Norway shares the same frequency with Finland, Sweden, and Eastern Denmark. Additionally, it has direct interconnections with Germany, the United Kingdom, Russia, and the Netherlands.

Since 2015 the two new additions of NordLink to Germany and North Sea Link to the United Kingdom have increased Norway's total cross-border capacity from around 6200

MW to 9000 MW export and 9250 MW import. NordLink has been operational since December 2020, with a capacity of 1400 MW, and North Sea Link started operations in October 2021 with the same capacity.

By 2026 Norway will have to decommission one of the oldest connections to Denmark, Skagerrak 1 and 2, due to technical wear and tear. Statnett is conducting a feasibility study to assess when it may be necessary to reinvest in this infrastructure. Statnett is also considering improving the capacity of Finland, which has limited capacity and is hard to control and limit the flow.

Due to the increased consumption forecast in Norway over the coming years, Statnetts short-term analysis for 2021-2026 shows the Norwegian power surplus may be reduced to 3 TWh in 2026 and trigger the need for investments and more transmission capacity. To keep the Nordic power balance stable, new wind power is provided, particularly in Sweden. Maintaining cross-border trade capacity thereby puts Norway in a position to benefit from market developments in the region without risking supply shortages [65].

Norway has been a net exporter of electricity for 16 of the last 21 years and a net exporter since 2011. In 2021, the country had its highest total net trade export of 20.5 TWh during the 21st century [66]. An overview of Norway's electricity net trade from 2000 to 2021 has been summarized and visualized in Figure 4.11.

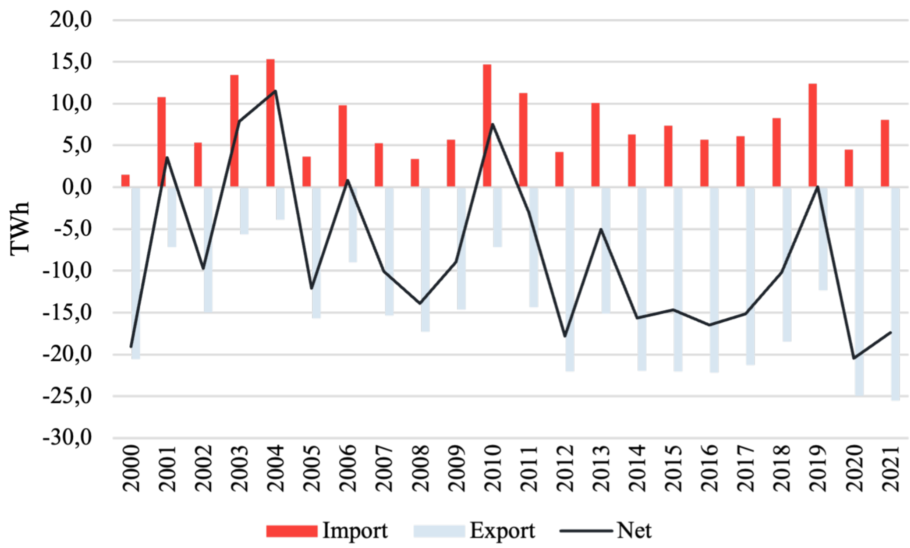


Figure 4.11.: Electricity import, export and net trade in Norway [66]

4.1.5. Future production & consumption

Norway's development in future power production and consumption is uncertain, and the two categories are often linked and dependent on each other. The development in power consumption depends, among other things, on national and global economic development, power prices, grid capacity, and power production development in Norway. How much power production is built out is primarily determined by the framework in the concession progress, where authorities weigh up the advantages and disadvantages of the development. The development of consumption and production in the future will thus largely depend on Norway's political choices.

The power system's ability to handle consumption growth also depends on whether the production system, international connections, and the grid within Norway can supply enough power where the consumption is located at all times [67].

Two different Long-term market analyses (LMA) have been studied, one from NVE, which is from 2021 to 2040, and the other from Statnett, which is from 2022 to 2050. Both are from governmental and state-owned enterprises. Statnetts LMA will be presented more broadly and NVE in more detail.

Statnett long-term market analyses

In the prognosis by Statnett, the energy demand for 2050 could be much higher than expected. Much of the growth will depend on establishing enough power production in Norway and that significant investments in the grid are carried out [68]. Statnett has provided three different scenarios from 2022 to 2050. In the standard scenario, the consumption will increase by 80 TWh to a total of 220 TWh in 2050. In the lowest scenario, the consumption will increase by 50 TWh to a total of 190 in 2050, and in the highest scenario, the consumption will increase from 120-160 TWh to a total consumption of 260-300 TWh in 2050 [1]. An overview of the different scenarios has been summarized and visualized in Figure 4.12.

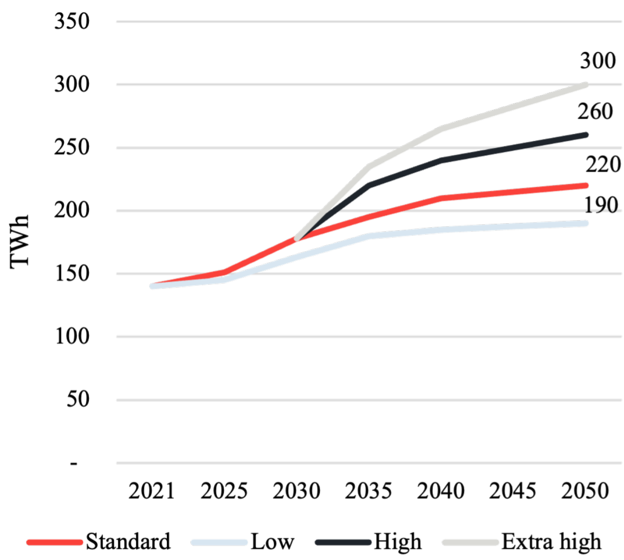


Figure 4.12.: Different scenarios of consumption in Norway [1]

New hydropower development, solar power, and some onshore wind power will cover approximately half of the need for new production and has been summarized and visualized in Figure 4.13. The second half is covered by offshore wind power, the technology that can provide the most significant volumes of new production by far. Provided that floating offshore wind power becomes cheap enough to mass-produce, there are three different production scenarios. In the lowest scenario, additional 20 TWh of offshore wind power is built. In the base scenario, 40 TWh is built, and in the highest scenario, 140 TWh of offshore wind power is established [1]. The different offshore wind scenarios has been summarized and visualized in Figure 4.14.

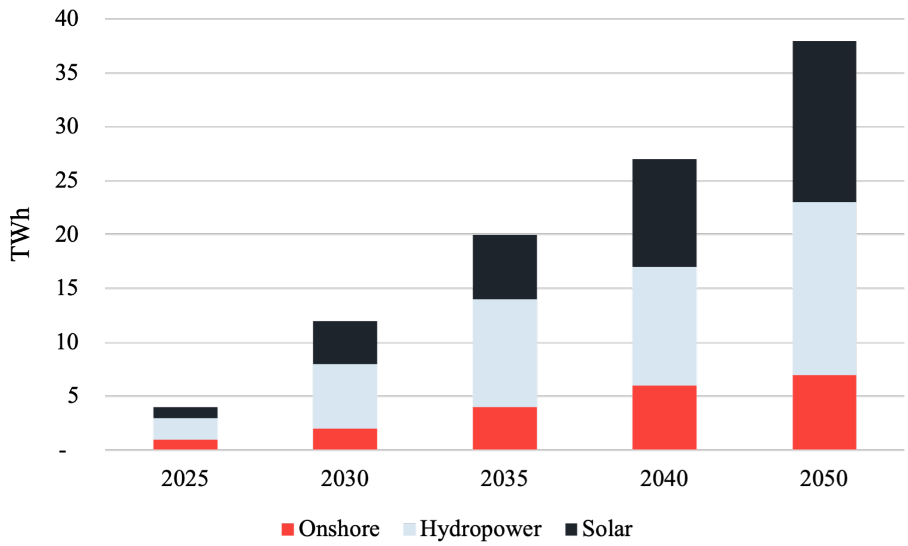


Figure 4.13.: Standard scenario of expansion of production of onshore wind power, hydropower and solar.

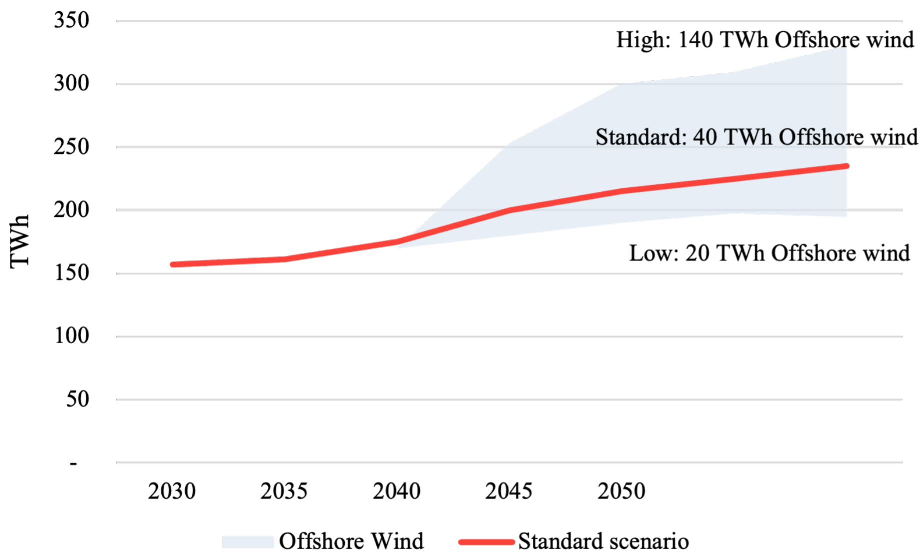


Figure 4.14.: Different production scenarios depending on expansion of offshore wind power.

NVE long-term market analyses

No new LMA was made by NVE in 2022, and a new LMA for 2023 will be published later in autumn 2023. Therefore, NVE LMA from 2021 is studied. The study was published in October 2021 and did not have the complete production and consumption numbers for 2021; instead, it predicted the rest for 2021. All production and consumption numbers for 2021 have, therefore, been updated to the correct numbers.

In NVE's LMA, from 2021 to 2030, new power consumption is expected to increase more than new power production. This is due to there being a long concession and planning processing processes for new power production. From 2030 to 2040, new power production will exceed new consumption. In NVE's base scenario, the 2021 power surplus of about 17 TWH falls to 9 TWh in 2040.

Consumption NVE LMA

Plans for the electrification of the petroleum industry, new industries, and transport will mainly drive the consumption growth in Norway towards 2040. This assumed consumption growth in the next 20 years would be twice as high as it has been in the last 20 years, and the growth will be about 36 TWh until 2040, from around 140 TWh today to 176 TWh.

How electricity consumption in Norway has developed from 2021 and how NVE projects it to be in 2040 has been summarized and visualized in Figure 4.15. NVE also assumes that energy efficiency measures will be taken, which means that consumption growth towards 2040 will be lower than it otherwise would have been.

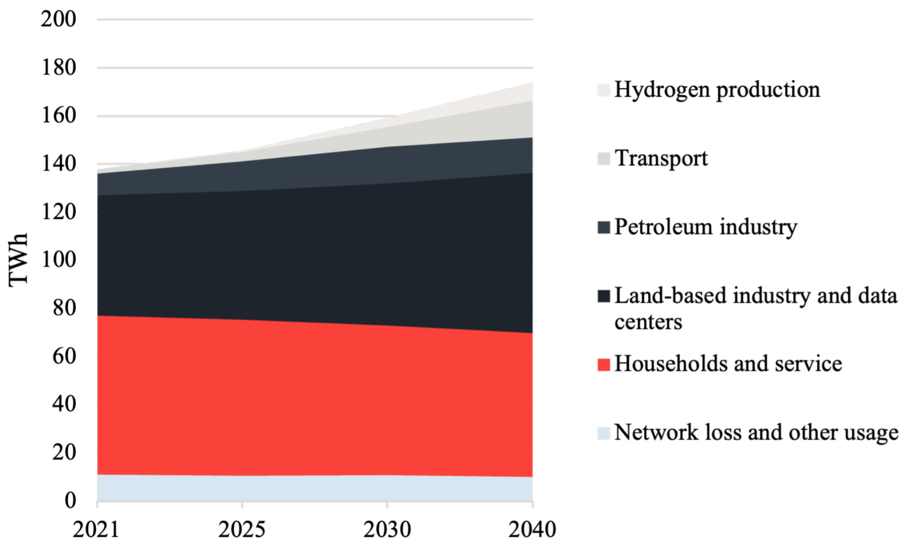


Figure 4.15.: Development and expected development of electricity consumption in Norway towards 2040 [11]

If more than those plans included in the base scenario are carried out, power consumption can increase to a level of 200 TWh in 2040. The increase will depend on power prices, the development of the power grid, and new power production.

Part of the new consumption in Norway will come from industries that grow in connection with the energy transition. This change increases the need for new land-based industries such as battery factories and increased consumption from data centers and will stand for 16 TWh from 2021 to 2040.

NVE also projects a significant increase in power consumption for the petroleum industry of over 7 TWh until 2035. After 2035 it is expected to reduce.

In 2021 the transport sector in Norway mainly used fossil energy, and only 3% of the energy used within domestic transport is electric. In 2020 54% of new passenger cars sold in Norway were electric. NVE expects the electrification to continue both for passenger cars and heavier transport and that the electricity consumption in the transport sector will increase by over 13 TWh by 2040.

Significant demand for hydrogen is also predicted at the end of 2040. Which will primarily be driven by transport and industrial purposes and are based on a few individual projects in the industry. NVE expects the power consumption from hydrogen production to be 7 TWh in 2040.

A warmer climate and more energy-efficient buildings will give lower consumption in buildings by 2040. This is driven by new strict energy requirements in new building technology standards, energy efficiency in existing buildings, and eco-design and energy labeling of products. In addition, a warmer climate in Norway, which reduces the need for heating. Overall, NVE expects Norway buildings to use less electricity than they did in 2021, even if the building stock is growing. A decrease of 6 TWh is expected from 2021 to 2040 [11].

Production NVE LMA

Until 2040 NVE expects the cost for both offshore wind power, land-based wind power, and solar power to fall further. In addition, consumption growth and an increase in CO_2 price will contribute to raising power prices in Norway, which will increase the profitability of new power production. How much new power production is opened up is primarily determined by the authorities. Grid capacity, area limitations, and future trade-offs between the value of new power production and other interests will impact how much new power production is built on the land. How quickly the costs fall will also impact the development of offshore wind power.

NVE expects that the power production will increase by 28 TWh in Norway until 2040. Most new power production must go through extensive licensing processes before being built and put into operation. In 2019 the licensing process for onshore wind power was halted and began again in 2022, and the licensing process for offshore wind power has yet to start. Therefore, it will only be a slight increase in annual power production until 2030, and most of this increase will come from hydro and solar power.

From 2030-2040 the significant development of new power production will come from wind and solar power. In addition, NVE expects hydropower production to increase. The increase in power production in Norway from 2021 to 2040 has been summarized and visualized in Figure 4.16.

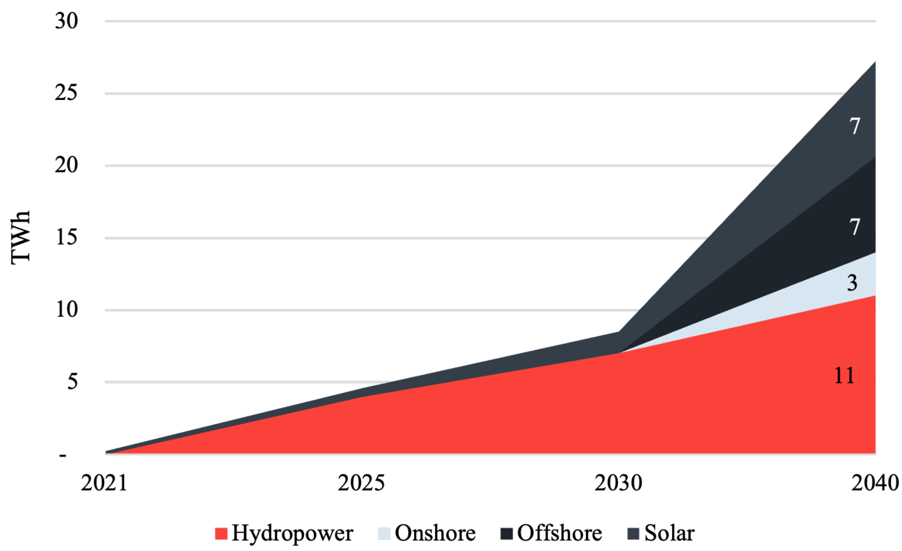


Figure 4.16.: Increase in power production in Norway 2021-2040 [11]

Two areas have been opened up for the construction of offshore wind power in Norway: Sørlige Nordsjø II and Utsira Nord. In these locations, the development is up to 4.5 GW in total, which can give about 20 TWh of power production [11]. (These two areas opened up for tenders in March 2023 with a capacity of 3 GW [69]). In NVE's LMA, it is assumed that 7 TWh of offshore wind power will be developed between 2030 and 2040. The costs of both floating and fixed offshore wind are currently well above the costs of solar power, hydropower, and wind power on land. NVE expects the costs of offshore wind to fall and therefore considers that it would not be profitable to build offshore wind without subsidies before 2030.

The technical-economic potential for onshore wind power in Norway is excellent. In the last five years, 11 TWh of new wind power has been built in Norway, and 4 TWh is under construction [11]. However, the licensing process was stopped in April 2019 due to a backlash to the construction on previously unspoiled land [70] (During 2021 and 2022, it was opened for processing again, but only if the host municipality agreed to it [71]). There are, therefore, a few wind power projects that have a license and that have not started construction. It is possible to build before 2030, but it is unlikely that a large volume will be built. Between 2030 and 2040, NVE assumes an increase of 3 TWh in onshore wind power production. But the extent of new production after 2030 will depend on both local and national political guidance. Towards 2040, it may also be necessary to reinvest in about a third of the existing wind power capacity just to maintain the wind power production in Norway in 2021.

The potential for solar power is great in Norway, both on buildings and for ground-mounted installations. In 2040, NVE expects solar power to contribute to power production in Norway significantly. The cost of solar installations will continue to fall, and eventually, the cost of kWh of solar power may become lower than that of hydro and wind power. However, it is not the costs alone that determine the relationship between these technologies. The solar power market is dominated by homeowners, owners of large commercial buildings, and lessors of solar installations.

Ground-mounted solar power plants are also being planned in Norway. These require space and can come in conflict with alternative ways of utilizing the area. NVE projects that solar power will produce 7 TWh in 2040.

In the last 20 years, 13 TWh of new hydropower production has been built in Norway. In addition, existing hydropower plants have increased production due to increased inflow. NVE projects that hydropower will increase by 11 TWh until 2040.

5 TWh of these are based on existing projects that NVE knows about through licensing and mapping. These include new power plants and expansion projects. In 2021 changes were made to the basic interest taxation for new hydropower projects. The changes make it more profitable to make investments in older power plants to increase power production. The effects of this taxation are not assessed in NVE's analysis, but several power companies have announced that this increases the probability that more of their upgrading and expansion projects will be profitable.

Part of the potential upgrading and expansion lies in increasing the efficiency of turbines. By 2040, NVE expects that many turbines will be replaced due to wear and tear and will increase production by 3 TWh.

The precipitation and supply to Norwegian hydropower plants vary yearly, but in recent decades the trend has been for the supply to increase. This trend in increase can generate 4 TWh more hydropower production in 2040 than in 2021.

In the coming years, several older hydropower regulations will receive new license conditions. The purpose of this is to improve the environmental conditions in regulated waterways but also to modernize the concession terms and repeal conditions that have been shown to be unnecessary. For some power plants, these new conditions could lead to reduced power production or place restrictions on operation. As a result, NVE estimates a power loss of 1 TWh [11].

Long-term market conclusions

Both LMAs from Statnett and NVE prognosis that Norway will significantly increase power consumption and that construction of new energy production is required. Statnetts prognosis is that consumption and production will match each other over the period and that offshore wind power will lead in matching new consumption.

In NVE LMA, the prognosis differs over two periods from 2021 to 2040. During the first period from 2021 to 2030, new power consumption will increase more than new power production, and most new production during that period will come from hydro and solar power. During the second period, from 2030 to 2040, new power production will be greater than new consumption, and the significant development of new power production will come from solar and wind power. However, from 2021 to 2040, NVE prognosis is that the 17 TWh power surplus from 2021 will fall to 9 TWh in 2040.

4.2. Operators of interests

This chapter aims to get an insight into the chosen county to motivate why the county was chosen. It introduces the county's geography, infrastructure, industry, energy balance, and future energy production and consumption. It aims to get an overview of the whole county to describe how and why some of the decisions regarding evaluation and restriction parameters were made in the SMR siting.

4.2.1. Choosing of county

The top three counties with the highest energy deficits were considered as subjects to the SMR siting. Because of time limitations, only one was chosen: Møre og Romsdal. The county was selected after mapping energy demand, supply, and balance in Norway. It has the second most negative energy balance and has 69% of its consumption coming from the industry sector. Compared to the counties Oslo and Viken, Møre og Romsdal has a significantly lower population density, with 19 inhabitants/km^2 compared to Viken 57 inhabitants/km^2 and Oslo 1664 inhabitants/km^2 [72]. A low population density is beneficial from a risk point of view. Also, most of the county has direct water access via fjords or ocean, which could be beneficial both for transportation and as a technical solution for cooling water. At the same time, the county is showing a significant interest in new energy technologies with the project Kystkraft being held in Aure. The county also recently had an intense energy debate on what power source to focus on in the future, with SMRs being one of the technologies of choice.

4.2.2. Møre og Romsdal

Møre og Romsdal is a county on Norway's mid-west coast with 26 municipalities. The county borders Trøndelag in the north, Vestland in the south, and Innlandet in the east. Møre og Romsdal has a land area of 13 840 km^2 and a population of 266 000.

The county's largest cities are Ålesund, Molde, and Kristiansund, with Molde as the administrative center. The housing in the county is close to the lowlands on the coast and inland along the fjords. A large part of the population lives on the county's islands [73]. The location of Møre og Romsdal in Norway can be seen in Figure 4.17.

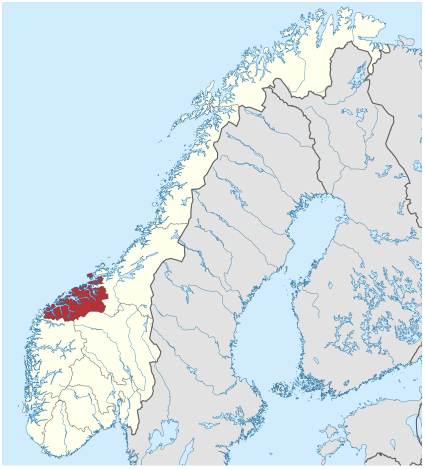


Figure 4.17.: Location of county Møre og Romsdal in Norway [74]

Geology

For easier delivery of the SMR modules, the county's geology is essential and, therefore, studied. Møre og Romsdal county has a low-lying coastal landscape that quickly transitions into high mountains over 1900 meters above sea level. The entire county is crossed by a vast network of fjords penetrating the landscape, which is often associated with the county's tourism industry. Around 55% of the county's area lies above the climatic forest boundary, which rises from approximately 200 meters above sea level in the outer villages to approximately 600 meters in the inner ones. Of the county's area, 4.3% is cultivated land, 30,8% is forest, 3,8% swamps, and 0,6% is permanent snow and ice [73].

Industry

Most of the energy consumed in the county goes to the industry, and mapping of this consumption is therefore studied. Fishing is an essential industry in the county, and after Nordland and Troms and Finnmark, Møre og Romsdal has the most registered fishermen in the country. The county stands for 10,5% of the fishing vessels in the country and 28,5% of the largest boats(over 28 meters long).

There are several limestone and marble quarries in Nordmøre and Romsdal. In Vanylven on Sunnmøre, there are significant olivine deposits in operation. Power development has been a strong impetus for industrial growth in the county. Even so, only the Hydro Aluminium plant in Sunndaløra, the largest and most modern aluminum smelter in Europe, and Equinor gas terminals, one of Northern Europe's largest gas terminals, belongs to the power-demanding industry in the area. In the municipality of Aure, there is also a significant energy-demanding plant that produces methanol. Primarily iron and metal industry is limited to 4,6% of employment. The workshop industry makes up 46,4%, most in the machine industry(18,3%), construction of ships and drilling platforms(14,5%), and metal goods industry(9.9%) [73].

Transportation

To transport the SMR modules, extensive land-based transport routes are important. The county's transportation network is therefore studied. The heavily cropped landscape with fjords, straits, and many islands has made traffic in Møre og Romsdal difficult. Nevertheless, the county has a relatively dense road network with a total of 3 600 kilometers of road, and both E-136 and E-39 run through the county. An extensive ferry network binds together the roads, and the largest ports are located in Ålesund and Kristiansund. In recent decades, there have been substantial investments in large bridge and tunnel projects to reduce the need for ferries. The three big cities, Ålesund, Molde, and Kristiansund have airports, and a fourth airport also exists in Volda [73]. The location of these airports can be seen in Figure 4.19b.

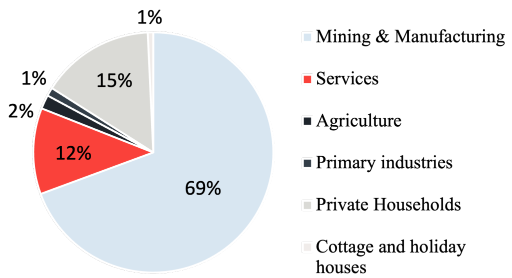
Transporting SMR modules through railroads is preferred. The county has one railway, Rauma Line, which starts in the middle of Møre og Romsdal in Åndalsnes and connects to the main rail network of Norway[50].

Energy balance

Møre og Romsdal total consumption for 2021 was 13 TWh, and the distribution of this consumption can be seen in Figure 4.18 where mining and manufacturing stands for the majority with 69% [75].

Consumption Møre og Romsdal	
Group	**GWh**
Mining & Manufacturing	9205
Services	1538
Agriculture	249
Primary industries	151
Private Households	2026
Cottage and holiday houses	99

(a) Consumption groups in Møre og Romsdal

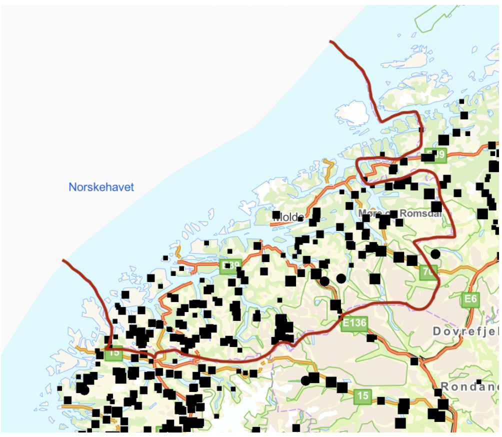


(b) Pie chart of consumption

Figure 4.18.: Consumption in Møre og Romsdal [75]

The total production of power in the county was 7.6 TWh, where 7.2 TWh was from hydropower and 0.4 TWh was from wind power [58]. The location of these hydropower plants and wind power plants can be seen in Figure 4.19a and Figure 4.19b.

This meant that Møre og Romsdal had a negative power balance of -5.4 TWh in 2021 and imported energy that year to meet the county's consumption.



(a) Locations of hydropower plants marked with black squares [60]

(b) Locations of wind farms marked with green dots [63] and airports

Figure 4.19.: Locations of power production sites in Møre og Romsdal

Future production and consumption

Møre og Romsdal has recently been discussed in the news in Norway, especially in the municipality of Aure, for its new projects in energy production. Aure is a municipality with a power-intensive industry that imports 42% of its energy consumption from nearby counties [58]. The municipality, therefore, has a power deficit, and to allow construction for new industries and with the industry now wanting to make its production green, even more energy is needed.

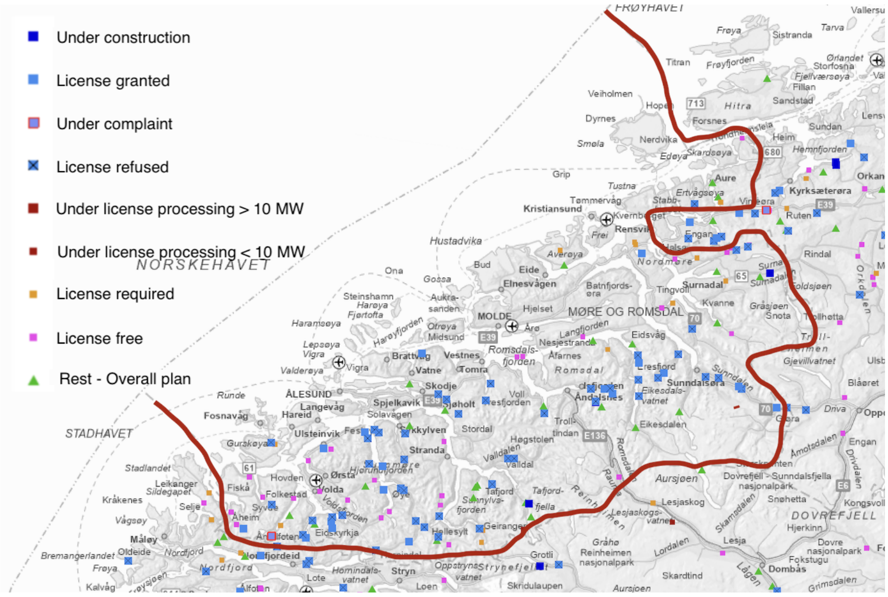
How to produce new energy in the county is still being determined, with decisions and plans constantly changing. A referendum in Aure said no to new wind power, and in an interview with Brekken, the mayor of Aure says the following:

“- We have had a referendum in Aure, and we have said no to wind power. But you can’t say no to everything. We depend on power to develop the municipality further, and then I think that nuclear power can be part of the solution for us.” [13]

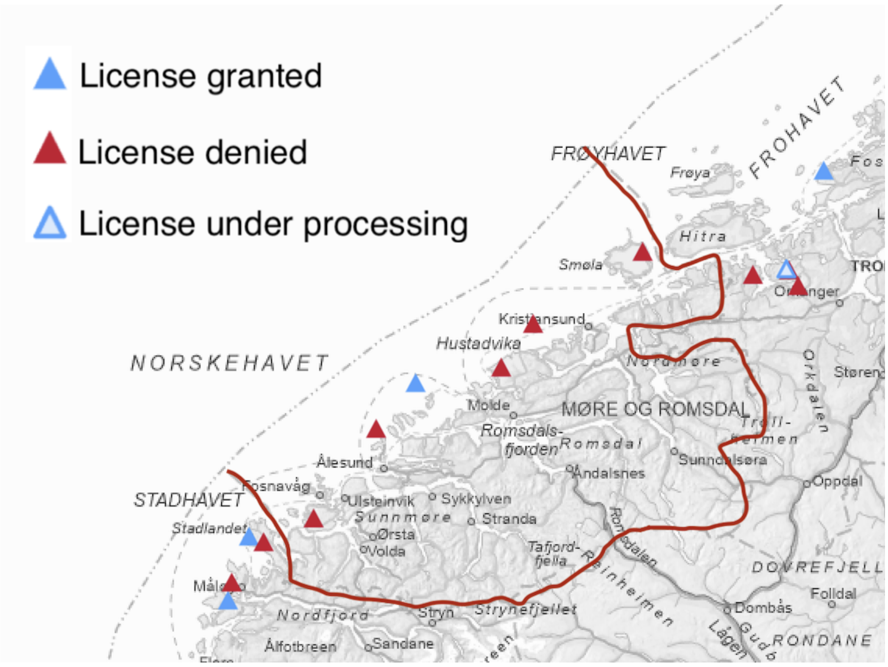
However, no plans or agreements have yet been made to make nuclear a reality. Aure has, therefore, become a pilot municipality in work to make Møre og Romsdal more self-sufficient in electricity in the project Kystkraft.

In the project, Kystkraft has identified a renewable energy potential equivalent to 290 GWh, which does not need the concession to be constructed and is equivalent to the entire electrical consumption in the municipality. 30 GWh comes from consumer energy savings, 89 GWh comes from hydropower, 22 GWh from wind power, 42 GWh from Bioenergy, and a total of 105 GWh from new solar energy [76].

The status of current new hydropower and wind power projects in Møre og Romsdal can be seen in Figure 4.20a and 4.20b.



(a) Status of new hydropower projects [60]



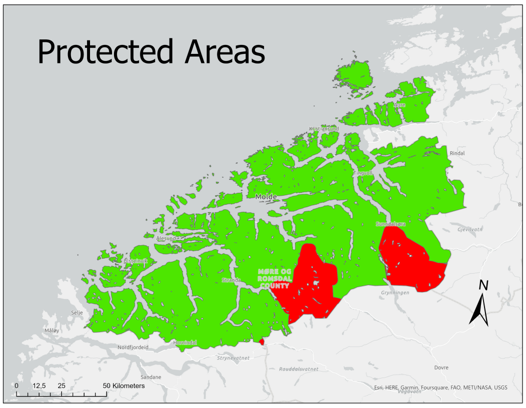
(b) Status of new wind power projects [63]

Figure 4.20.: Locations of future power production sites in Møre og Romsdal

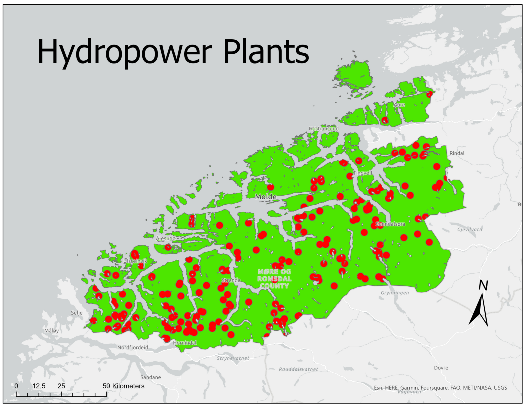
4.3. SMR siting

4.3.1. Restriction criteria maps

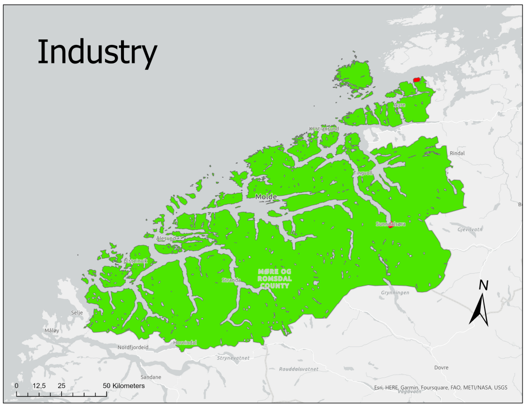
Figure 4.21 shows the individual site criteria map layers for the restriction criteria in the Open case. In Figure 4.21a, protected areas are shown in red. In Figure 4.21b, hydropower plant locations and their restricted areas are shown in red. In Figure 4.21c, the areas restricted due to use by industry are shown in red. In Figure 4.21d, areas occupied by airports are shown in red. In Figure 4.21e, areas restricted due to large populations are shown in red. In Figure 4.21f, areas restricted due to flooding risks are shown in red. Figure 4.21g shows areas restricted due to landslide risks in red.



(a) Protected Areas

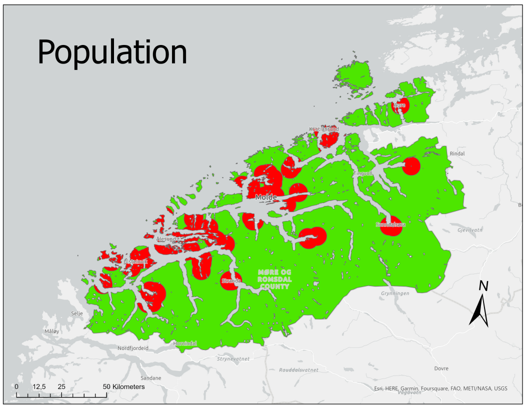


(b) Hydropower Plants

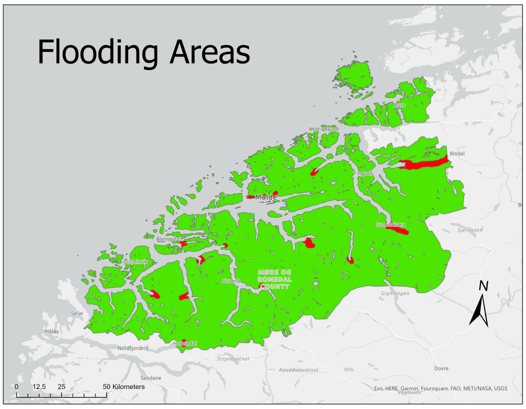


(c) Industry

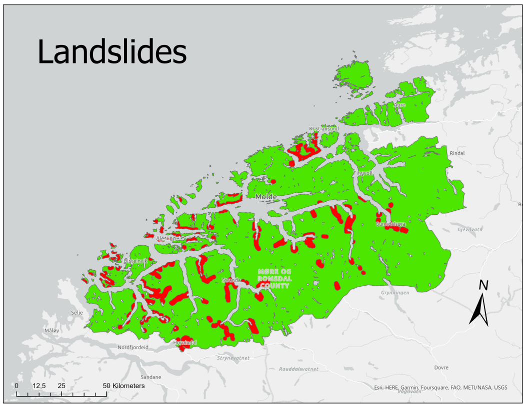
(d) Airports



(e) Population



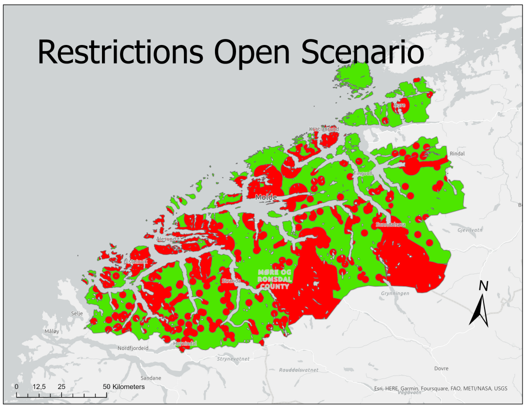
(f) Flooding Areas



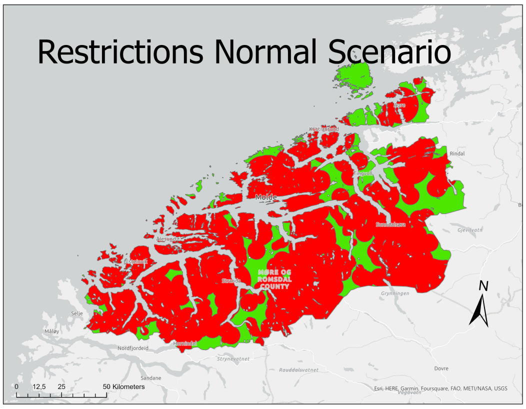
(g) Landslides

Figure 4.21.: Restriction criteria maps in the Open case. Red shows unsuitable area and green suitable area.

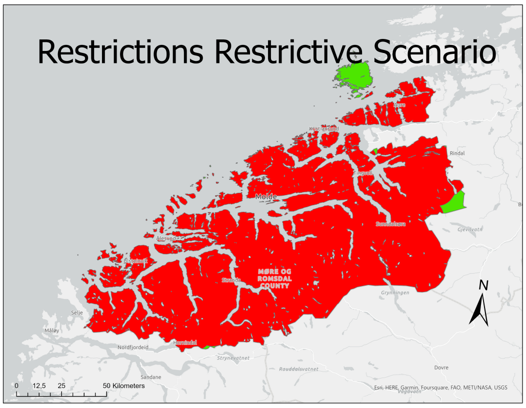
Figure 4.22 shows all the restriction criteria combined in the three different cases Open, Normal, and Restrictive.



(a) Restrictions combined Open Case



(b) Restrictions combined Normal Case

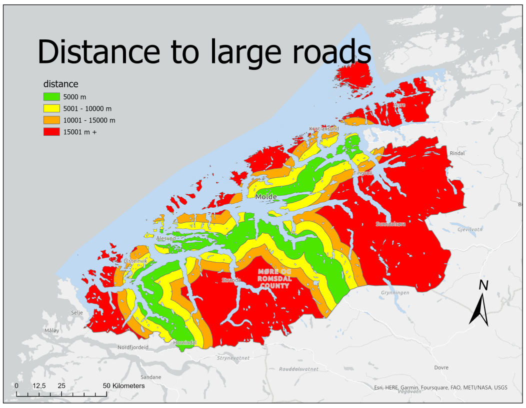


(c) Restrictions combined Restrictive Case

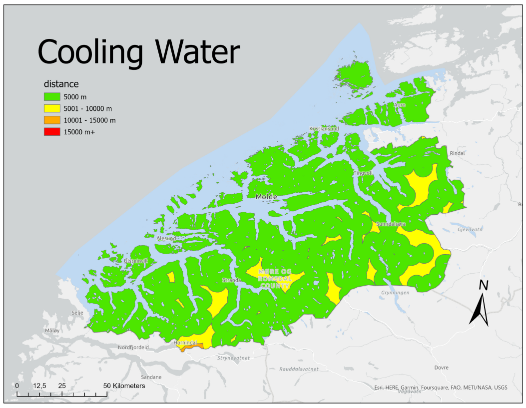
Figure 4.22.: Restriction criteria maps combined in the three different cases Open, Normal and Restrictive. Red shows unsuitable area and green suitable area.

4.3.2. Evaluation criteria maps

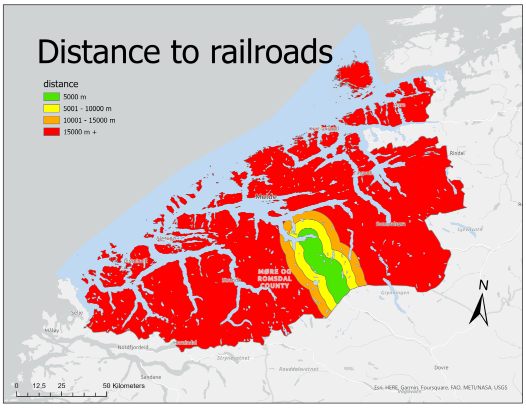
Figure 4.23 shows the individual site criteria map layers for the evaluation criteria. In Figure 4.23a, distances to large roads are shown in 5000 m intervals. In Figure 4.23b, the distance to the cooling water are shown in 5000 m intervals. In Figure 4.23c, the distance railroads are shown in 5000 m intervals. In Figure 4.23d, the distances to large transmission lines are shown in 5000 m intervals. Figure 4.23e shows the topography over Møre og Romsdal in 500 m intervals.



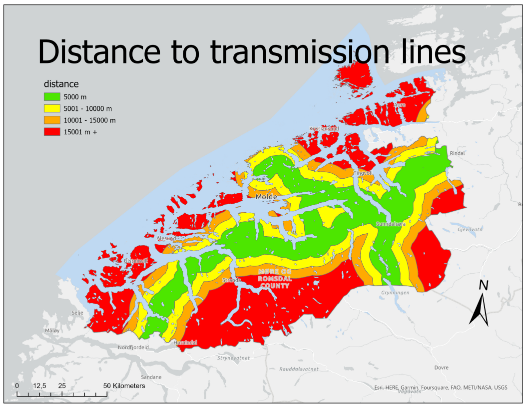
(a) Distance to large roads



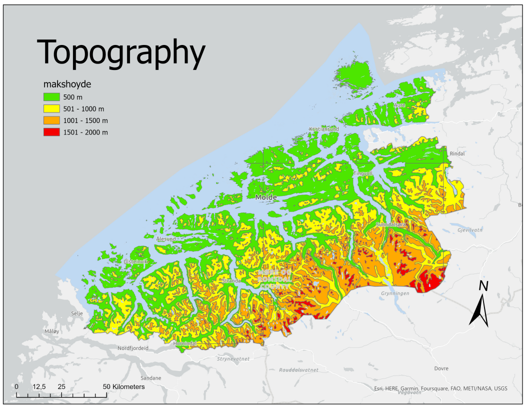
(b) Distance to cooling water



(c) Distance to railways



(d) Distance to transmission lines

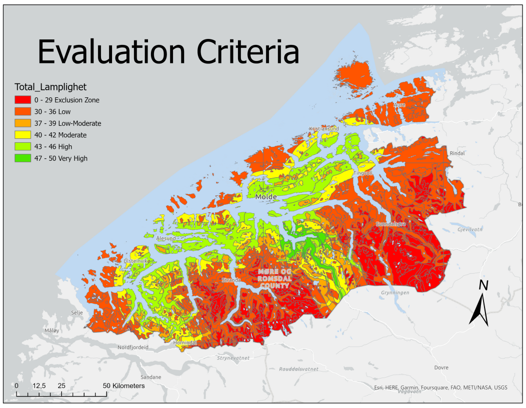


(e) Different altitudes

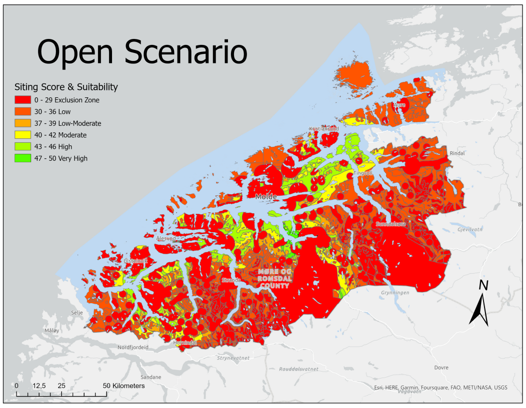
Figure 4.23.: Evaluation criteria maps.

4.3.3. SMR siting suitability maps

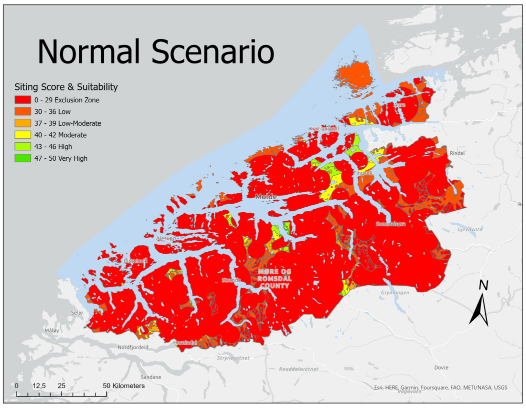
All the suitability and restriction criteria were combined to produce SMR siting suitability maps. In Figure 4.24a the combined evaluation criteria are combined to form a suitability map without restrictions. In Figure 4.24b, 4.24c and 4.24d, the evaluation criteria are combined with the restriction criteria to form the three different cases Open, Normal, and Restrictive.



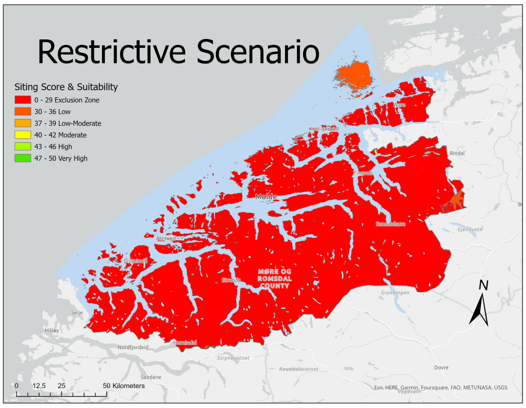
(a) Map of all evaluation criteria combined



(b) Open Case



(c) Normal Case

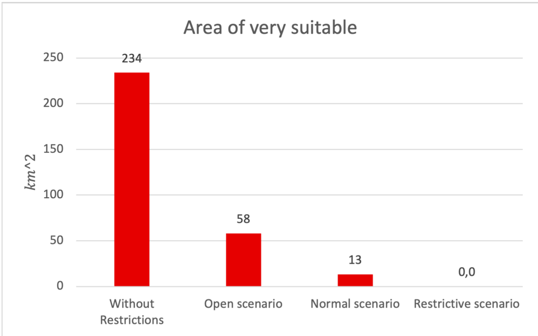


(d) Restrictive Case

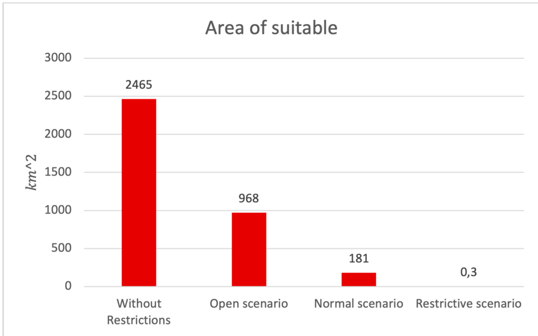
Figure 4.24.: Final suitability maps with evaluation criteria and restrictions criteria combined in the three cases. Scoring and suitability can be seen in each figures legend.

The following chart 4.25a compares the total areas of the class of the very suitable area in the final maps for three cases and the map without restrictions. The map without restrictions offers more potential than the other cases due to no limitations being introduced in that map. The Open case provides the most potential between the three cases due to the geographical distances considered for both the evaluation and restriction criteria. The Restrictive case offers the least suitable area compared to the others due to the high geographical distance considered for all the criteria. Based on Figures 4.24

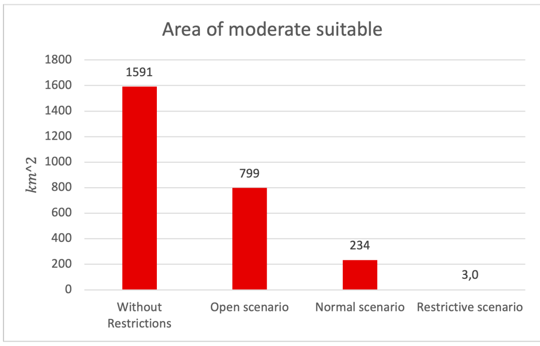
and 4.25, the Open case features several suitable areas compared to the other cases. Notable relevant characteristics include meeting the restrictions and evaluation criteria of accessibility to utilities such as surface water, transmission lines, topography, roads, and railways. These positive attributes offer significant SMR siting opportunities. Figure 4.25 illustrates the area for each suitability group, and Figures 4.25a, 4.25b, and 4.25c show the categories of suitable construction areas. The other three, Figures 4.25d, 4.25e, and 4.25f, show how much area is unsuitable for constructing an SMR and the total area that's being left out.



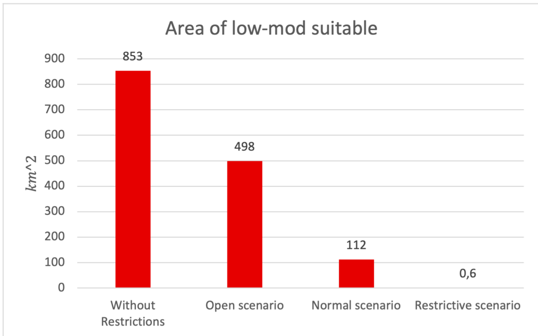
(a) Area of the category very suitable



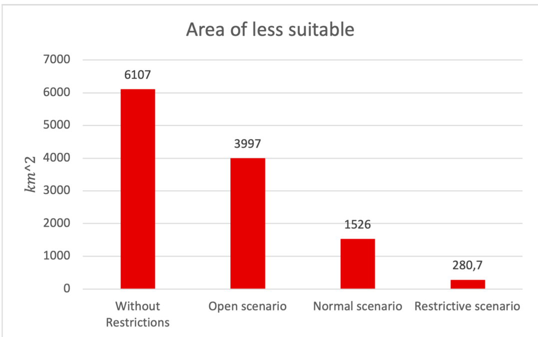
(b) Area of the category suitable



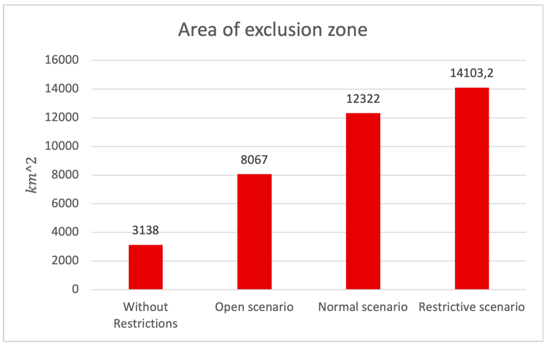
(c) Area of the category moderate suitable



(d) Area of the category low-mod suitable



(e) Area of the category less suitable



(f) Area of the category exclusion zone

Figure 4.25.: A comparison of total area of every suitability category

Chapter 5.

Discussion

5.1. Results

The Open case shown in Figure 4.24b, offers the largest area with a very suitable area for SMR siting due to its small geographical distances for the restriction criteria exclusion zones. The Restrictive case, shown in Figure 4.24d, offers no area within the very suitable area for SMR siting due to the large geographic distances for the restriction criteria exclusion zones. The Normal case, shown in Figure 4.24c, falls between the Open and Restrictive cases and has fewer very suitable areas than the Open case but more than the Restrictive case.

The results are concentrated in the proximity of transportation and transmission infrastructure, and for an area to receive the category scoring of very suitable, it needs points from all parameters. Due to the weighting of the parameters and the fact that access to railroads only exists in one area, where all the other parameters exist as well, the category of very suitable, therefore, only exists near the railroad. The suitable category, however, is not dependent on the points from railroads and therefore follows where it is easy to access transportation and transmission lines. This category is also close to cooling water and at a low altitude. All other categories are a mix of distances to transportation, transmission, and on different altitudes.

5.2. Restrictions and evaluation criteria

The restrictions introduced in this study are the dominant factor in how much very suitable area is available for an SMR siting. Establishing appropriate criteria is, therefore, a crucial step in any site selection study. The restriction criteria chosen for this study were primarily adapted to fit a conventional SMR technology and power production site of less than 300 MW. However, the evaluation process may also identify areas suitable for power production with higher capacity, but the site itself has never been evaluated on that basis. Different SMRs have different criteria and safety standards depending on what technology of SMR is utilized. SMRs also have different criteria and safety standards than traditional larger nuclear reactors. For example, a conventional reactor either needs access to a significant source of cooling water or utilizes a cooling tower, but some technologies of SMRs have significantly reduced cooling needs and, therefore, can be sited in proximity to smaller water sources or with a size reduced cooling tower. The same principle works when discussing the distance to the population centers. With a conventional nuclear power plant, you would want an extensive safety zone and distance to population centers, however, with the reduced size and increased inherent safety design with SMRs, the safety zone decreases significantly, and the power plant can be situated closer to the consumer. Due to this study not being a siting for a specific type of SMR technology and more being a proof of concept of how a siting could work for Norway and Møre og Romsdal, broad parameters and distances were chosen. The three cases, Open, Normal and Restrictive, were selected and studied to evaluate the possibilities with different restriction distances and therefore create a siting for different types of needs of SMRs technologies or other types of rules and regulations that the government could introduce.

The siting evaluation criteria used in this study are based on similar studies and regulation documents made by IAEA [50] [51] [55] [56]. All criteria established in these studies and documents need to be considered, however, some criteria are specific to a unique scenario or a given country's geography, location, strategic policies, and environment. Different places lead to different site analyses and, therefore, different evaluation criteria and weighting of those criteria. The same applies to the restriction criteria. For example, access to cooling water in Møre og Romsdal is almost negligible, and almost all areas shown in Figure 4.23b are very suitable. The area that is not very suitable is often at a high altitude; therefore, because of the weighting, is not considered a potential SMR site anyway. But in a different scenario where a siting is done in Saudi Arabia, the SMR siting locations would be preferred to be in coastal regions due to its lack of lakes, fjords, and water resources. Another example considers how the topography could lead to different scenarios if it were built in Denmark, which has a flat surface compared to Norway. The importance of the evaluation and restrictions parameters chosen, therefore, constantly changes depending on what country is studied.

The assigning of weighting criteria is a sensitive issue in siting studies as experts with unique perspectives can have biased value judgments and opinions about the relative importance of criteria. The weighing system was also not chosen for a specific type of SMR technology and was more adapted to the geography and infrastructure of Møre og Romsdal. Considering this, and as mentioned before, access to cooling water was not a priority, and more focus was directed toward the lack of an extensive transportation network and the topography in the county. Two out of five criteria in this study were linked to transportation. Because of the lack of a railroad in the county shown in Figure 4.23c, an area could only get the result very suitable if it were connected to the small area where railroads existed even after the criteria were weighted. Therefore, if railroads were neglected in this study, all highly suitable regions would get the highest score of very suitable. This can be visualized in Figures 4.24a and 4.25, where the lowest allowed score for very high suitability would move from 47 to 43. This shows that the criteria and weighting system used in an SMR siting study is crucial and different parameters could lead to a completely different result.

5.3. Transportation to site

Regardless of the type of SMR design, the reactor core and plant infrastructure require access to large transportation to be delivered in its modules to keep its economic advantages. Also, an extensive and safe transportation network is crucial for waste transportation and roads for workers, construction, and emergency response. Møre og Romsdal's geography of low-lying coastal landscape that quickly transitions to high mountains and a vast network of fjords crosses the entire county makes transportation difficult. High priority should, therefore, be applied to assessing the transportation network throughout the county concerning enabling SMR module transportability. Standard railways are the preferred mode of delivery, but the county lacks an extended railway network, and the county road network consists of many tunnels, bridges, and use ferries, which is not preferred when delivering SMR modules or for safety measures due to risk for ques or inaccessibility if accidents occur. The only railway used in Møre og Romsdal is a tourist attraction for nature attractions and is not adapted for heavy and oversized transportation. But the access to the sea and the county's vast network of fjords enables access with ships to almost every potential suitable SMR site. Therefore, an option for transportation in the county is building a new port close to the site or even being a part of the nuclear power plant site. This port could continuously act as a transportation hub for the site, a delivery point for the SMR modules, construction materials, receiving new nuclear fuel, shipping spent nuclear fuel, etc. This mode of delivery is used in Sweden, i.e., the nuclear power plants in Oskarshamn and Forsmark, where both sites have their own ports and use the ship m/s Sigrid to transport the sites spent nuclear waste [77].

5.4. Slope and altitude

Figure 4.23e shows that the county consists of low-lying coastal land that drastically transforms into high mountains. This extreme topography gave the altitude parameter the highest weighting priority. Finding a flat surface that is accessible for the delivery of SMR modules, close to water, not in a flooding or landslide area, is crucial for the siting. These kinds of areas in Møre og Romsdal are limited, and the very suitable results shown in the three cases shown in Figures 4.24b, 4.24c, and 4.24d are concentrated in those areas.

Instead of using slope as a parameter, altitude was used in intervals of 500 meters. This is not ideal because high elevation differences can happen within 500 meters, meaning that the intervals could include uneven land and high slope elevations. Just because an area is in the first interval of 0 to 500 meters does not mean that the area is flat and suitable for constructing an SMR. However, this was the smallest and easiest interval dataset found that did not acquire great expertise in ArcGis and would not take too long to transform into a suitable format for evaluation and scoring.

5.5. Distance to population

SMRs pose a lower risk than larger traditional nuclear power plants, they can therefore be built relatively close to consumers. Safety improvements also include a smaller emergency planning zone. Thus, SMRs can be relatively close to population areas and minimize the potential consequences of accidents. The country's laws and politics will, however, determine the distance from the nuclear power plant to the nearby population, and it is hard to foresee before any official rules and regulations are in place in the area where the siting is performed. Therefore, this study covers a vast area in three cases, which covers 5 to 20 km. These restrictions result in losing many suitable areas and are the most significant restriction introduced in this study which can be seen in Figure 4.21e. It should also be mentioned that this study only evaluated a population density of more than >100 persons/200x200m, and the density could be less and more challenging or manageable depending on chosen regulations and type of SMR technology.

5.6. Distance to transmission lines

As mentioned, SMRs pose a lower risk than larger conventional nuclear power plants, and they can, therefore, be built relatively close to the population. This also means that they can be constructed closer to consumers and, thus, minimize the cost of service transmission. Distance to transmission lines was therefore added as an evaluation criterion. Only the high-voltage grid was considered. Figure 4.23d shows that the transmission lines go through the whole county in the middle and follow the large roads. It, therefore, grants excellent access to a large part of the county.

5.7. Map limitations

The area and county Møre og Romsdal chosen in this study is a very small county compared to the areas chosen in similar studies for Maine and Saskatchewan. Maine is 6.6 times bigger, and Saskatchewan is 47 times bigger than Møre og Romsdal. This is one of the primary reasons for the significant difference in very suitable areas between these studies. Many restrictions criteria were also introduced to the county, and the lack of area to study led to restrictions taking over most of the county.

This study did not consider neighboring counties, which could lead to more possibilities or restrictions near the county's borders. An example is in Figure 4.23a northeast corner, where the distance to large roads is being researched. Møre og Romsdal surrounds a part of the neighboring county where the large road continues in the neighboring county. However, this led to the area surrounding the neighboring county being visualized as far away from the road network when it, in reality, is just next to it. The population situation or restricted areas, e.g., are not studied in that area, which could lead to considerable restrictions. Considerations like this can be done all over the borders of Møre og Romsdal, and the area near neighboring counties is, therefore, a grey area.

5.8. Data and time limitations

Some criteria considered in this study are not expected to vary much over time. Such static criteria include access to cooling water and topography. Other criteria, such as flooding areas, landslides, and population density, are more dynamic. A larger safety buffer was therefore introduced than probably needed in, for example, flooding and landslides.

Due to simplifications and time management, the total area of suitability and not the amount of 200x200m squares which a standard SMR uses was used in this study. This means that the area, for example, a very suitable area, could be split up into small pieces all over the county.For the same reasons, the topography was studied in intervals of 500 meters instead of slope or smaller intervals, which would get a more accurate overview of how the landscape is behaving in a specific area.

5.9. Operators of interests and energy mapping

Møre og Romsdal was chosen in this study for the SMR siting due to its energy deficit, low population density, access to water, and willingness for new energy projects. The counties Oslo and Viken also had large energy deficits, and had Oslo been chosen instead, with its high population density, almost the whole county would have been in the non-suitable category because of the distance to population restrictions, and the whole evaluation criteria, restriction criteria, and weighting system would have to be redone. How the process for Viken would have looked like is harder to say without a proper siting. The county is larger than Møre og Romsdal but has a higher population density. The county does not border as much water but probably has a better transportation network due to its higher population density.

Both Oslo and Viken require new energy production and, therefore, need a siting over their counties. Without doing an extensive siting in Oslo and Viken, it is hard to know precisely how the results would compare against Møre og Romsdal. The counties could offer great opportunities for new construction of energy production such as SMR, or they could offer none, which, in that case, other actions are required, such as energy savings within the county and energy imports from neighboring counties.

Chapter 6.

Conclusions

6.1. Research question 1: Energy mapping

In 2021, Norway had an electricity production of 157 TWh and an installed capacity of 40 000 MW. Most of the electricity production in 2021 came from hydropower, wind, and thermal power. From 2020 to 2021, hydropower increased by 1.5% in production, while wind power increased by 19%. Thermal power had a decrease of 39% from 2020. The largest producing county in the country is Vestland, with 36 TWh, the second largest is Agder, with 18.5 TWh, and the third is Nordland, with 18 TWh.

In 2021, Norway had a gross electricity consumption of 140 TWh, mostly from Mining and Manufacturing. The three most significant consumptions came from the county Vestland with 23 TWh, Viken with 20 TWh, and Rogaland with 13 TWh. The counties with the highest energy deficit balance were Oslo with - 9 TWh, Møre og Romsdal with -5 TWh, and Viken with -3 TWh.

Norway's future power production and consumption development are uncertain, and the two categories are linked and dependent on each other. How much power production is built out is primarily determined by the framework in the concession progress. The development of consumption and production in the future will thus largely depend on Norway's political choices.

The research from Statnett estimates an increase in consumption that varies from a total consumption of 190 to 300 TWh, depending on three different scenarios. New hydropower, solar power, and onshore wind will cover half of the new production, and the other half will be covered by offshore wind.

According to the research from NVE, from 2021 to 2030, power consumption is expected to increase more than power production. From 2030 to 2040, the power production will be greater than the consumption. The power surplus in 2040 will be about 12 TWh. Most of the new power production from 2021 to 2040 will be from hydropower, but from 2030 to 2040, the significant development of new power production will come from wind and solar power.

The three counties with the highest energy deficits were considered subjects to the SMR siting. Møre og Romsdal was chosen due to its lower population density, direct water access, and the county's ongoing energy debate.

6.2. Research question 2: SMR siting

An SMR siting is entirely possible in Møre og Romsdal according to the evaluation and restriction criteria chosen in this study, and are visualized in Figures 4.24 and 4.25. The selected evaluation criteria fitted for this siting were: roads, railways, cooling water, transmission lines, and topography. The selected restriction criteria for this siting were airports, flooding areas, protected areas, industry, landslides, population, and hydropower plants. The restriction criteria and evaluation criteria were combined in three different case scenarios: Open, Normal, and Restrictive. In the Open case, the reactor was placed near the siting criteria, contrasted with the Restrictive case in which the SMR was placed at a distance from the siting criteria. The Normal case falls in between the Open and Restrictive case.

The Open case is the most promising, with around 58 square kilometers of very suitable area for an SMR siting. The Normal case offers some opportunities with approximately 13 square kilometers of very suitable area. The restrictive case, however, provides no area within the very suitable category. As mentioned before, these results are very dependent on the transportation network within the county. If the county would choose another type of transportation, such as transportation by ship mentioned in the discussion, a significantly larger area would be in the very suitable category in all three cases, and the possibility for an SMR siting would be more promising.

Chapter 7.

Future work

This siting study is only the first step of a detailed SMR siting, giving a broad overview of the county's possibilities. If one wishes further to assess the potential of SMR deployment in the county, a detailed SMR siting needs to be performed. The detailed SMR siting process could use this study as a baseline input. The most promising areas in the county identified by this study can be thoroughly analyzed, and a handful of potential sites can be selectively be chosen for a comparative detailed siting study. Considering all the relevant site evaluation aspects mentioned in "Site Survey and Site Selection for Nuclear Installations" [78], could be a natural step when conducting the comparative detailed siting study.

Furthermore, one could assess the cogeneration possibilities for a nuclear power plant in the county, meaning using nuclear power plants for electricity production and processing heat or regional heating.

Appendix A.

Interview guide

A.1. WSP nuclear experts

Interviews with nuclear consultants from WSP.

1. What criteria are the most important when doing a siting for an SMR?
2. What criteria would be the most important in Norway, especially in Møre og Romsdal, which geography includes fjords and large mountains?
3. What criteria should be seen as restrictions, and what criteria should be seen as evaluation?
4. How should the criteria be weighed compared to each other?
5. What distances should the intervals have within the evaluation criteria?
6. What distances should the restriction criteria have?

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