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Comparing hydro- and wind electricity sources in Norway

by

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Thesis

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Abstract

The motivation for this study was to get a better understanding of the two main power production methods, as more and more wind power plants are appearing in Norway, alongside a rise in the export of electricity overseas.

This thesis examines the key aspects of hydro- and wind energy, focusing on their environmental impact, technological considerations, overall efficiency, economics, ethics, and implications for the common good. By evaluating these factors, this research aims to provide a comprehensive understanding of the advantages, challenges, and trade-offs associated with both energy sources.

The conclusion of this study highlights that both hydro- and wind energy are proven to be environmentally friendly and economically viable. Wind power plays a crucial role in Norway's efforts to achieve a net-zero carbon emission target, considering the growing electricity demand to meet climate goals. The government's strict regulation and careful consideration of ethical, economic, and common good factors are emphasized.

The findings of this study contribute to the broader discussion on sustainable energy development and inform decision-making processes towards a more efficient, ethical, and environmentally responsible energy mix in Norway.

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INTRODUCTION

The need for energy is constantly rising as the world population increases and technology develops. Troubled times in the world have put the world's energy infrastructure and energy politics to the test and led to a global energy crisis. The crisis was caused by a variety of economic factors, including the rapid post-pandemic economic rebound that outpaced energy supply, and escalated into a global energy crisis following the Russian large-scale invasion of Ukraine (Figure 1 – December 2021-January 2022) (The Editors of Encyclopaedia Britannica, 2023). Figure 1 shows the change over time of four energy price categories. Notice the sharp increase in prices from September to October 2021 when pandemic restrictions were lifted in Europe (Norwegian Government, 2021).

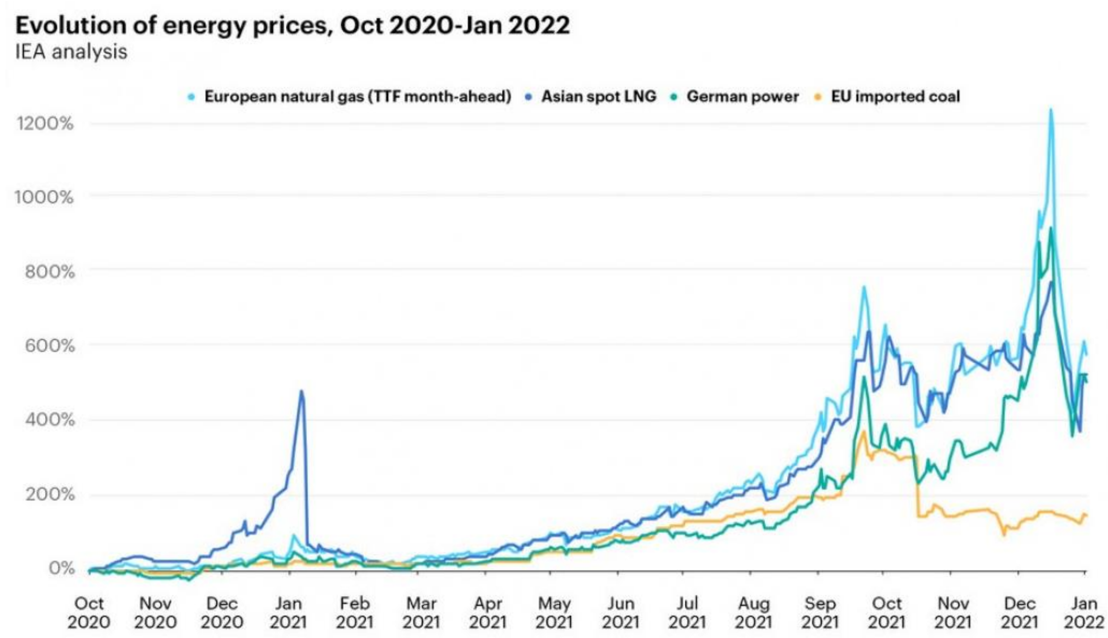

Figure 1. Evolution of energy prices. From IEA (2022).

At the same time as the demand for energy and energy prices are increasing, climate change is becoming more and more prominent. Since 1950, the world's average temperature has risen 1.1°C (IPCC, 2023) (Figure 1). One of the main causes of global warming is the burning of fossil fuels such as coal, oil, and gas, which releases carbon dioxide (CO_2) and other greenhouse gases into the atmosphere. These gases act like a blanket, trapping heat from the sun, causing a gradual rise in temperature. This is a reinforcing effect which will continue to increase with the current trend and will have significant consequences for the global population (IPCC, 2023).

Addressing global warming requires collective action on a global scale. Efforts to mitigate and adapt to climate change include transitioning to renewable energy sources, improving energy efficiency, reducing deforestation, and adopting sustainable agricultural practices. To reduce the effects of global warming, the international community set a 2°C target. The "2°C target" was an outcome following the 2015 Paris Agreement, a global climate accord aimed at limiting global warming well below 2℃ and pursuing efforts to limit it to 1.5 ℃ (Figure 2 – shaded blue area). The agreement emphasizes the importance of taking collective action to reduce greenhouse gas emissions, increase resilience to climate impacts, and support sustainable development (European Commission, 2023).

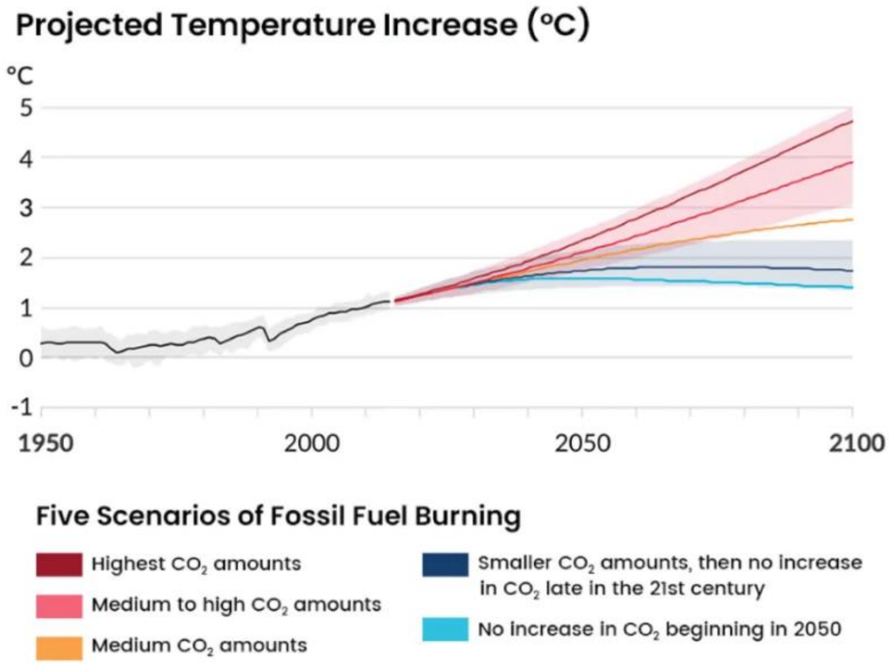

Figure 2. IPCC-Projected temperature increase (IPCC, 2022).

The issue of global warming is forcing the energy industry, or rather, politicians are motivating the industry, to be more sustainable by encouraging and facilitating the use and investment in renewable energy sources. From January to June 2022, world electricity generation from renewable sources increased while electricity from nuclear, coal, and gas decreased; during the same period, total demand increased nearly the same amount as the increased production (Figure 3) (Ember, 2022). Figure 3 shows the year-on-year changes in electricity demand from January to June in 2022 and demonstrates that the production of green energy met the demand for the period of 389 terawatt-hours (TWh).

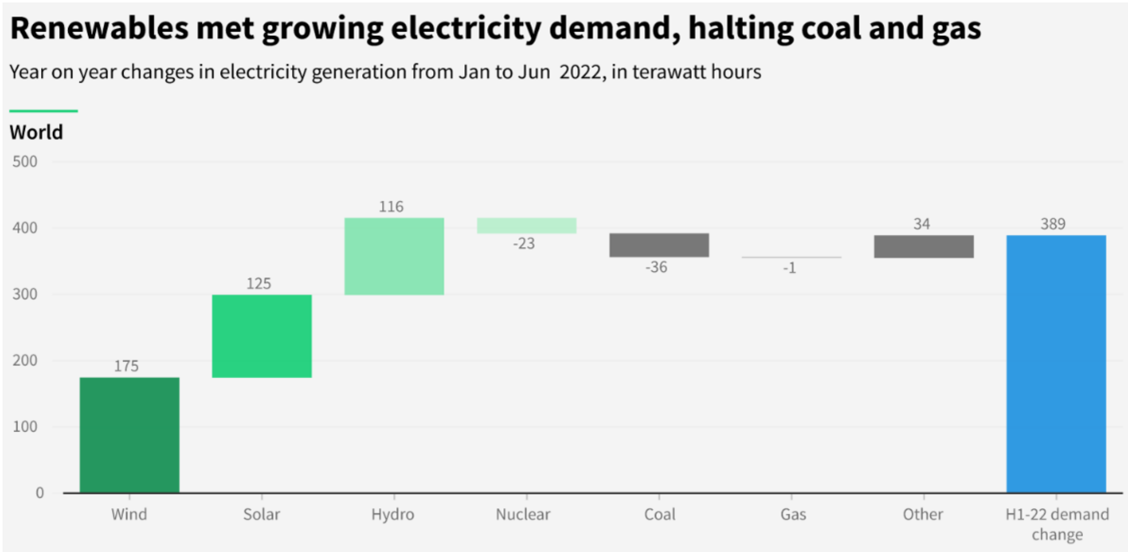

Figure 3. Electricity generation and demand by electricity source (Ember, 2022).

Norway's diverse landscape offers an ideal environment for producing green energy. Its rivers and waterfalls enable the generation of hydropower, while the strong coastal winds are perfect for wind energy. The country's numerous rivers and waterfalls offer ideal conditions for hydropower, which has been a cornerstone of Norway's energy production for decades (The Norwegian Centre for Climate Services, 2017).

Moreover, Norway's extensive coastline and strong winds make it an excellent location for harnessing wind energy. Wind farms situated along the coast and in suitable inland areas take advantage of the consistent winds, converting their kinetic energy into sustainable electricity (The Norwegian Centre for Climate Services, 2017).

Hydroenergy is the main supply of electrical energy. The opinion among many in the population is that this should be sufficient to serve the energy need (Motvind Norge, 2023).

However, in recent times the amount of wind power plants has increased substantially, as well as the price of energy.

Norway has become an exporter of electricity through 17 cable connections to 7 different countries (Embed artikkel, 2022). 25.8 TWh were exported from Norway in 2022, which is roughly the same as 2021 (Holstad, 2023). This represents approximately 21% of Norway's total electricity consumption. 13.3 TWh of electricity were imported into Norway in 2022. The increase from 8.2 TWh in the previous year and 4.5 TWh in 2020 to the current level is significant, possibly attributed to the utilization of water reservoirs to support Europe during the energy crisis. Additionally, the preceding year experienced a scarcity of rainfall, further impacting the situation (Holstad, 2023).

Figure 4 shows the normalized production and consumption for Norway from 1990 to 2020. The graph shows a gradual increase in hydropower production and a noticeable increase in wind power since 2016.

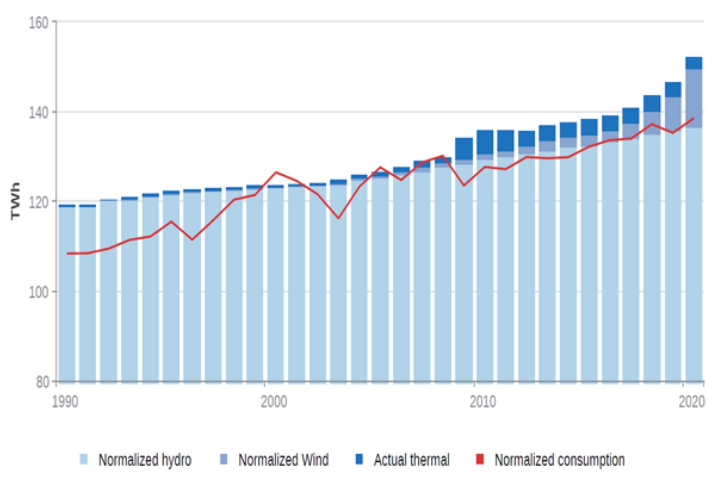

Figure 4. Normalized production and consumption of electricity 1990-2020, TWh (Energy Facts Norway, 2021).

The improved infrastructure with the latest "North Sea Link" cable, which became operational in October 2021, is a political strategy to secure the power supply for Norway. The cables allowed for consistent power supply and reduced influence of weather conditions (Embed artikkel, 2022). An expansion of the power infrastructure and increase in export to other countries, mainly Denmark, Sweden, England, and Germany, has led to a significant increase in energy prices for the Norwegian people (Rosvold K. H., 2022), despite a large increase in power plants, especially wind power plants (Norway, Statistic, 2023). Figure 5 shows the 17 connections between Norway and the 7 surrounding countries.

The primary objective of this study is to assess the economic viability and effectiveness of the two main renewable energy resources in Norway. It will compare hydropower to wind power in terms of efficiency, sustainability, economics, taxes, ethics, and the common good. Three questions are:

1. Are there any clear advantages or disadvantages of either hydro or wind over the other?
2. Is wind power economical for larger Norwegian investment?
3. Can Norway achieve net-zero carbon emissions with wind and hydro power alone?

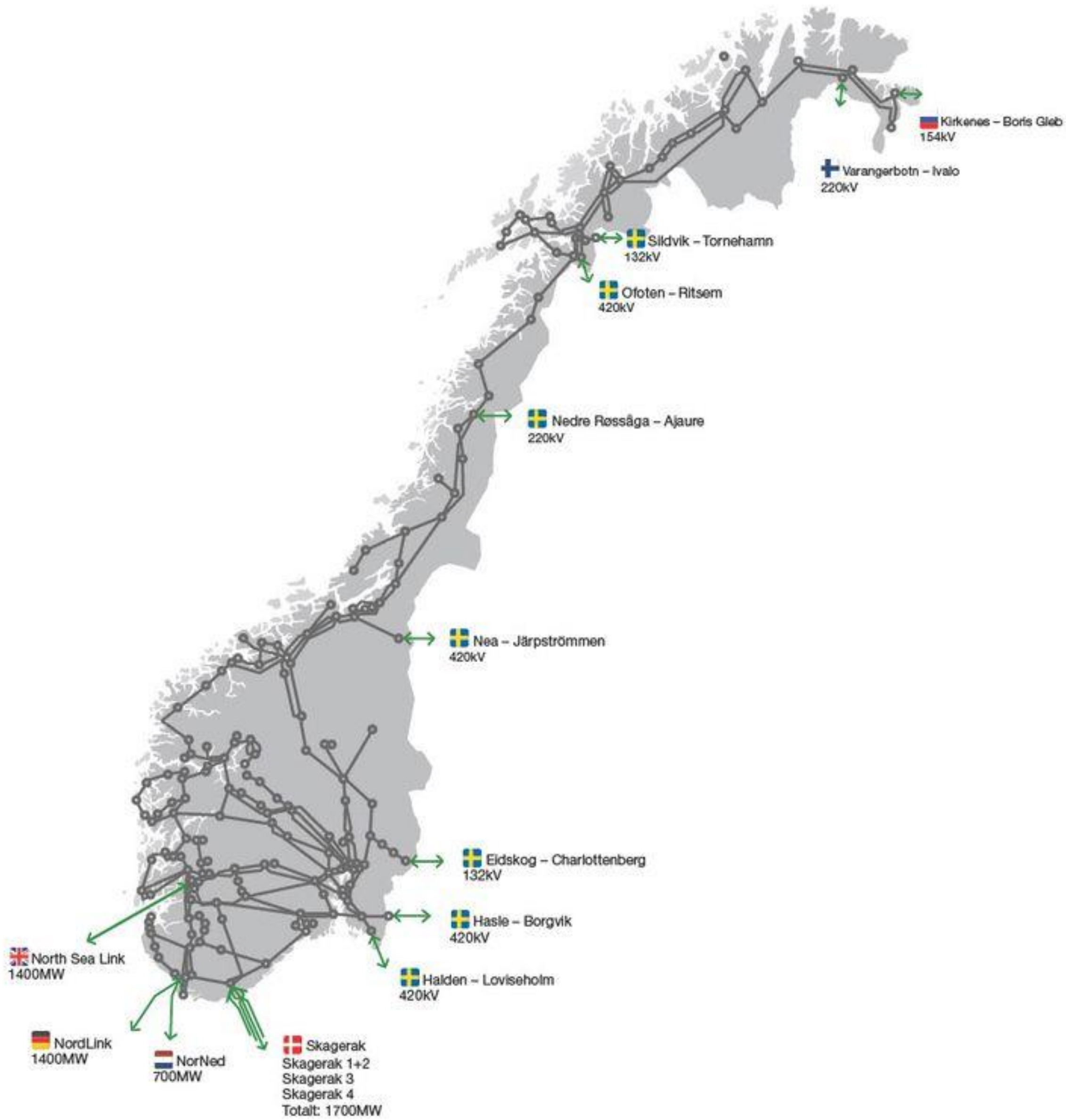

Figure 5. Map of power grid and export capacity (Statnett, 2022).

HYDROPOWER

Hydropower, or hydro energy, is a renewable energy source that uses the energy of moving water to generate electricity. On a global scale, hydropower accounts for 17% of total power production (Statkraft, 2023). The electricity production method has a vital role as Norway's primary source of electricity production. Today, hydropower plants normally produce 136.7 TWh yearly, which accounts for approximately 89% of Norway's electricity production, making it the most important source of electricity in the country. There are a total of 1761 hydropower plants in Norway today (NVE, 2023).

One of the biggest advantages of hydropower is that it is a clean and renewable energy source that produces negligible greenhouse gas emissions during operation. Plants in Norway have low emissions. This is due to low vegetation in the areas where the magazines are located. The emission from a typical Norwegian plant is calculated to be 3.3 g/CO2e/kWh (Modahl, 2019), which is well below the 100 g/CO2e/kWh set by EU Taxonomy (Europeen Commision, 2022).

Another benefit is that it's one of few sources of "green" energy that can be stored. There are 1000 storage reservoirs in Norway, with a storage capacity of 87 TWh. These reservoirs have the capacity to supply 62% of the annual Norwegian energy consumption, 87 TWh (Norwegian Ministry of Petroleum and Energy, 2021). Hydropower is today the world's largest renewable energy source and the biggest source of electricity storage with 99.9 % of the global capacity of electricity storage (Staftkraft, 2022).

Overall, hydropower's importance to Norway lies in its contribution to energy production, environmental sustainability, economic growth, energy independence, and the country's ability to provide a stable and reliable power supply to its citizens and neighboring countries (Norwegian Government, 2019).

Technology

The natural water cycle in our climate is exploited to generate electricity by taking advantage of the potential energy in the water, which is naturally transported through evaporation from sea level up into the mountains via condensation (Figure 6). Increased air pressure extracts the water from the clouds in the mountains as precipitation.

Water is dammed up in the mountains, also known as magazines, where the energy in the water is stored and regulated based on energy demand (Figure 7). To convert the potential energy to electricity, water flows through a pipe, also known as a penstock, and then spins the blades in a turbine generating mechanical energy. This energy is then converted to electricity by a generator and connected to a transformer and eventually transmitted (U.S. Energy Information, 2023).

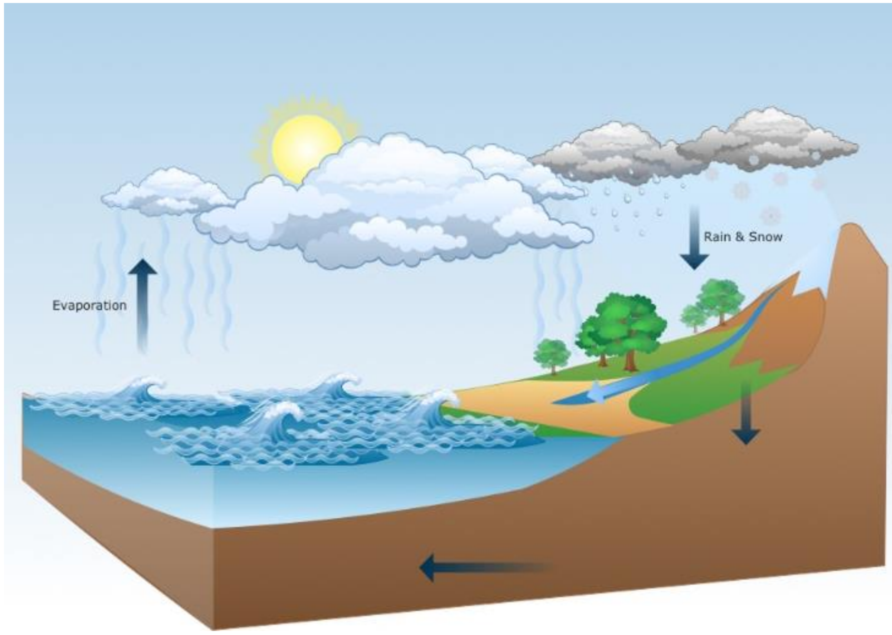

Figure 6. Water cycle (ConceptDraw, 2023).

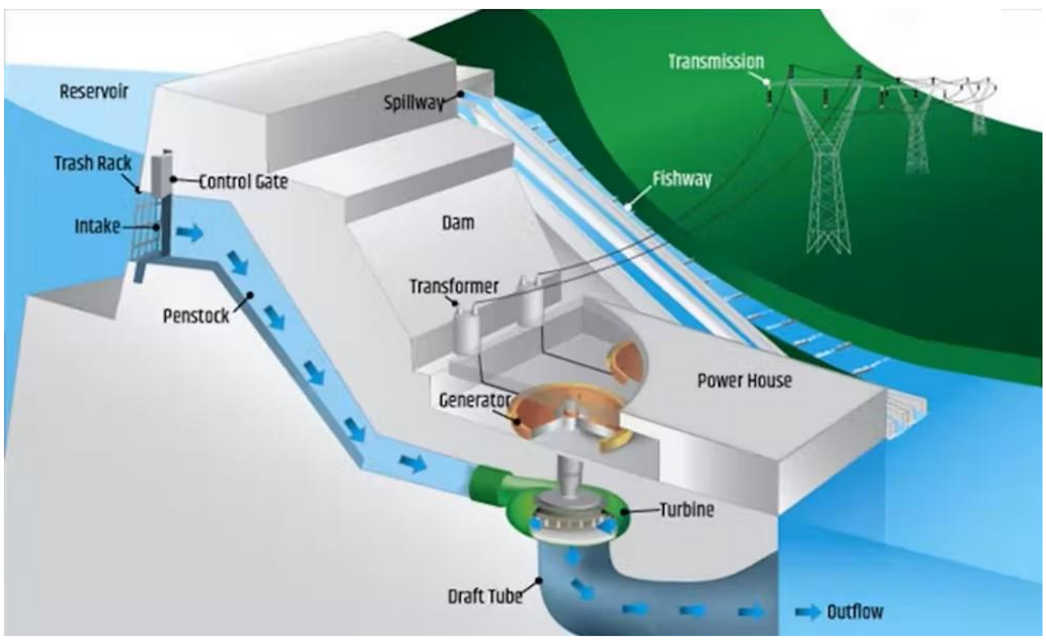

Figure 7. Hydropower electricity generation (U.S Department of energy, 2023).

History

The use of energy from water gravity dates as far back as the first century B.C.E. However, it was not used in Norway before the 14th century (Hofstad K. A., 2022). Water wheels were used to grind grain, saw wood, and power machinery.

Hydropower has played a significant role in Norway's history and economy. Norway's abundant rivers and waterfalls provide a tremendous opportunity for hydroelectric power generation. Hydropower has been the main source of electric energy in Norway, ever since the first plant was opened at Senjens Nikkelverk, which is a former mine in Senja, in the northern part of Norway in 1882 (Hofstad K. A., 2022). Initially, the electricity was produced to power eight arc lamps.

In 1917, the Norwegian government decided to nationalize the country's waterfalls and rivers to ensure that the country's hydropower resources were used for the benefit of the Norwegian people. This led to the creation of Statkraft, a state-owned company that is now one of the largest producers of hydropower in Europe.

After World War II, Norway's economy grew rapidly, and so did the demand for electricity. To meet this demand, several large hydropower projects were initiated, such as the building of the massive Røssåga power plant in the 1950s. The plant opened in 1961 and has an annual production of 963 GWh (Statkraft, 2023).

In the 1990s, Norway deregulated its electricity market, which led to increased competition and a focus on renewable energy sources. This has led to further investment in hydropower and the development of new technologies to make hydropower more efficient and sustainable (Halvorsen, 1998).

Efficiency and Upgrade

It is possible to upgrade hydroelectric power plants to increase their efficiency. Many hydroelectric power plants in Norway have been upgraded over the years to improve their performance and increase their power output. There are several ways to upgrade a hydroelectric power plant. One common method is to install new, more efficient turbines that can generate more electricity from the same amount of water. This can be done by replacing the old turbines with new ones that are designed to produce more power or by retrofitting the existing turbines with new components such as blades or bearings (NVE, 2020).

Another way to upgrade a hydroelectric power plant is to modernize the control and monitoring systems. This can include installing new sensors and automation technology that can optimize the operation of the plant and improve its efficiency. It is beneficial to modify the plants to be more flexible, so that power output can be adjusted quickly. This way the plants won't produce an excessive amount of electricity (NVE, 2022). According to the NVE, increased flexibility in power plants will have a negative effect on prices. This is because it will result in less excessive power, which typically helps reduce electricity prices (Energi21, 2022) (NVE, 2021).

Upgrading the penstocks, which are the pipes that transport water from the reservoir to the turbines, can also improve the efficiency of a hydroelectric power plant. By replacing old or corroded pipes with new ones, the amount of water lost due to leaks or friction can be reduced. Old pipes could be replaced with larger diameter pipes to allow more water and bigger turbines, which can increase the power output of the plant (NVE, 2022).

In addition to these upgrades, there are other improvements that can be made, such as upgrading the generators, transformers, and other electrical equipment. With the right upgrades, hydroelectric power plants can operate more efficiently, produce more electricity, and have a longer lifespan (NVE, 2020).

Half of the large hydropower plants have undergone reinvestment the last 20 years, resulting in an additional power production capacity of 4.5 TWh. These reinvestment projects have been given high priority in the past, and they will continue to be prioritized in the future. (The Norwegian Government, 2023).

One example of renovation that has been performed to a hydropower plant is “Nedre Røssåga kraftverk” in Nordland County. This project is one of the largest renovation projects performed to a hydropower plant after the millennium. The total capacity of “Nedre Røssåga” increased from 200 Megawatts (MW) to 350 MW. Increasing the total yearly production from approximately 200 GWh to 2150 GWh (Statkraft, 2023). Other additional benefits as a result of the renovation were the improved conditions for salmon and sea trout in Røssåga. Among other things, the river got back a salmon-carrying stretch that accounts for 30 percent of the spawning grounds in the entire Røssåga watercourse.

If Norway were to exploit every waterfall in the country, they could potentially produce 600 TWh (Norwegian Water Resources and Energy Directorate, 2020). However, a calculation conducted in 2020 indicates that the economic potential with current technology is estimated to be 216 TWh. It is possible to extract 6-8 TWh by upgrading existing plants. Figure 8 shows the status for the potential of hydropower plants in Norway (Norwegian Water Resources, 2020). According to the study performed by NWR, there is potential for nearly 23 TWh to be produced. 64% has already been developed and 23 % of the potential development areas has been protected by the government.

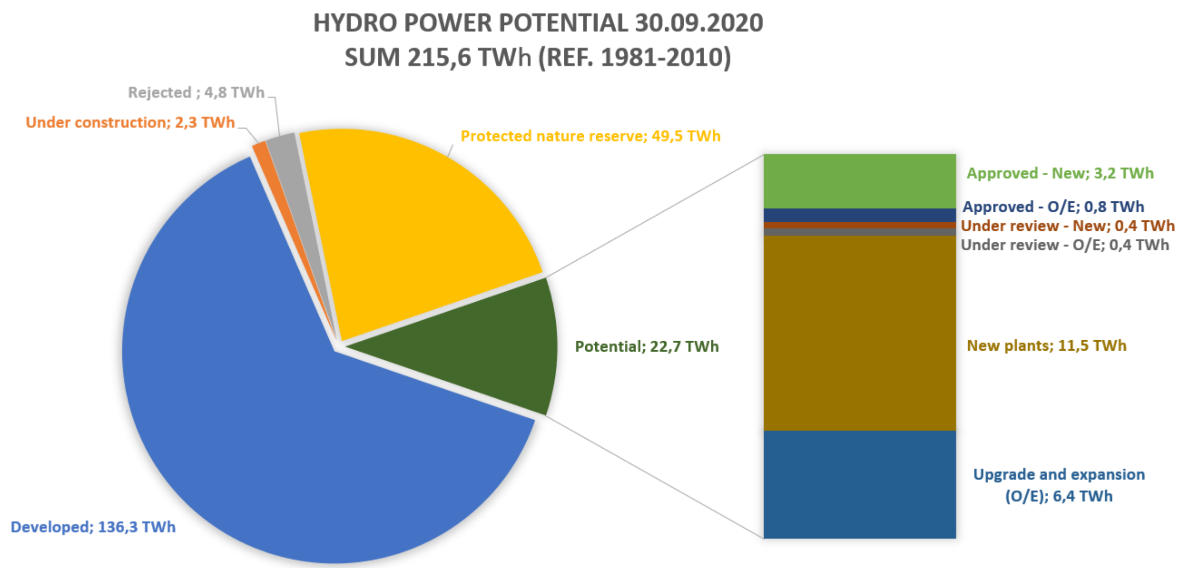

Figure 8. Hydro power potential (NVE, 2020).

Governmental support

The Norwegian government has a long history of supporting the development and upgrading of hydroelectric power plants, and it is likely that they would be willing to provide subsidies to support upgrades that improve the efficiency and performance of these plants. For example, the government offers tax incentives and other financial support for the construction and upgrading of hydropower plants, as well as for research and development in the field of hydropower technology (Skatteetaten, 2023). In addition, Norway is a signatory to the Paris Agreement on climate change and has committed to reducing its greenhouse gas emissions. Upgrading existing hydroelectric power plants to improve their efficiency is one way to reduce emissions and increase the share of renewable energy in the country's energy mix (Miljødirektoratet, 2023) (Norwegian Government, 2021). This may motivate the government to provide further support for such upgrades. Overall, while the availability of government subsidies and incentives for hydroelectric power plant upgrades may vary over time, it is likely that the Norwegian government will continue to prioritize the development and modernization of its hydropower infrastructure to support its renewable energy goals and reduce emissions (Norwegian Government, 2021).

Sustainability

Hydropower can be implemented in three different ways, each with varying environmental impact. The first method is run-of-river power; this is the simpler version of hydropower where a small dam creates a pond for power generation. Water passes through a turbine and returns to the river downstream. Most of the water flows through the dam without generating electricity, and the power output is dependent on the river flow. If the water level decreases due to factors like drought, the electricity generation also decreases. This approach can impact the freshwater ecosystem (Sustainable Sanitation and, 2012).

Hydroelectric plants are the most common and described in the hydropower section. The ecological footprint of hydroelectric power primarily arises as a one-time effect during the construction phase, but it can also result in significant environmental disruptions that harm biodiversity and cause disturbances. For instance, fish populations face challenges as their prey struggle to adapt to changes in the environment caused by the fluctuating water levels in regulated rivers and reservoirs (UngEnergi, 2023). Other disadvantages of hydroelectric power plants include the drying up of rivers, the disappearance of waterfalls, and the flooding of large land areas due to reservoir construction in major dam projects. Particularly significant drawbacks arise when the reservoirs are drained, revealing substantial desolate areas that are visually unappealing (Skildrud, 2022).

Pumped-storage stations also utilize reservoirs but operate by pumping water from a lower reservoir to an upper reservoir using excess electricity. The stored water in the upper reservoir can be released through a turbine when electricity demand is high. Pumped-storage plants are often compared to batteries due to their ability to store and release electricity as needed. This may seem counterproductive since the energy balance becomes negative: It costs more energy to pump the water back into the reservoir than what you gain during production. Yet, from an economic perspective, it can still be beneficial due to the fluctuating demand and prices (Rosvold K. A., 2023).

Levelized Cost of Electricity

The cost of an energy generating asset is meassured in "Levelized Cost of Electricity" (LCOE). It refers to the estimated average cost of producing one kilowatt-hour (kWh) of electricity from a specific energy source. This calculation takes into account expected costs for investment, operation and maintenance, fuel expenses, lifespan, and production capacity of the power plant or energy system in question (CFI, 2023).

According to the Norwegian Water Resources and Energy Directorate (NVE), a new large hydropower plant will provide electricity at a cost of 39 øre/kWh over its lifespan. The investment costs amount to 35 øre/kWh, while the operating costs will be 4 øre/kWh. A smaller hydropower plant is cheaper, with a total price of 35 øre/kWh. In contrast to wind power (and solar power), the LCOE is anticipated to remain constant in the future (NVE, 2021).

Opposition

Hydropower is generally well-regarded and supported by the Norwegian population. Still, there has been one well-known protest opposing the construction of the Alta-Kautokeino hydroelectric power plant. It gained attention for its concerns about environmental and social impacts, particularly on the indigenous Sámi people. The movement led to modifications in the dam plans and had a lasting impact on Norwegian environmentalism and indigenous rights (Mikkel Berg-Nordlie, 2023).

WIND POWER

Land Wind

The second largest source of electricity in Norway is wind power. More than 10% (16,9 TWh) (Holstad, 2023) of the electricity produced are generated by the 64 wind farms along the coast ("Store Norske Leksikon", 2022) (Norwegian Ministry of Petroleum and Energy, 2021). Norway has a long coastline and many high-altitude areas that are well-suited for wind energy development (The Norwegian Centre for Climate Services, 2017). According to “Energikommisjonen” it is realistic to estimate 5 -10 TWh increase in wind production on land by 2030 (Energikommisjonen, 2023). Nonetheless, NVE’s studies estimates a total production of 19 – 38 TWh by 2040 (NVE, 2019).

Estimating the practical development of the potential for wind power is challenging. Initially, the government supported the development of wind power through an electricity certificate scheme. This scheme has since been terminated, and although new wind power has become competitive due to current power prices, environmental conflicts have temporarily halted new land-based wind power development (Hofstad K. , 2023). In 1997, the government committed to renewable resources, among them wind power. Yet, the industry only developed 1.1 TWh from 1997 to 2005. From 2008 to 2013, the industry expanded with 1 TWh (Enova, 2013). Wind power production development gained momentum significantly in 2017 as shown in figure 9 and 10. New production records have been set every year since 2017. This is attributed to significant investments in new capacity in recent years (Øvrebø, 2022). Figure 9 visually demonstrates the power generated by wind plants since 2020, highlighting the notable growth in capacity from 2017.

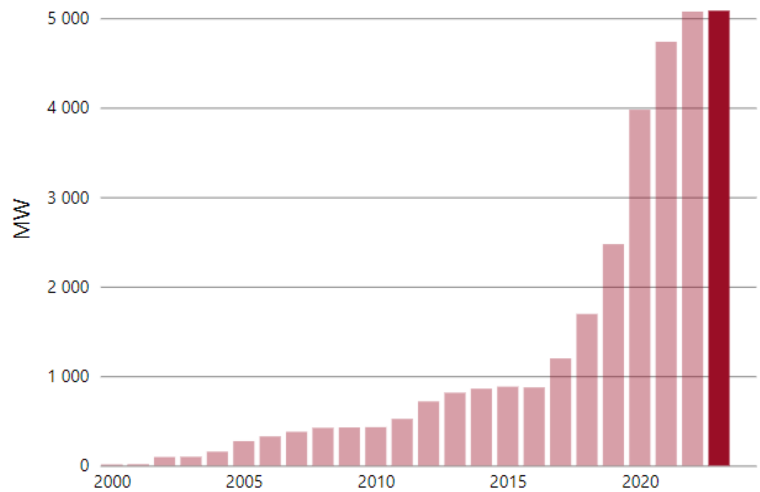

Figure 9. Installed power yearly from 2000 to 2023 (Energifakta Norge,2023).

Figure 10 displays the growth in power production from wind plants. It demonstrates a notable increase in electricity generation from wind sources. This rise is attributed to advancements in wind technology, substantial investments in wind infrastructure, and the expansion of wind farm installations (figure 9).

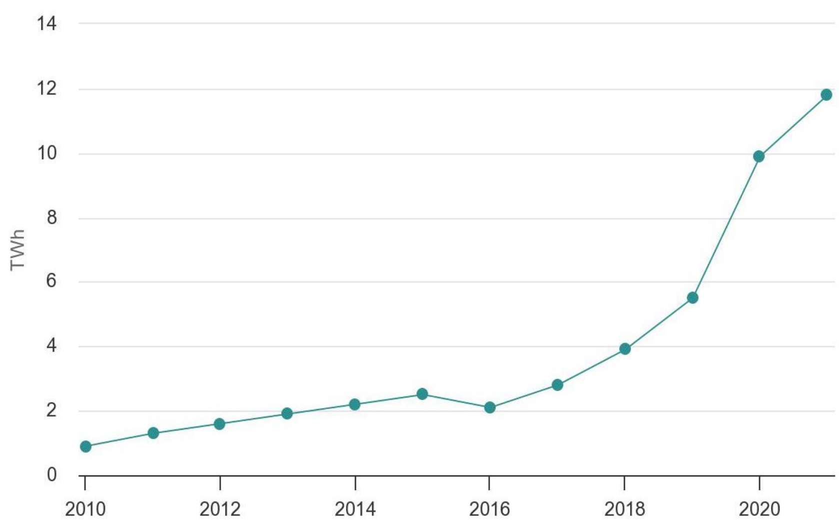

Figure 10. Yearly wind power production from 2010 to 2021 (SSB, 2021).

Opposition

Opposition to wind farms exists among certain segments of the population in Norway. Some concerns raised by opponents include visual impact on the landscape, noise pollution, potential effects on wildlife, and impacts on local communityes (Bjørnøy, 2023) (E24, 2023) (Motvind Norge, 2023).

In the coming years, the planned areas for wind power in Norway, as indicated by the Norwegian Environment Agency, are expected to cover approximately 4-500 km^2. It is important to note that only a small portion (3-5 percent) of these planned areas will undergo physical interventions, unlike urban or industrial developments. To put things into perspective, the current and ongoing wind power projects require an area just above one per mille (‰) of Norway's land area (The Norwegian Government, 2023).

Offshore wind

An alternative to building windfarms on land is placing the wind turbines offshore. Offshore wind energy plays a vital role in achieving climate targets and addressing the increasing global energy demand. While offshore wind power is currently more expensive than onshore wind, ongoing research and innovation are driving cost reductions. Norway is a frontrunner in the development of floating offshore wind technology, leading in both research and technological advancements (Tande, 2023). NVE has mapped Norway's offshore wind power potential, estimating a development potential of 6,000 to 30,000 MW in shallow areas with depths under 20 meters. Factors such as distance to the mainland and protected areas were considered, but limitations and constraints may limit the actual development of this potential (Knut Hofstad, 2008). In 2020, a significant step was initiated when the Norwegian government opened the first areas on the Norwegian continental shelf for renewable energy production at sea. In 2023, the first project areas for offshore wind at Utsira Nord and Sørlige Nordsjø II will be announced (The Norwegian Government, 2023). The first phase of "Sørlige Nordsjø II" is estimated to provide a minimum of 1400 MW and a maximum of 1500 MW of power (The Norvegian Government, 2023). Norway is committed to its goal of designating specific areas to produce 30,000 MW of offshore wind energy by 2040 (The Norwegian Government, 2023).

Technology

The energy from the sun is exploited in windmill technology. The earth's surface is made up of different types of land and water, which absorbs heat differently; land is heated up faster than water. Warm air over the land is heated up by the sun, then the air expands and rises. The cold air from the ocean then rushes in and takes its place, as the cold air is denser as demonstrated in figure 11. This shift creates what we know as wind (U.S Energy Information, 2022).

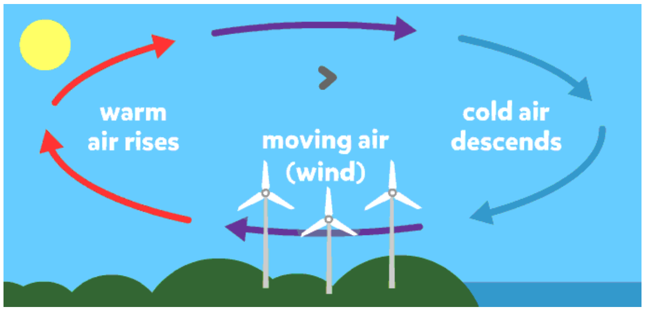

Figure 11. Wind is generated by the sun (Stile Library, 2023).

From the energy in the wind, energy is produced by using windmills. Windmills have large blades that create resistance for the wind. The rotor is connected to a generator through drive shafts and a gear box (Figure 12). Finally, the generator converts the kinetic energy into electricity that can be used by the consumer (U.S Department of Energy, u.d.).

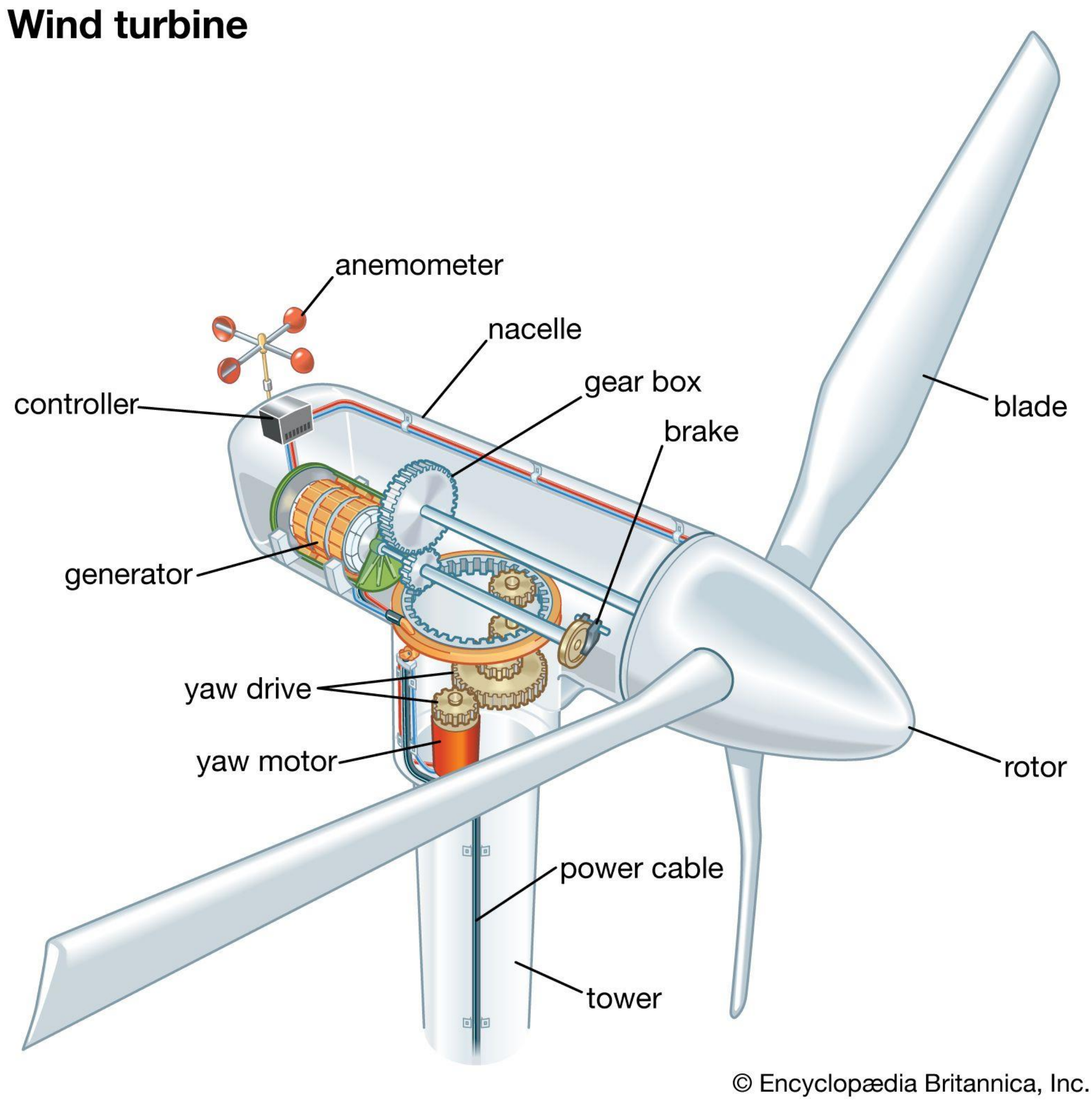

Figure 12. Detailed wind turbine (Britannica, 2023).

To optimize the power generation from wind, the control system continuously adjusts the generator housing and rotor blades based on the actual wind direction and speed. The power curve of a wind turbine represents its theoretical production at different wind speeds. Large-scale wind turbines typically start generating electricity at a wind speed of approximately 3-4 m/s and reach their maximum output at 11-15 m/s. As the wind speed increases beyond this range, the blade angles are automatically adjusted to allow more wind to pass through, preventing excessive strain on the turbine while maintaining a consistent maximum output. When wind speeds exceed 25-28 m/s, most wind turbines need to be completely shut down due to excessive stress on their components (NVE, 2023).

History

Humans have been using the wind as a power source for close to 6000 years. Wind was used for sailing, but it took millennia for the technology to be developed. Windmill technology is known to be about 4000 years old (HOW, 2023). However, it was in medieval Europe that windmills gained widespread popularity. Between 11th and 16th century, European windmills began to appear, primarily in the Netherlands and England. These windmills were mainly used for grinding grain and pumping water, revolutionizing agricultural practices and industrial activities. Over time, windmill designs evolved and became more efficient. The Dutch windmill, with its distinctive tower design and rotating cap, became an iconic symbol of the Netherlands. In the 19th century, the introduction of steel blades and more advanced machinery further improved windmill technology. In the modern era, windmills have transformed into wind turbines, capable of generating electricity on a large scale. The development of wind power as a renewable energy source gained significant momentum in the late 20th century driven by concerns about fossil fuel dependency and environmental sustainability (HOW, 2023).

In a Norwegian perspective, windmills have been utilized in various applications throughout the country's history. Large windmills were commonly used for grinding grain in coastal towns in Southern Norway, with at least 70 different installations identified. While wind power played a minor role compared to other energy sources such as hydropower, it had significant importance in maritime activities, where wind was essential for sailing. Windmills also played a role in small-scale industrial applications and agriculture, particularly in areas with limited access to hydropower resources (Dybesland, 2008).

Efficiency and upgrade

The advancement of wind turbine technology has had a rapid development in recent years, resulting in increased installed power, taller structures, and longer rotor blades. By extending the length of the rotor blades, wind turbines can capture more wind and generate more power during periods when the wind speed is not sufficient for maximum power output. The installed power in a wind turbine relies heavily on factors such as the rotating mass, rotational speed, and the generator's windings that generate electromagnetic fields. By modifying any of these factors, a wind turbine can generate more power without capturing additional wind. This capability is particularly beneficial during periods of strong winds when the turbine is already operating at maximum output. Regardless, increasing the installed power in wind turbines poses challenges in terms of transportation, construction, and operation. Consequently, extensive research and technological advancements are being conducted in this field (NVE, 2023).

Control systems have enabled turbines to optimize their utilization of wind and climatic conditions. Older turbines were required to shut down production when wind speeds exceeded certain levels, typically around 25 m/s, to avoid overloading. However, new wind turbines can continue producing electricity at higher wind speeds and in icy conditions when ice accumulates on the blades, by continuously automatically monitoring the forces acting on the turbine and adjusting the blade positions to withstand strong winds (NVE, 2023).

These technological advancements have resulted in modern wind turbines producing more power than older models. For example, a wind turbine installed in Norway in 2019 is expected to generate twice as much electricity as one built in 2012 (NVE, 2023).

Governmental support

In addition to its abundant wind resources, Norway has a supportive policy environment for wind energy development. The government has set a target of reducing greenhouse emissions by 55% by 2030, compared to 1990 (The Norwegian Government, 2022). Furthermore, the country's goal, following the "Paris agreement" is to become climate neutral by 2050 (The Norwegian Government, 2020). Wind power is expected to play a significant role in achieving this target. Reducing emissions by 55% could imply increasing the share of renewable energy in the country's energy mix to 80% (Fornybar Norge, 2021).

The government has offered financial incentives to support for the construction of new wind farms.

According to the Ministry of Finance, Norway provided a total support of 1.23 billion NOK between 2016 and 2020 through favorable tax depreciation rules. This support was implemented after aligning with the Swedish regulations and had a positive impact on the installed capacity of the wind power sector, as depicted in Figure 9. The annual amounts of support experienced a significant increase over the five-year period, starting at 25 million NOK in 2016 and reaching 610 million NOK in 2020. These favorable tax depreciation rules played a crucial role in driving the growth of the wind power industry during this timeframe (Søndeland, 2022).

Wind power in Norway and Sweden is also supported through the electricity certificate scheme, commonly referred to as green certificates. This scheme was introduced in 2012 with the objective of promoting and incentivizing renewable energy production. It provides financial support to wind power projects, encouraging their development and growth in both countries (NVE, 2022). A power plant approved for electricity certificates will receive one electricity certificate per megawatt hour (MWh) of electricity produced. Approved power plants receive certificates for up to 2023 (nve., 2023), providing additional income alongside the power price. Power suppliers and certain electricity customers are required to purchase these certificates, with the costs being covered by electricity customers through their bills. The scheme is managed by NVE in Norway, and any changes require joint decision-making between Norway and Sweden. However, it's important to note that this scheme only applies to facilities completed before the end of 2021. While most wind power projects in Norway benefit from this scheme, only a small portion of hydropower production is eligible due to limited installations since the scheme's introduction in 2012 (NVE, 2022).

Sustainability

Like hydropower, wind power is classified as a clean and renewable energy source. Studies reviewed by the Norwegian Water Resources and Energy Directorate (NVE) indicate that the carbon footprint of wind power ranges from 3 to 46 g CO_2/ kWh (Odal vind, 2020). In comparison, the carbon footprint of coal-fired and gas-fired power plants is approximately 1000 g CO_2/kWh and 500 g CO_2/kWh, respectively, depending on the efficiency of the power plants. Studies also show that it takes between 3 to 7 months for a wind turbine to generate the same amount of energy required for its production and installation. Emissions from wind power plants primarily originate from the transportation of turbines and the production of concrete for foundations. The release of greenhouse gases associated with land use changes and soil processing during construction depends on factors such as soil mass reuse, local climate conditions, soil types, and the methods employed for processing (Krogvold, 2019). Technological advancements can further reduce this timeframe. Wind power is internationally recognized as one of the most climate-friendly energy sources, according to the United Nations' Intergovernmental Panel on Climate Change (IPCC, 2022).

Yet, there is currently a lack of recyclability in wind turbine blades. The media has raised concerns about the proper disposal of decommissioned wind turbines (Griffit, 2022). Findings from the University of Strathclyde indicate a global increase of wind turbine blade waste from around 400,000 tons per annum in 2030 to around two million tons by 2050 (University of Strathclyde, 2021). Only the blades pose a problem. They are made of a composite, and it would be ideal to separate these materials to recover them (Volard, 2023). Currently two Norwegian companies, Aker Offshore Wind and Aker Horizons, are collaborating together with the University of Strathclyde on accelerating recycling glass fibre products (Oslo børs, 2021). In addition, another Norwegian company has received NOK 33 million in support from the EU for a project for recycling wind turbine blades (Nyhammer, 2023). Furthermore, there are various initiatives within the EU focused on developing sustainable technologies for recycling waste generated from wind turbine blades (Bjerkomp, 2020). Among the methods that have come the farthest is using material from the rotor blades in cement production. This is already done in the world today, but on a small scale (Akerbæk, 2020). Figure 13 shows one example of landfill where wind turbine blades were buried.

Figure 13. Wind turbine blades are buried in Casper, Wyoming (Bloomber,2020).

Levelized Cost of Electricity

Based on calculations performed by NVE (2021), land based wind power will provide electricity at a cost of 30 øre/kWh (LCOE 2021). Nevertheless, LCOE is expected to be reduced to 22 øre/kWh (NVE, 2021).

Currently, the offshore wind alternative is more expensive. The LCOE for offshore wind turbines installed on the seabed is calculated at 69 øre/kWh in 2021, while floating installations have an LCOE of 117 øre/kWh (NVE, 2021). On the other hand, by 2030 the cost is calculated to be 51 øre/kWh for seabed installations and 68 øre/kWh for floating installations. The costs for 2030 are calculated using a technology improvement factor based on assumptions made by NVE (NVE, 2021).

NORWEGIAN POWER MARKETS

In 1990, the Norwegian government implemented "The Energy Act," a new law governing the market price of power, with the aim of promoting the collective welfare of society. The objective was to introduce competition, improve efficiency, and facilitate cross-border electricity trading (Halvorsen, 1998). The previous practice gave the suppliers a monopoly, as the consumers were "forced" to buy power from the local supplier. The new law revolutionized the power sector by granting Norwegian consumers the freedom to choose their power supplier, making them among the first worldwide to have this option. This transition from a monopolistic market to a free-market environment enhanced competition among power suppliers.

The implementation of the law led to the establishment of a new state entity called the Energy Fund (Enova) to oversee the management of the power grid. This new structure marked a significant change in how the power grid was operated and regulated. To finance the operations of the entity, as well as the connection to and utilization of the power grid (grid tariff), a new fee was incorporated into the power bill. This fee was introduced to ensure the sustainable funding of the grid and support the services provided by the power infrastructure.

Following the liberalization of the energy legislation, Nord Pool was established in 1993 (Statnett, 2019). In 1996, Nord Pool Spot power exchange opened as the world's first power exchange, enabling electricity trading across border lines among the Nordic countries. It has lately expanded to 20 countries, involving 360 companies (Nord Pool, 2023). It functions as a spot market platform where participants can engage in real-time buying and selling of electricity.

The exchange market will secure a steady power supply throughout the year. The power production methods in Norway are vulnerable to seasonal climate, especially hydroelectric power which covers 90% of electricity consumption. In times with little rain and low temperatures, in Norway demand will be high and production low. The market enables Norway to buy cheaper electricity elsewhere, as the prices otherwise would have increased in these circumstances.

Electricity differs from other goods as it cannot be easily stored, requiring precise balance between generation and consumption. Through market-based trading, the power exchange establishes daily prices that aim to achieve a planned equilibrium between overall generation and consumption. The market price of power is determined daily on the power exchange by a complex algorithm, based on supply and demand.

In general, the Nord Pool Spot power exchange market functions as any other market. It is in the interest of power companies to produce power as efficiently as possible and sell it for the highest possible price on the market.

Reaching net-zero carbon emissions by 2050

As previously mentioned, Norway has set ambitious targets to reduce greenhouse gas emissions and achieve climate neutrality (The Norwegian Government, 2020). To achieve these goals, strategies has been outlined to decarbonize key sectors such as cement, steel, plastics, trucking, shipping, and aviation, which currently contribute to 30% of energy emissions and may increase to 60% by 2050 (Energy Transissions Comission, 2018). In any viable pathway towards a net-zero carbon economy, the share of electricity in total final energy demand is expected to increase from the current 20% to over 60% by 2060 (Energy Transissions Comission, 2018). Consequently, global electricity generation needs to expand from approximately 20,000 TWh to 85-115,000 TWh by 2050, accompanied by a transition from high-carbon to zero-carbon power sources (Energy Transissions Comission, 2018). However, direct use of electricity requires less energy compared to burning fossil fuels in most cases, meaning less energy is required to produce the same service, work, or heat (Staftkraft, 2022). According to estimates from Statnett, the transition to electricity, in Norway, in sectors where it is feasible would result in the replacement of 95 TWh of fossil fuel energy with 40 TWh of renewable power. This represents a reduction of more than 50% in energy consumption (Statnett, 2019). Figure 14 illustrates transmission from fossil and electric primary energy use to fully electric use with hydrogen, excluding biomass.

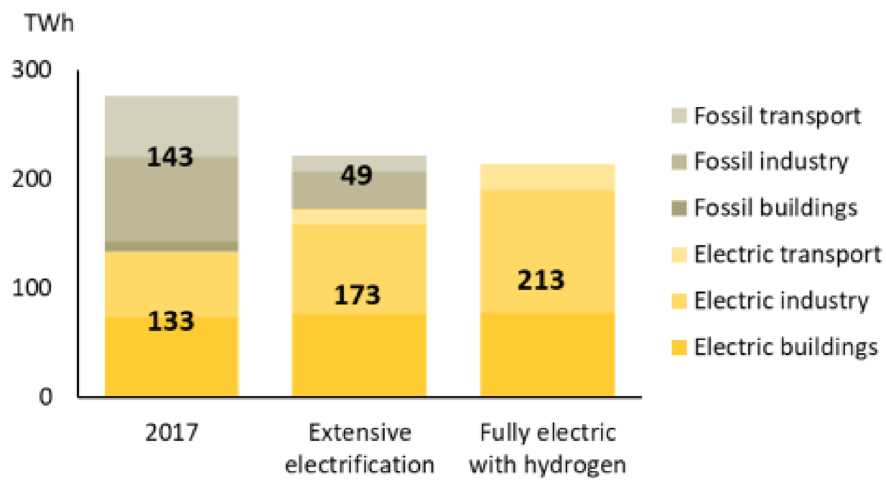

Figure 14. Energy use in 2017 compared to electric alternatives(Energy Transissions Comission, 2018).

There is significant potential to reduce greenhouse gas emissions in Norway, primarily from sectors such as industry, transport, and other commercial activities. In 2017, domestic greenhouse gas emissions in Norway amounted to 52.7 Mt CO2e, and when including emissions from international shipping and aviation, the total reached 67.3 Mt CO2e (Statnett, 2019). Through extensive electrification, it is possible to achieve a substantial decrease in emissions, equivalent to approximately half of domestic greenhouse gas emissions, which is around 25 Mt CO2e. The transport sector accounts for 11 Mt CO2e of this reduction, while 7 Mt CO2e can be attributed to oil and gas extraction. These estimates provide a rough indication of the magnitude, although there is some uncertainty involved (Statnett, 2019). Considering this change, NVE has projected a 34.5 TWh increase in electricity consumption by 2040, resulting in a rise from 139.5 TWh (2021) to 174 TWh (NVE, 2021).

“Energi 21”

In 2008, Ministry of Petroleum and Energy initiated “Energi21” which is a national strategy that focuses on research, development, and commercialization of climate-friendly energy technology to enhance value creation and resource efficiency in the energy sector. The strategy aims to coordinate and target research and technology efforts, with increased engagement from the energy industry. Energi21 sets goals and ambitions for Norwegian research and development in renewable energy, energy efficiency, and CO_2 capture and storage. The Ministry has formed a board for Energi21 to oversee the strategy and provide advice on research funding. The strategy identifies six priority areas, including balancing power, offshore wind, solar cells, carbon capture and storage, flexible energy systems, and energy utilization (The Norwegian Government, 2022).

COMPARISON: HYDRO VS. WIND

Efficiency

The efficiency of hydro power and wind power can vary depending on several factors. In general, hydro power is considered to be a more efficient form of renewable energy compared to wind power.

Hydro power plants typically exhibit high efficiency levels, ranging from 80% to 90%. This means that a significant portion of the energy in flowing water can be effectively converted into electricity. The efficiency of hydro power primarily relies on factors such as turbine design, water source height (head), and flow rate (Mohamed, 2021) (Bureau of Reclamation, 2005).

On the other hand, wind power efficiency is influenced by variables such as wind speed, turbine design, and tower height. The theoretical maximum efficiency of a turbine is ~59% (Betz Limit). Still, most turbines can only extract 40% - 50% of the energy from the wind. Nevertheless, it is essential to acknowledge that wind power efficiency can fluctuate based on the specific wind conditions at a given location.

Sustainability and Lifespan

Balancing renewable and profitable energy production with the value of biodiversity is a challenge. Hydro- and wind power are considered as environmentally friendly and is expected to play a crucial role in counteracting global warming and limit the depletion of the earth's storage resources.

Both industries have among the lowest greenhouse gas emissions electricity production. Additionally, hydropower has the highest degree of efficiency and the longest lifetime of all techniques for power generation. The lifetime for a hydropower facility is 100 years or more (U.S Department of Energy, 2004) (hydroreviewcontentdirectors, 2020); in comparison, modern wind turbines have an average of about 25 years (Bjerkomp, 2020) (TWI, 2023). With current technology, it is possible to recover approximately 85-90% of the mass from a wind turbine once its operational lifespan ends. Most of this mass consists of steel, which has a high recycling capability. Nonetheless, the remaining 10-15 percent mainly consists of engine housings and turbine blades, which are (currently) constructed from composite materials that have a lower potential for recycling (NVE, 2023).

There is primarily an ecological footprint associated with also these forms of power generation. For hydropower, this footprint is largely a one-time effect during the construction phase, which can result in significant environmental impacts and disruptions to biodiversity. To minimize these damages, it is important to implement measures such as minimum flow requirements to ensure sufficient water and restrictions on rapid changes in water flow to prevent stranding (Borge, 2019).

On the other hand, wind power poses ongoing challenges throughout its lifespan. According to a study, wind turbines were found to cause the mortality of approximately 0.27 birds per gigawatt-hour (GWh) of energy generated (Sovacool, 2012). Nevertheless, this is considered to be relatively low compared to other threats to bird life. Wind power development can also impact wildlife through habitat loss, disruption, and displacement.

This affects various species including large predators, deer, small mammals, amphibians, and reptiles. Issues like habitat fragmentation, disturbance from noise and human activity, and direct habitat loss contribute to these effects. Limited research in Norway has been conducted on the specific effects of wind power on wildlife. Studies in Portugal showed that wolves avoided wind farms during construction and early operation, with negative impacts on reproduction. More research is needed to understand the regional effects of wind power development on wildlife (NVE, 2022).

Construction-related human activity has a greater impact on bears and wolves than the power infrastructure itself (NVE, 2022).

In addition to the ecological footprint, wind turbines pose negative effects on people living near windmill farms. Studies on the impact of wind turbines near residential areas suggest that the noise can be bothersome, causing sleep disturbances and irritation. However, there is no evidence of health issues. Visibility of wind turbines is also associated with negative health effects (Environment International , 2014) (Schmidt, 2014).

Wind turbines generate noise from rotating blades and mechanical components. Factors like blade speed, shape, and machine noise affect noise levels. Tonal noise can occur from gears, generators, or worn blades. Distance, wind conditions, and vegetation influence noise propagation. Background noise and wind speed can mask turbine noise. Mitigation measures include insulation, technology, and creating quieter spaces. Research is needed on local conditions and ice effects (NVE, 2022).

Power production normally require large areas to develop. This is particularly disadvantageous in the case of harnessing wind energy due to the prominent visibility of large turbines over long distances. The visibility range can vary from 2 to 3 kilometers, depending on factors such as terrain, windmill design, and line of sight. The visibility factor also has an impact on the overall natural experience (NVE, 2021).

If a facility is closed, the previous concession holder is obliged to dismantle the facility and restore the landscape to its original state as much as possible. The Norwegian Water Resources and Energy Directorate (NVE) has the authority to establish a timeline for this work and establish guidelines for the restoration process. Throughout the operational period, the concessionaire is obligated to allocate financial resources to cover potential expenses (Lovdata, 2012) (NVE, 2023). There are however serious concerns related to owner structure for the concessionaires of the wind power plants. With a significant portion being linked to tax havens (Tax Justice Network, 2021), it may become difficult to hold the various actors accountable for the expenses related to decommissioning.

Hydropower's ability to store the energy is beneficial compared to wind power. Norway's strategy is to a greater extent to supplement hydropower energy with alternative energy sources, where wind has been, and currently is, the biggest area of investment. By doing so, the magazines can be used as a supplement when wind power production is low (Energi21, 2022). However, if electricity prices return to 2022 levels, production companies will likely seek to profit by exporting electricity. While this would benefit the global population in terms of emissions, it would lead to increased electricity bills for Norwegian consumers.

Economics

As mentioned earlier, the "Levelized Cost of Electricity" (LCOE) is used to measure the cost of an energy-generating asset, considering all relevant costs. This allows for a comparison of different energy sources.

When examining the two primary power sources in Norway, the thesis indicates that hydropower plants involve a considerable upfront investment cost. Still, their maintenance costs are relatively cheaper compared to wind energy, which has a lower initial investment cost. The calculations show that the LCOE for hydro in 2021 is found to be 9 øre/kWh higher than that of land-based wind plants. Moreover, there is a potential for it to become 17 øre/kWh more expensive by 2030. Offshore wind is a costlier option compared to hydro energy. Currently, installations on the seabed generate half the profitability at 69 øre/kWh, while floating installations are three times less profitable at 117 øre/kWh. These figures are projected to decrease by 2030, with seabed installations expected to reach 51 øre/kWh and floating installations anticipated to reach 68 øre/kWh.

These calculations are based on a relatively complex model, despite several simplifications being made. One simplification is that only income tax and natural resource tax for hydropower, and only income tax for wind power, are considered. This means that the economics of hydropower may be somewhat underestimated, while the opposite may be true for wind power, as revenues from the certificate scheme are not included (Skonhoft, 2021).

Both hydropower and wind power generation methods were found to be profitable when compared to the average electricity price for households in 2022, which amounted to 235 øre/kWh (including taxes and network rent) (Statistic Norway, 2023). It is expected to become even more profitable compared to non-green energy resources in the future, due to tax increases related to emissions of greenhouse gases.

Although wind power has been proven to be profitable, there are concerns regarding the ownership structure of the concessionaires. A report by the Tax Justice Norway reveals that a significant percentage of Norwegian wind power production is linked to tax havens. The study shows that 7 out of the top 10 wind power companies have connections to tax havens through ownership or financing (2021). The report emphasizes the need for stricter transparency requirements to prevent profit shifting. The international tax regime is criticized for its unfairness, allowing companies and investors to exploit loopholes. The report calls for changes in tax regulations and increased awareness of the issue. However, it does not compare wind power to other sectors in terms of vulnerability to profit shifting (Tax Justice Network, 2021).

Taxes

In Norway, power companies are subject to various taxes and tolls that are determined based on factors such as income from power production, sale, transfer, distribution, and environmental impact (Skatteetaten, 2023). Nevertheless, there have been notable differences in the tax treatment between wind power and hydropower generation (Skonhoft, 2021).

Routines for taxing the hydropower production is well established in Norway. The facilities face an extensive taxation regime, including corporate tax, resource tax, property tax, concession fees, and local production levies. In addition to the standard corporate tax on profits (22%), hydropower plants are subjected to resource tax (increased to 45% in 2022, lead to a total effective marginal tax rate of 62 percent), property tax on the power infrastructure, concession fees, and local production levies (Skatteetaten, 2023) (Skonhoft, 2021).

In contrast, wind power has been facing regular corporate tax but no resource tax. Depreciation rules have been more favorable, resulting in higher tax deductions and increased profitability. However, this depreciation method only applies to wind power investments completed before 2021, resulting in financial benefits for the municipalities hosting these facilities (Skonhoft, 2021) (Jenssen, 2019).

In recent years, the Norwegian government has implemented tax reforms to provide more equitable treatment for the wind power industry. Wind plants are now subjected to various taxes, including corporation tax, property tax, and a specific production tax for onshore wind power. Corporation tax is imposed at a rate of 22 %, while property tax is based on the assessed value of the wind power plant. The production tax is applicable to onshore wind power plants and the revenue generated is distributed to the host municipalities (NVE, 2022).

Furthermore, in 2022, the government proposed a new production resource tax exclusively for onshore wind power plants. The suggested tax rate is 40 percent, resulting in a total effective marginal tax rate of 62 percent when combined with corporate tax. This tax obligation applies to onshore wind power plants that require licensing under the Energy Act and have more than 5 turbines or a total installed capacity of 1 megawatt (The Norwegian Government, 2022) (Malin Noem, 2023).

Ethics

As aforementioned, there have been some protests related to power development in Norway, but while hydropower has one well-known protest (Alta-Kautokeino hydroelectric power plant), the development of wind power has generated much greater engagement.

There has been significant opposition and resistance to the development of onshore wind farms in Norway. The latest example is the Sami people's demonstrations against development of wind parks on the Fosen Peninsula. In addition, many local communities and environmental organizations have expressed concerns about the consequences of such projects, including the impact on the natural environment, loss of natural resources, and visual pollution.

This opposition led to a temporary halt in the planning of new licenses for onshore wind farms in 2022. The government wanted to take the time to carefully evaluate and review the plans, as well as listen to the concerns raised (Olje- og Energidepartementet, 2022).

There are several ethical questions raised, related to developing power plants in Norway (and globally) following the opposition to developing power plants, including: environmental impact, local community engagement, indigenous rights, transparency and corporate responsibility, and energy justice. It is crucial to address these concerns through careful planning, stakeholder engagement, and responsible development and operation of wind power projects.

Common good

Norway has significant natural resources for both wind and hydro power. A balanced combination of the two seems to be a reasonable solution. Both sources contribute to renewable energy goals and have their advantages. Hydropower is already well-established in Norway and provides a reliable and relatively low-impact source of renewable energy. However, the development of additional hydropower projects may have limitations due to available sites and potential environmental consequences, such as altering river ecosystems and affecting fish populations. On the other hand, wind power has a smaller environmental footprint and can be harnessed in various locations, but it may have visual and noise impacts, as well as potential effects on wildlife.

A diversified energy mix that incorporates both sources can help mitigate climate change and ensure a resilient energy system, as the latest prognoses show that the electricity demand will increase by up to 75 TWh by 2030 (Energikommisjonen, 2023).

Table 1 shows a comparison of main factors related to Hydro- and wind energy.

Table 1- Comparison of main factors between hydro and wind power

	Hydro	Wind
Current yearly production (TWh)	136.7	16,9
Potential yearly production (TWh)	23 (49.5*)	19 – 38**
Emission (g/CO2/kWh)	3.3	11.5
Average efficiency (%)	85	45
Cost (LCOE) (øre/kWh)	39	30 (22***)
Tax (%)	62	62****
Visability	Low visual presence.	Large visual presence.
Environmental concerns	Fish spawning, permanent construction.	Wild-/bird life, noise pollution

**Protected by the government*

*** Estimated by 2040.*
**** Estimated cost by 2030.*
***** Pending approval*

Table 2 provides information on the anticipated year of commissioning for power generation projects that are currently being constructed. The year of commissioning is determined based on the specified year in the progress plan upon approval of the detailed plan or as indicated by the developer through news releases or other sources (NVE, 2023).

Table 2- Plants under construction, Technology and commissioning year [GWh]

	Put into operation	2023	2024	2025	Total
Minor Hydro plans (<10 MW)		329	237		**566**
Upgrading and expansion		300		50	**530**
Hydropower > 10 MW		70			**70**
Wind power	18	38			**56**
Total	18	737	237	50	**1042**

CONCLUSION

In summary, both hydro- and wind energy are found to be environmentally friendly and economical in this thesis. However, there is room for improvement, especially in wind power. Nevertheless, wind power is crucial for achieving Norway's net-zero emission target, considering the expected increase in electricity demand for climate goals.

There are trade-offs between the two energy sources. Based on the data available, there are no clear advantages or disadvantages between the two sources when comparing the 5 points of efficiency, economics, taxes, ethics, and the common good. However, given that wind turbine blades use significant amount of resources that are not recyclable, hydro power has clear advantages in terms of sustainability. Given the current tax scheme, more investment in wind power seems to be economical. However, more research needs to be conducted on this point. Based on the electrical power production reporting of reduced hydrocarbon-based sources versus increased wind and hydro production, Norway can achieve net-zero carbon emissions.

The study emphasizes the importance of strict government regulations when approving energy projects, considering ethical considerations, economic factors, and the overall common good. Looking ahead, how Norway can provide green energy to Europe while benefiting the government, power companies, and individuals is a crucial question.

While individual parties and companies have financially benefited from rapid wind power development, the government has also seen advantages in terms of significantly increasing the energy mix and reduced carbon emissions. Future comprehensive economic studies are essential for gaining a better understanding and providing an answer to Norway's role in Europe's energy structure.

The study relies on published figures, acknowledging the connection of several sources to the Norwegian government. Future research could investigate subsidies and the involvement of foreign entities in wind power. These aspects have broader implications beyond the scope of the current thesis.

Furthermore, exploring alternative options for Norway's energy mix, including solar and nuclear power, and investigating the potential impact of energy efficiency measures and carbon capture solutions on reducing power demand would be valuable areas of research.

APPENDIX I

These studies provide significant information regarding hydro, wind, and other energy resources.

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https://energiognatur.no/vind-og-vannkraft-lonnsomhet-og-beskatning

Fakta, Energi og vassdrag i Norge, 2013 -
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Mer av alt – raskere Energikommisjonens rapport
https://www.regjeringen.no/contentassets/5f15fcecae3143d1bf9cade7da6afe6e/no/pdfs/nou202320230003000dddpdfs.pdf

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