TEKNILLINEN TIEDEKUNTA

EROI-based analysis of wind and nuclear energy development in the North

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ABSTRACT

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Finland has stated that carbon neutrality will be achieved by the year 2035. This will partly happen by replacing fossil fuels with renewable energy sources. However, the ongoing debate on the subject is increasing, and therefore the need for research is crucial.

This thesis is a literature review of the development of wind and nuclear power in the future of Finland. The aim of this thesis was to discuss and compare wind and nuclear power development within a baseline in their EROI values. The EROI-based analysis was made in frame time within Finland’s low carbon roadmap 2035. The purpose of the comparison was to find out the advantages and disadvantages of both energy technologies and their EROI values in different scenarios. EROI as a metric informs the ratio between the energy input and energy output. It can be applied to all energy technologies and therefore is a competitive factor to conduct a comparative analysis.

The results achieved in the thesis show that the development of wind power is siting wind farms offshore and increase in the physical aspects, such as rotor diameter and hub height. The EROI of wind power correlates strongly with the siting of the turbines and progressive technology. However, the values obtained were with a wide range between 10 and 50, depending on the turbine type and turbine location. Furthermore, the development of nuclear power is to diminish to small modular reactors. Since SMRs are in the research and development phase, the EROI values for SMRs were assumed from data from conventional nuclear power plants. However, the EROI of SMRs is confidently larger than the EROI of wind power.

Keywords: wind power, nuclear power, EROI

TIIVISTELMÄ

EROI analyysi tuuli- ja ydinvoiman kehityksestä Pohjoismaissa

Eedith Vähä

Oulun yliopisto, ympäristötekniikan tutkinto-ohjelma

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Suomen tavoite on olla hiilineutraali vuoteen 2035 mennessä. Tavoite toteutetaan osittain korvaamalla fossiiliset polttoaineet uusiutuvalla energialla. Tavoitteen saavuttamiseksi ovat tutkimukset aiheesta ratkaisevia.

Tutkielma on kirjallisuuskatsaus tuuli- ja ydinvoiman kehityksestä tulevaisuuden Suomessa. Tavoitteena on analysoida tuuli- ja ydinvoiman kehitystä EROI-analyysin kannalta. Tarkoitus on vertailla näiden kahden hyötyjä ja haittoja sekä niiden EROI arvoja. EROI-analyysi on tehty aikarajalla Suomen hallituksen laatiman vähähiilisten tiekarttojen mukaan. EROI on mittari, jolla voidaan arvioida ja vertailla eri energiateknologien tuotettavuutta ja kannattavuutta. EROI perustuu tuotetun energian ja vaaditun energian suhteeseen.

Tuulivoiman kehitys tulevaisuudessa tulee olemaan tuulivoimaloiden asettaminen vesi olosuhteisiin sekä kasvavat fysikaaliset ominaisuudet, kuten roottorin halkaisija ja maston korkeus. Tuulivoiman EROI-arvoilla on vahva riippuvuus turbiinien fysikaalisten ominaisuuksien ja turbiinien sijainnin kanssa. Saadut EROI-arvot sijoittuivat laajasti skaalalle 10–50, riippuen turbiinin sijainnista ja ominaisuuksista. Ydinvoiman kehitys liittyy vahvasti reaktorien pienentymiseen, jolloin puhutaan pienistä modulaarisista ydinreaktoreista. Näiden ollessa vielä vahvasti kehitysvaiheessa ja EROI-arvojen puutteiden vuoksi, tulokset on oletettu perinteisten ydinvoimalaitosten EROI-datan perusteella. EROI-analyysin ja vertailun perusteella voidaan sanoa, että tuulivoiman EROI-luvut ovat huomattavasti vaatimattomampia kuin ydinvoiman EROI-luvut.

Asiasanat:tuulivoima, ydinvoima, energia suhdeluku

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LIST OF ABBREVIATIONS

DFR	dual fluid reactor
EPT	energy payback time
EROI	energy return on investment
EWEA	The European Wind Energy Association
FWPA	Finnish Wind Power Association
GW	gigawatt
IAEA	International Atomic Energy Agency
IRENA	International Renewable Energy Agency
m/s	meters per second
MW	megawatt
MWh	megawatt-hour
NEI	Nuclear Energy Institute
NPP	nuclear power plant
PEF	primary energy factor
PJ	petajoule
PWR	pressurized water reactor
R&D	research and development
SMDFR	small modular fluid reactor
SMR	small modular reactor
STUK	Radiation and Nuclear Safety Authority
TWh	terawatt-hour
VTT	Finnish Technical Research Centre
WNA	World Nuclear Association~~n~~

1 INTRODUCTION

Utilizing and choosing a good energy technology, is challenging in the modern society. It needs to satisfy loads of different factors. Among other things, the environment and our economy demand certain kinds of requirements. The present and future agenda is to cut out emissions and achieve carbon neutrality in the following decades (Ministry of the Environment 2015¸European Commission 2022).

This thesis is a literature review of an energy return on energy investment (EROI) analysis and comparison of two energy technologies. Additionally, their development is discussed on the base of their EROI values. The methods studied for this paper are wind and nuclear power. The selection is based on renewable and clean energy used in the Nordic countries. Due to the factor that renewable and clean energy is going to play a significant role when battling the increasing carbon emissions. According to the Finnish Government, heat and electricity production are required to be emission-free in the near future (Finnish Government 2023). The aim is to analyse what the EROI-based analysis looks like within the frame time of Finland's low-carbon roadmap 2035. The paper will discuss and compare how different scenarios of applying wind and nuclear power will make a difference and help Finland achieve carbon neutrality.

Wind power is a constantly growing renewable energy source in Finland. It has the potential of playing a role in the renovation of energy production both in Finland and worldwide. Research made in the North and also outside the Nordic countries are utilized in the analysis, to get a wide perspective of the results. The technology development of wind power has been limited to a certain point. The technology will be discussed along the lines of three-blade, horizontal-axis, and pitch-controlled turbine types. Both onshore and offshore wind farms are discussed. The divergence in the values of EROI with the different conditions is estimated to be significant. Given the rapidly evolving technology, one challenge is to make sure that the data used is still relevant today. When looking back just a few years, the literature shows how quickly indeed the technology of wind power has developed (Diesendorf et al. 2020).

In the EROI-based analysis made of nuclear energy, both conventional nuclear power plants (NPP) and small modular reactors (SMR) are discussed. The choice of technology was based on several factors. As stated in the energy sector of the Low-carbon roadmap, SMRs may be part of the solution when achieving carbon neutrality in Finland. (Paloneva ja Takamäki 2021). According to the Finnish state-owned energy company Fortum, Finland could have the benefit of applying SMRs to their energy production plan in the future (Kattainen 2022). Due to SMRs practicality in size and increasing efficiency in heat production, it has remarkable potential in utilizing the enormous amount of thermal power it outputs. Since SMRs are still in the development and research phase and therefore no practical EROI values are presented of the subject, the EROI of SMRs are assumed on the base of the EROI of NPPs. The paper will not discuss the electrical transmission, distributions, and elements utilized in the mentioned.

The definition of EROI is going to be explained briefly in the following chapters. Due to the fact that EROI considers all the energy achieved in the process over the energy that is invested, it gives a good understanding of the technology in question. EROI can be used to explain the profitability of the technology. Which will be needed when considering the use of these technologies to benefit the most of them. Still, any value above 1 indicates that the energy technology produces more than it consumes and resulting in a net energy surplus (Feng et al. 2020), but if it is rational, is a different question.

Chapter 2 will discuss briefly background subjects on the thesis, such as an overview of Finland's Low-carbon roadmap and briefly explain the definition of EROI. Chapters 3 and 4 will discuss the factors that influence the EROI values and present the current EROIs of both wind and nuclear power. Additionally, it will contain an EROI-based analysis of the development of both energy sources. Chapter 5 will discuss the comparison of wind and nuclear energy. Lastly, chapter 6 will deal with the conclusions and discussion, and also contain personal thoughts and observations on the topic.

2 BACKGROUND

2.1 Finland's low carbon roadmaps 2035

This paper is made with a frame time within Finland's Low-carbon roadmap 2035 (Paloneva and Takamäki 2021). Finland's Government stated that Finland will be carbon neutral by the year 2035 and carbon negative soon after that. The specific carbon negativity date is still unknown. The low-carbon roadmap is the plan how this goal will be achieved. The roadmap was made with the cooperation of companies and organizations, which the roadmap is made for. To successfully implement the roadmap, the Government is going to modify the climate and energy policy scenarios, policy measures to reduce emissions, and allocation of research and development funding. All these modifications are expected to help Finland to reach carbon neutrality. According to the summary of the low carbon roadmap, greenhouse gas emissions are going to be cut down by electrification of industry and rest of the society. This translates into a large increase of renewable energy sources share in the energy mix, like wind and solar energy technologies. This fact leads to the reason why wind power was chosen to be one of the discussed technologies in this paper. Additionally, the electrification of industry and whole society is going to be implemented by nuclear power and specifically with small nuclear reactors (Paloneva and Takamäki 2021). The consequence of this is that both wind and nuclear are expected to play a large role in a low-carbon future energy system. The comparison of the two energy technologies helps us to understand their advantages and disadvantages. The comparison of wind and nuclear energy is going to happen through a metric called energy return and energy investment (EROI).

Implementing the roadmaps will require major investments. Especially when studying the quickly growing wind power production, which is very weather sensitive. Maintaining a balance constantly in different weather conditions demands huge investments to connect electricity distributions and active electricity markets between countries. In a low-carbon energy system with a significantly larger share of wind power in the mix, the potential drop in emission is expected to be proportionally large. According to the roadmap, the emissions from electricity generation will drop from 131 kg CO_2/MWh to 10 CO_2/MWh and district heating emissions from 148 CO_2/MWh to 34 CO_2/MWh by the year 2035. This is going to be performed by increasing the capacity of both onshore and offshore wind farms. Additionally, the roadmap's plan is to grow wind power by 600% (22 TWh) and double the nuclear power capacity. The need for nuclear power growth is solved partly by speeding up the authorization of small modular nuclear reactors in Finland and manufacturing nuclear power plants in large quantities (Paloneva and Takamäki 2021).

2.2 Definition of EROI

Energy return on investment (EROI) is a metric that was proposed by Hall et al. 2011 and it expresses the relation of invested energy and gained energy in a certain energy system or power plant. Energy investment describes the total amount of energy that is used during the system's whole operation time, which specifies the construction, maintenance, decommissioning, and waste management. If the system requires fuel to operate, it indicates that also energy invested into mining, refining, and transporting the fuel, needs to be considered. Energy output is considered as the amount of energy produced during the whole operating time or the primary energy equivalent to the amount of energy produced (Diesendorf 2020).

Depending on the boundaries and the examined energy system, EROI values can vary between a broad range (Ecclesia et al. 2022). It is very important to have clear boundaries when studying a certain energy system's EROI values. Nevertheless, any generally agreed regulations or rules do not exist, therefore the determination needs to be expressed within the considered framework. This means, for example, that it is important to remember that there is not just a single value of EROI for each energy technology. Rather, there are several different estimations, depending on the boundaries set and the situation of the study. When defining EROI for certain energy technology, the challenge is to identify the multiple direct and indirect energy sources for the energy inputs (Walmsley et al. 2018). Presumably, the EROI of wind power varies more than the EROI of nuclear power. This is assumed because the factors that impact the energy output of wind power can't be influenced by humans, speaking of factors like geography and climate.

EROI analysis can be utilized in economics. This means, the higher the EROI values are the less energy is likely needed to obtain a certain amount of energy. Since the economy plays a critical role in modern human society. It explains the popularity of utilizing fossil fuels on the behalf of satisfying our societal needs, despite the major disadvantages. However, the predicted path of the EROI values of fossil fuels is predicted to be decreasing in the future. The EROI values of fossil fuels today follow a range between 17 and 40 (Kowalska et al. 2018). Various studies present different values of EROI that needs to be achieved for a project to be considered viable: e.g., EROI values lower than 7 have been often considered to be not convenient in modern society (Kowalska et al. 2018). However, a study made on the subject states that there is a minimum EROI to keep our modern standard of living. EROI under 15 matters and EROI under 10 starts to be relevant to reformation (Dupont et. al 2018).

As an illustration wind power has a lower EROI than for example thermal power plants, which means wind power requires more energy to create the same amount of energy than thermal power plants. Additionally, meaning that wind turbines built with energy produced by wind power require more energy, have a lower EROI, and cost more, than wind power built with fossils (Fabre 2019), which is a demanding situation. Simultaneously, according to Diesendorf (2020), the EROI of wind power is going to increase in suitable locations, which is a hopeful situation.

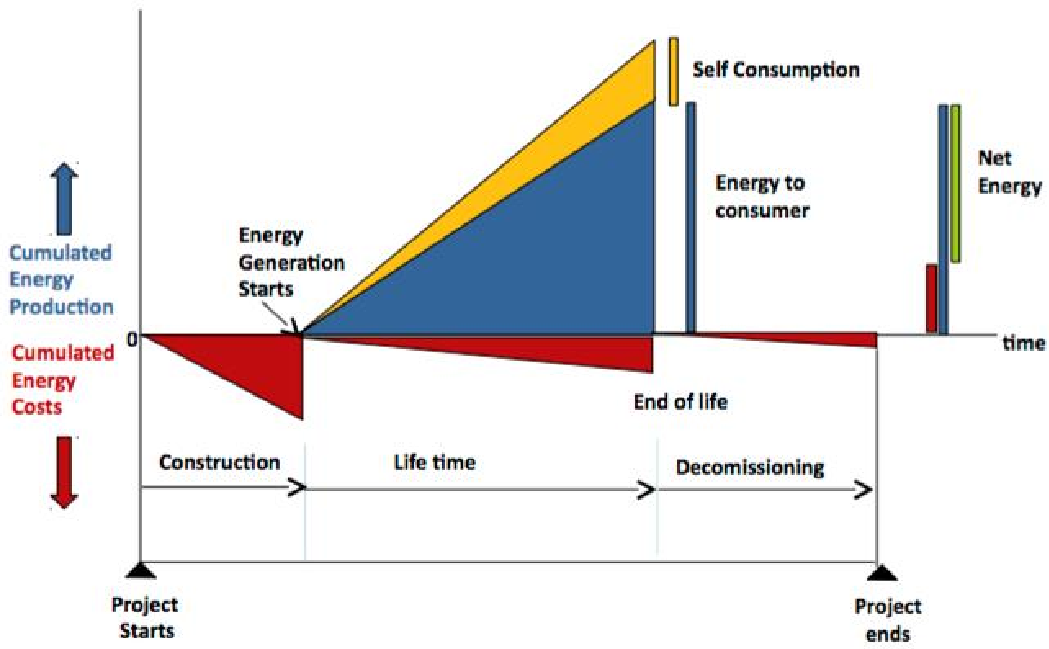

Fig. 1 A simplified scheme of energy outputs and energy investment of a hypothetical electricity generation facility (Kubiszewski et al. 2010).

Fig 1. illustrates a scheme of a hypothetical electricity generation facility. From the scheme can be noticed that the amount of output energy outgrows the amount of energy invested during the whole lifetime. This means that the technology manages to be beneficial and its EROI is greater than 1. The red colour represents the invested energy, and it can be seen as largest at the construction phase. The yellow and blue colours represent the energy output of the electricity generation facility.

3 OVERVIEW OF WIND POWER

According to the energy sector of Finland's low-carbon roadmaps, wind power is going to be identified as the major source of clean energy by the year 2035 (Paloneva and Takamäki 2021.) Wind power is a renewable energy technology, which does not need fuel to operate, and it does not release emissions while operating. Regardless of its fuel-free operating ability, it does not mean that a wind turbine's lifecycle is fully emission free. Material demands and energy needed to build and to maintain such a plant needs to be considered. Although, if carbon neutrality will be achieved within the near future, the results will have an impact on the emissions formed in the beginning of the life cycle of a wind turbine. Additionally, decommissioning of wind turbines face challenges. The factors that influence wind energy's EROI calculations will be discussed in the following chapters. Wind power technology has developed a lot in the past decades, but to keep up with the increasing energy demand due to the increasing population, it still needs to be developed. Researchers have evaluated that the growth is possible (Jacobson and Delucchi 2011; Dupont et al. 2018).

This paper will discuss horizontal-axis turbines. A horizontal-axis turbine consists simply of a support tower, generator, gearbox, and rotor blades. The factors that need to be considered, to enable the highest energy output possible with wind turbines, are wind resources, technical specifications, and site conditions (Awasthi 2018). Chapter 4.2 will discuss these factors more in depth. Wind power's function is based on capturing kinetic energy from the wind and converting it to mechanical work, which further is converted to electricity through a generator.

3.1 Offshore wind

When discussing the future development of wind power, offshore wind farms represent an overwhelmingly important component. Offshore wind farms are, among other things, usually more efficient, furthermore, they generate a larger and more constant output. Simultaneously, they come with challenges like cost-effectiveness, construction, and maintenance work. Even though offshore wind farms do have a higher energy demand in base construction, network connection, and maintenance, their increasing energy production is expected to compensate for it. Generally, an offshore turbine can generate more energy in less time than an onshore turbine, meaning the EROI may be higher in the aquatic environment (Huang et al. 2017).

3.2 Energy invested

When studying the EROI of certain energy technology, it is important to be familiar with the process during manufacturing, construction, decommissioning and deconstruction.

All the steps mentioned require a certain amount of energy, which influences the EROI. Depending on the case study, the energy input in wind power consists shortly of 25-30% extraction and processing, 35-40% of the manufacturing of the turbine and grid infrastructure, 7-8% of operational parasitic load, 7-15% of installation, and 8-10% of maintenance. The values vary a bit depending on if it is an offshore or an onshore wind turbine and whether it is floating or fixed. The values calculated for the total life cycle primary energy input for a 1 GW onshore wind farm is 20,2 PJ, for an offshore wind farm 25,9 PJ, and for a floating offshore wind farm 30,5 PJ (Dupont et al. 2018). These values will be utilized in chapter 4.5 EROI of wind power.

3.3 Factors that influence the EROI of wind power

Physical factors like size, solar radiation, heat gradient, geography, and electricity transport distance can have a sizeable impact on the EROI values. The following chapter will discuss these factors more in detail.

3.3.1 Turbine design

In Finland the rotor diameter has grown from 15 meters to over 150 meters in the past decades (FWPA 2022). The technology of wind turbines has developed rapidly. The change has been, among other things, higher hubs, and longer blades. According to Kubiszeweski's meta-analysis, the size of the turbines is of great importance. With a larger rotor diameter, EROI increases due to the greater capability to take advantage of the wind and it enables capturing energy more efficiently. The taller turbines can reach higher winds much better than the smaller ones (Kubiszewski et al. 2010).

3.3.2 Siting of wind turbines

The location of a wind turbine is also an important factor on EROI calculations. EROI increases notably when the turbines are placed in flat, open areas or on top of mountains, where the wind speed can increase fast. Wind speed is a fundamental atmospheric quantity at which air moves through the atmosphere and it is a key factor in functionality. Considering the functionality, the key rates are cut-in speed, 3-4 m/s, where the turbine starts to generate power, rated wind speed, 11-14 m/s, where the turbine achieves the rated capacity depending on the turbine type, and cut-out speed, 20-25 m/s, where turbine needs to be automatically stopped to avoid damage (Awasthi 2018).

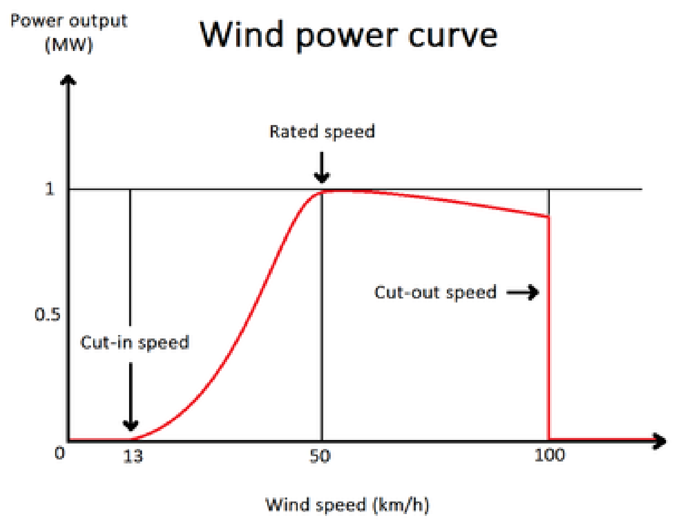

Fig. 2. The wind power curve (EnergyEducation.ca)

The challenge with wind power is the fact that it is a non-dispatchable, intermittent and irregular source of energy. Modern technology enables the successful locating of wind turbines in places with good wind potential. In winter the air density is higher due to the colder climate and in these conditions, the energy production is higher in the same wind speed as in warm air. This enables more efficient conditions for a wind turbine to generate electricity, which also increases the EROI (FWPA). This explains the popularity of utilizing wind energy in a future sustainable energy solution in Finland, considering also Finland's cold winters. There is also an inconvenient side of cold winters, because of the cold and snow, turbines can freeze, and this can lead to problems in the function. Icing can be solved by ice detection and protection systems. Nonetheless, according to a study by Ziemowit (2022), climate change has already negative impact on the energy production of wind power, because of the global change in historical wind patterns. A study case states that the annual wind speed could drop by up to 10% and in certain places, the drop has already been up to 15% (Yale Environment 2022). This might have a negative impact on the wind power field in future Finland.

Additionally, the challenge is that it is not permissible to arbitrarily build wind power turbines anywhere, due to environmental, cultural, and landscape restrictions. Especially in Northern Ostrobothnia, the restrictions are, among other things, reindeer herding, defence forces, and national parks (FWPA 2022). This equals to decreasing possibilities of places where to locate the turbines. Additionally, the lifetime of the turbine matters also in EROI values. According to the European Wind Energy Association, a wind turbine can generate electricity for 20-25 years. This means they will be running continuously for approximately 120000 hours. By comparison, a car engine's lifetime is 4000 to 6000 hours (EWEA 2022). The lifetime matters when calculating the EROI, the longer it generates electricity the more electricity is generated, and the higher EROI is achieved.

As a proof and illustration of the variation of the EROI values depending on the location; two different wind turbines, in different locations, but with exactly the same features were compared, and further EROIs achieved were 12.5 and 6.1(Kubiszewski et al. 2010). As seen the difference can be huge and this definitely is an important determinant.

3.3.3 Capacity factor

Capacity factor plays an important role when considering the EROI values and the amount of electricity generated from energy technology. At any circumstances, wind turbines can't generate 100% of wind energy into electricity. This is explained by the capacity factor. Capacity factor depends on many factors, such as wind speed, maintenance downtime, and repair downtime and it is calculated over a period of time. Simplified as the actual power output of the turbine divided by the optimal power put of the turbine, both are studied in the same time period. Siting the wind turbine right and choosing the correct type of design in certain locations, influences and improves the capacity factor. (Luvside 2020). The higher the capacity factor is, the higher EROI can be achieved.

Wind turbines installed in Finland have a capacity factor of 33%, however, the best-produced has a factor of 40% to 47% (Finnish Wind Power Association 2019). As a comparison, on 11.11.2022 Finland had an onshore wind capacity factor of 20%, Sweden had 35,9%, Norway had 57,3% and the UK had 46,2%. Simultaneously, offshore wind capacity factors for Finland, Sweden, and Norway are 0%, and for the UK 48,8% (Wind Europe 2022).

3.4 Energy output of wind power in Finland

This paper takes into consideration four different wind turbine models, which were under production in North Ostrobothnia. All in all, there is 412 wind turbines under production in the exact region. The purpose was to choose different features to be able to make comparisons.

Table 1 was made from the data provided by the Finnish Wind Power Association (FWPA 2022).

LOCATION	ONSHORE	ROTOR DIAMETER, m	HUB HEIGHT, m	YEAR	CAPACITY MW
II, FINLAND	yes	150	175	2019	4.2
II	yes	117	141	2014	2.4
II	yes	64	70	2009	1
II	yes	40	50	1998	0.7

The following conclusion can be made based on the data; developing technology means both increasing turbine diameter and hub height. The increase in appearance follows by an increase in the capacity of energy production. Simultaneously, it could be assumed that the EROI increases while the size and capacity increase. In the chart above shows the most efficient turbines capacity is 4,2 MW. However, today Finland’s largest turbines capacity is 5 MW, while the future estimate is over 7 MW (Finnish Wind Power Association 2022). Although, too high-capacity wind turbines can lead to curtailment, meaning loss of useful energy. As an illustration, a case study showed that an annual capacity of 26 GW and 33 GW, could have a curtailment of, respectively, 0.28% and 1.67%. This case is only if the transmission between neighbouring countries is likely to increase (Nycander et al. 2020).

3.4.1 Energy Output of offshore wind power in Finland

Currently, Finland does not have a large number of offshore wind farms under construction, and there are none in Northern Ostrobothnia. Therefore, for this work, offshore wind farms in the Satakunta region, in Western Finland, were considered. It is a wind farm including 10 turbines, with a turbine rotor diameter of 130 m, and a turbine hub height of 90 m. The farm was built in 2017. The total power output is 42 MW. When viewing a single turbine, the power output is approximately 4.2 MW (FWPA 2022). With the data provided in this chapter, assumptions can be made; offshore wind turbines have higher energy output, even with a smaller turbine size. Therefore, the EROI of offshore wind farms is also likely to be bigger than the EROI of onshore wind farms. The future EROI values could also be assumed to be higher if the physical aspects continue growing and the turbines are located offshore.

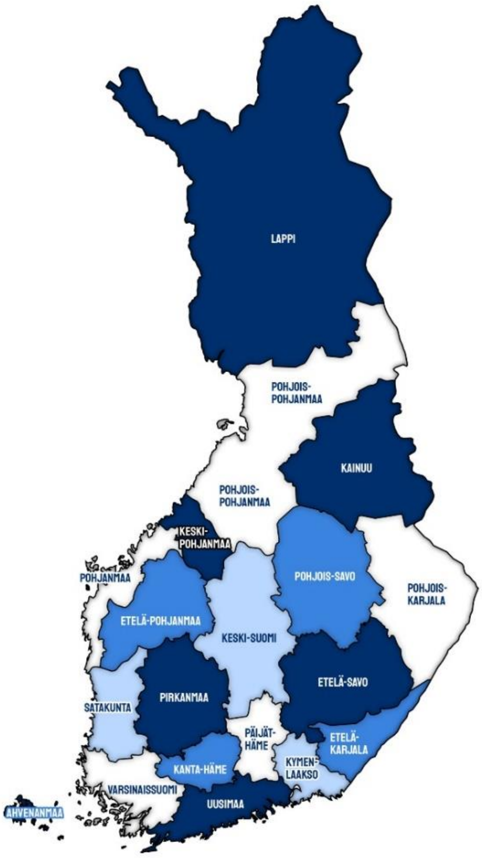

Fig. 3. The regions of Finland (https://www.learnit3d.fi/fi/suomen-maakunnat-kartta/).

3.5 The background and potential of wind power in Finland

According to Nordic Co-operation (Nordic Energy Research), the consumption of wind-generated electricity has increased significantly, which means that the need of producing wind generated energy needs to increase also. The increase was from the mid-90s all the way to 40 TWh in 2018 and by 24 %, from 42.6 to 48.6 TWh between 2018 and 2019 in Nordic countries (Nordic Energy Research). In 2020 Finland's wind power capacity was 4 037 MW with a total of 1112 operating wind turbines (FWPA). The electricity generated was 7.9 TWh, which is 11% of the total electricity generation of Finland. By comparison, nuclear power's electricity generation was 23.3 TWh, which is 34% of the total (WNP). Yet, the Finnish Wind Power Association has stated that the capacity will grow from 7.9 TWh to 30 TWh by the year 2030, which could lead us up to 25% of the total electricity generation (FWPA 2022). As a reminder, according to Finland's roadmap, the increase will be 22 TWh (Paloneva and Takamäki 2021), which equals and possibly will take place.

In 2021 Finland had a capacity of 21 300 MW of wind turbines under development, but most likely not all of them will be applied because for various reasons. However, at least 30% of the projects do have a land use plan and a building permit. (FWPA 2022). The Northern Ostrobothnia had 412 turbines under production in April 2022, with a total capacity of 1597,3 MW. In the planning phase, there was a capacity of 6000 MW (Pohjois-Pohjanmaan liitto 2022). This tells us that the capacity of wind power is constantly growing widely in Finland.

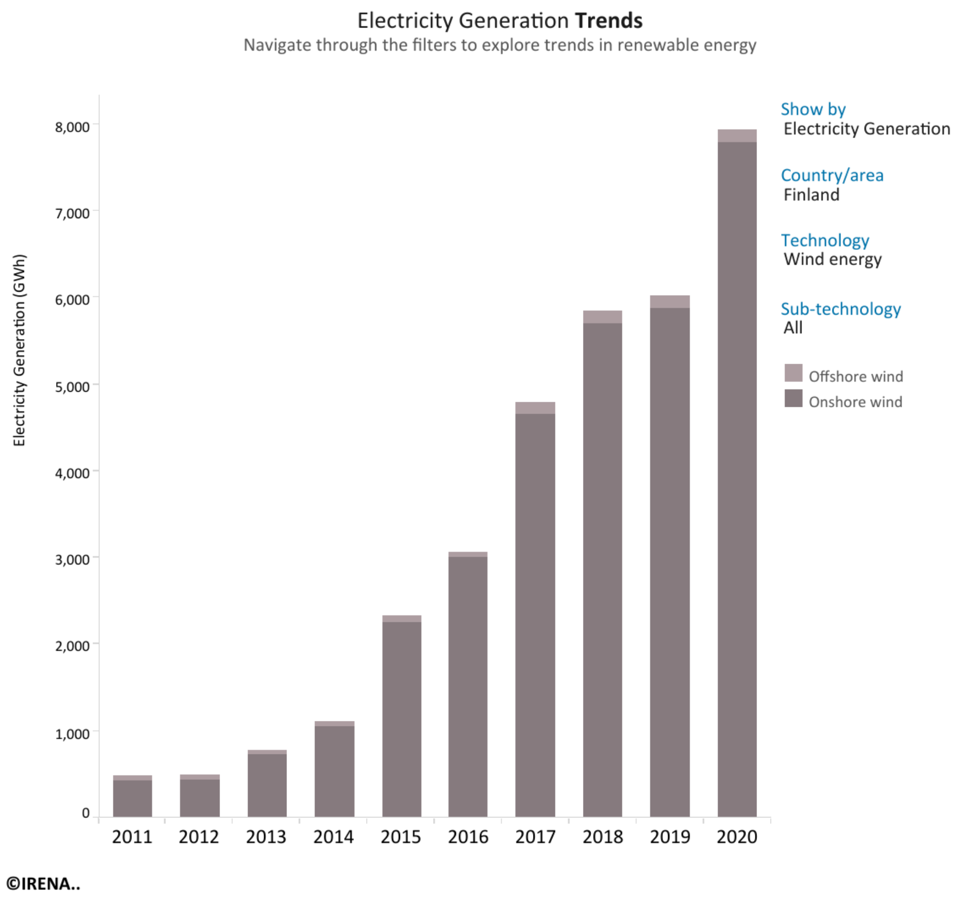

Figure 4. Finland’s electricity generation trends between 2011 and 2020 (International Renewable Energy Agency 2020).

3.6 Conclusions of EROI of wind power

This analysis is made based on several different research and literature. As already studied in the previous chapters, the rotor diameter plays a significant role on EROI; a bigger size of rotor diameter is equivalent to bigger EROI. Even though larger rotors require a higher amount of energy under construction, the energy output compensates for this. Additionally, the location of the turbine matters grandly (Kubiszewski et al. 2010). To get an idea how the EROI could be in the wind power sector in Finland, several research and literature made of the subject were considered. This chapter includes a comparison of data found from several analyses. Analyses utilized in this paper are not only from the Nordic countries but also from the United Kingdom.

In the study Energy Policy (Raugei and Leccisi 2016) they analyzed EROI for several energy technologies including wind energy in the United Kingdom. The baseline for the research was the wind technology used in 2013 in the UK. This included 2.5 - 3 MW onshore wind turbines and 3 - 5 MW offshore wind turbines, with a turbine lifetime of 20 years, which is comparable with the technology considered in the Finnish case. The trend was a growing rotor diameter and hub height but also floating turbines. The results of the research were that onshore EROI was 17 and offshore EROI 18 (Raugei and Leccisi 2016). Additionally, the electricity generation capacity went from 28 TWh to 71.2 TWh between 2013 to 2022, which shows that development has happened (Renewables Now 2022). Bearing in mind that the UK has greater facilities to utilize wind energy. Including very strong winds and relatively shallow waters and the capacity factor in the UK is relatively bigger than in Finland (WindEurope 2022). The conditions are not straight comparable with the conditions in Finland, but this gives a direction, which gives us an EROI much greater than 10. Can also be assumed that the capacity factors are nowadays somehow greater than back in 2013.

Similar results were obtained in a research work made in 2013; according to that study (Weibach et al. 2013) a 1.5 MW turbine, with a lifetime of 20 years, a lifetime energy output of 216 TJ, energy demand for construction of 12.9 TJ, and energy demand for maintenance of 0.3 TJ would give an EROI value of 16. The same study provides a viewpoint: if the same turbine with the same facilities is in such a place with extremely good conditions for a wind turbine and a high load of peak hours, the EROI may be twice as high (Weibach et al. 2013). Therefore, it cannot be underlined enough that it is extremely important to pay attention to the location of the turbines. It will have a huge impact on the EROI. Additionally, a study presents an EROI value range of 10.3 to 32.4, depending on where the turbines are located. These values were studied by accounting for the time value for energy. As a comparison, when not accounting for the time value for energy the results were between the range of 18.7 and 43.9 (Walmsley et al. 2018).

Another study gives values for an energy input like the following: the values calculated for the total life cycle primary energy input for a 1 GW onshore wind farm is 20.2 PJ, for an offshore wind farm 25.9 PJ, and for a floating offshore wind farm 30.5 PJ (Dupont et al. 2018). Utilizing these values and different capacity factors, it is possible to calculate EROI for different scenarios. Calculating EROI for 1 GW wind farms with an operation time of 25 years results in 788.4 PJ total output energy.

Table 2. By utilizing different capacity factors from FWPA and WindEurope, the following EROI values were achieved.

SCENARIO	**OFFSHORE/ ONSHORE**	**ENERGY INPUT**	**ENERGY OUTPUT**	**CAPACITY FACTOR**	**EROI**
1	ONSHORE	20.1 PJ	260.2 PJ	33%	**12.9**
2	ONSHORE	20.1PJ	370.5 PJ	47%	**18.3**
3	ONSHORE	20.1PJ	203.4 PJ	25.8%	**10.1**
4	OFFSHORE	25.9PJ	487.2 PJ	61.8%	**18.8**
5	OFFSHORE (FLOATING)	30.5PJ	487.2 PJ	61.8%	**16**

Scenario 1: the average value of CF in Finland, 33%.

Scenario 2: the best-produced CF in Finland, 47% (FWPA 2022).

Scenario 3: average CF in Europe in November 2022, 25.8%.

Scenario 4: average offshore CF in Europe in November 2022, 61.8%.

Scenario 5: average floating offshore CF 61.8 %, average in Europe in November, 61.8% (WindEurope 2022).

3.6.1 Conclusions

When considering wind power, noticeably, the EROI varies significantly, depending on the boundaries set to the analysis. The EROI of wind power achieved from all the considered analyses varies between a range of 10.1 and 43.9. Additionally, as already stated earlier, any technology does not have one single value of EROI. Despite the large range between the values, the analyses give a direction about how the EROI of wind power somehow looks like. These values of EROI are achieved with the technology in the past decade. However, there are possibilities for development. The development of the wind industry today in Finland are an increase of 4 MW capacity turbines to 7 MW capacity turbines, an increase in both hub height and rotor diameter and offshore placement of the turbines (FPWA 2022). Nevertheless, the increase cannot happen limitlessly. The development might offer greater EROI values owing to better technology overall.

There are external factors that influence wind energy production, which cannot be changed through development. Such factors are wind speed and air density. It can be influenced to a certain state by siting turbines right. Furthermore, as the capacity of big wind farms grows, it is inevitable that the availability of land resources decreases (Sliz-Szkliniarz et al. 2019). As an illustration, a case study provided a viewpoint; with perfect and impractical facilities of energy conversion efficiency of 75 %, the replacement of 1 GW of conventional energy installed, would require 5 GW of combined wind and solar installations and high amounts of energy storage facilities (Ziemowit 2022, p4071). However, the article is related to a very negative way of thinking when considering the transition to low-carbon energy production and it fails to prove the claim. Additionally, the study points out that along with the increase in renewable energy sources, the quality of life will degenerate (Ziemowit 2022, p4071). The claim is proven by an argument; the less human activity that is required to achieve the amount of energy to satisfy society, the higher the quality-of-life factors are (Lambert et al. 2014). However, it doesn't correlate with the fact that fossil fuels have somehow greater EROI values and also are a big risk to human health because of the released emissions. Regardless, it is clear that the high-space demand is going to be a problem in the future due to the fact that there are not endless places to locate wind turbines (Sliz-Szkliniarz et al. 2019). In these cases, offshore wind farms can be part of the solution. Nevertheless, electricity distribution may become a problem, and the fact that intermittent wind energy needs energy storage to be beneficial.

4 OVERVIEW OF NUCLEAR POWER

As stated in the Finland's Low-carbon roadmap nuclear power and additionally small modular reactors (SMRs) are going to play a role when implementing carbon neutrality in Finland. When looking back on history, it is noticeable that Finland has always been keen to grow its nuclear capacity. This trend is still favoured today. Nuclear power has grown from 430 MW to 4394 MW between 1977-2022. (World Nuclear Association 2022). As a comparison, nuclear power energy production in Denmark has been shut down completely in 2001. Despite its promising development in the field back in the 19^{th} century when nuclear fission was verified experimentally in Denmark. In Sweden, the trend has been anything else than growing, with 452 MWe in 1971 and in 2022 the capacity was 6 885 MWe. It was at its highest in 1998 with a capacity of 10 035 MWe. The future is still somehow uncertain (WNA 2022). The discourse of whether it is profitable and worthwhile is remaining, including an open public debate regarding social acceptance and risks associated, for example, with the possibility of accidents.

Nuclear energy is based on energy released from a fission reaction when atoms split. When the atoms split in chain reactions, they release energy in the form of heat and radiation, which can furthermore be converted into electricity. The heat is produced most commonly using uranium-235. The fuel's function is to warm up the reactor's cooling water, producing steam. Steam will the spin turbines which are connected to an electricity generator. Depending to the considered technology, the principle can slightly vary according to the reactor type, but it is fundamentally the same. Furthermore, energy can also be using nuclear fusion (IAEA 2022). However, fusion reactors are still in the research and development phase. The near future of the nuclear industry in Finland is most likely to include SMRs (Paloneva and Takamäki). The next chapters will discuss the benefits of utilizing SMRs and their influence on EROI.

4.1 SMR

The capacity of Finland's 4394 MW nuclear industry includes 5 operating nuclear power reactors, containing one reactor with a capacity of 1600 MW. The historical trend in the nuclear industry has been toward ever larger reactors, however, the potential and knowledge of SMRs have been favoured recently (WNA 2022). Classified as SMRs are the reactor under 300 MW according to the IAEA. The options for different SMRs are water-cooled SMRs, high-temperature gas-cooled SMRs, fast neutron spectrum SMRs, molten salt SMRs, and micro-sized SMRs. In May 2020 Russia developed and began the operation of two floating SMRs, which had a capacity of 35 MW. This was a major milestone in the SMR industry. Currently, over 70 different designs are under development (IAEA 2022). The support behind developing SMRs is valid because of their enormous potential. The advantages are mostly because of the small size and modularity, which enables higher quality and more efficient production, due to the controlled factory setting and more systematic installation, the possibility to have multiple units on the same site, safer usage, easier control, flexibility, smaller radioactivity inventory and more suitable for remote regions because of lower requirements of cooling water. Additionally, SMR designs are expected to reduce cost, fuel requirements, and construction time (WNA 2022).

4.2 Factors that influence the EROI of nuclear

4.2.1 Fuel

Uranium (more specifically U-235) is the most widely used fuel in nuclear power plants. It has been utilized for a long time and still, the struggle of what to do with the used nuclear fuel is remaining. The challenge with nuclear fuel is that it remains radioactive for a good time after it has been used. Possibilities are to recycle and handle the used fuel to provide fresh fuel or geological disposal (Peluzo and Kraka 2022). Geological disposal is not a very long-lasting solution since the radioactivity remains in the fuel for ages. According to WNA, recycling and utilizing the used fuel allows 25-30% more energy from the original uranium to be utilized (WNA 2022). This indicates that mining will be less important in the future, and furthermore, higher EROI could be obtained.

According to a case study (Kowalska et al. 2018), mining, milling, and conversion of uranium plays a big part in the lifecycle of the fuel, as seen in Fig. 4 and obviously demands certain amount of energy. The difference between old mining techniques and new mining techniques has a remarkable influence on the EROI values. A highly energy-demanding diffusion enrichment has been replaced with a centrifuge or laser enrichment, which decreases the energy demand on the enrichment process. As an illustration, with an old diffusion enrichment, the EROI was calculated to be 24, which is undoubtedly low. When changing the old diffusion enrichment to centrifuge or laser, the EROI increased, respectively, to 105 and 115. The same study provided values of the fuel energy demand, which are 30900 TJ and 21750 TJ, depending on the enrichment process (Kowalska et al. 2018). Simultaneously, according to Walmsley et. al (2018) a nuclear technology where centrifuge technology covers 83 % of the fuel development, hands an EROI of 69.6 and with a 100% centrifuge, an EROI of 96.2 is specified. These EROI values were studied by accounting for the time value for energy. As a comparison when not accounting for the time value for energy the EROI values were, respectively, 101.7 and 170.5 (Walmsley et. al 2018).

Furthermore, when nuclear technology develops, removing the enrichment of uranium from the process will increase EROI surely. The research and development of nuclear reactors have successfully developed a reactor, which runs by used nuclear fuel. This is called the dual fluid reactor (DFR). This enables even higher EROI values in nuclear technology. A DFR can also be utilized as an SMR (Böhm et al. 2020). Even though it is predicted that the mining of uranium will be less in the future, the recycling of used nuclear fuel demands a certain amount of energy, which also has an implementation on the EROI values.

Along the closed fuel cycles, it is assumed based on calculations, that the extraction of uranium from natural sources is more likely to come to an end. Closed fuel cycles demand only fissile materials, which can be produced by uranium-238 and thorium-232. The number of fissile materials received from the used nuclear fuel is enough to satisfy both fast neutron and thermal reactors. To get an effective synergetic system, the process should be implemented by producing fuel from fusion reactors and energy from fission reactors (Velikhov et al. 2020 pp. 1023).

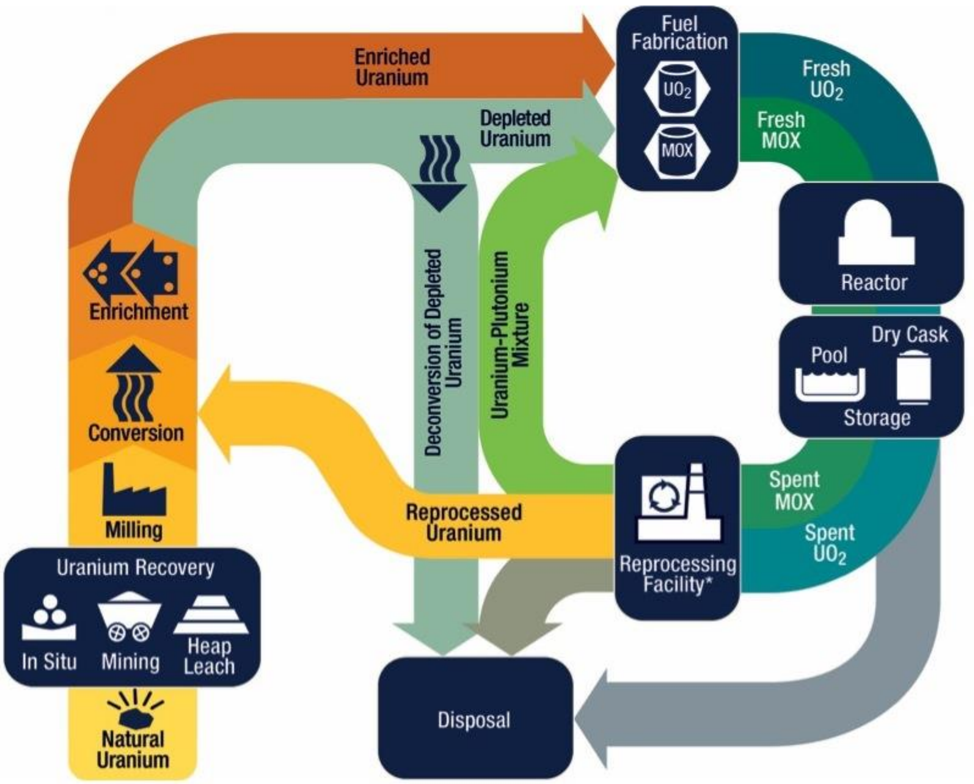

Fig 4. Scheme of the nuclear fuel cycle (Unites States Nuclear Regulatory Commission 2019).

4.2.2 Construction and maintenance, lifetime

The construction, maintenance, and decommissioning work in a big nuclear plant demand high amount of energy. As an illustration, a study (Kowalska et. al) provides values as following: construction 4050 TJ, maintenance 6900 TJ, and decommissioning 1150 TJ for a typical 1340 MW pressurized water reactor (PWR), which operated for 60 years and owns an energy output of 2,315,000 TJ (Kowalska et al. 2018). It can be noticed that the maintenance of a nuclear plant requires the highest share of energy. However, development of the nuclear industry focus on lower requirements of energy demand during its construction, maintenance, and decommissioning phase, all characteristics expected from SMRs.

Depending on the considered research and studies, the lifetime of a nuclear power plant varies between 40 to 80 years. This either increases or decreases the EROI significantly. Finland’s first nuclear plants Olkiluoto 1&2 started operating in 1978-80. In 2010 their lifetime had been extended to 60 years and additionally in 2017 TVO applied for 20 years more. Their capacity has grown from 660 MW to 880 MW between 1978 and 2010, it is proposed that the capacity will grow even further to 1000 MW. Notable, this poses challenges in accurately predicting the overall contribution of a nuclear plant (WNA 2022).

4.2.3 Reactor type

Nuclear reactor is thermo-electric plant where nuclear reaction produced heat energy is transformed into electricity. There are a number of different type of reactors in use as well as in the research and development phase. The most common reactor type is a pressurized water reactor (PWR). PWRs use water in both coolant and moderator. A similar reactor to PWR is a boiling water reactor, with slightly different features. In addition to these, there are about 425 water-cooled reactors globally, which sizes varying between 30 – 1660 MW.

According to Kowalska et. al (2018), the type of nuclear plant has a huge impact on the EROI value. As an illustration, an EROI of 105 is calculated for a PWR. Simultaneously, an EROI for a DFR is estimated to be 2000. To take into consideration, DFR can completely function by using recycled nuclear fuel. This lowers the external fuel processing and disposal, Additionally, small modular DFRs are smaller in the size, which equals to far simpler construction and easier maintenance. It is indicated that DFRs also have essential safety features, high fuel breeding, fuel utility, and efficiency. It is clear without saying that the development of nuclear power plants increases the value of EROI, as in the wind power industry (Kowalska et al. 2018).

Simply, a DFR is a combination of two different technologies: The Molten Salt Reactor (MSR) and the Lead-Cooled Fast Reactor. This means it is functioning with liquid fuel and uses liquid metallic coolant. DFR operates in very high temperatures like 1000°C and this enormous heat can be enabled in the production of hydrogen. Hydrogen can be produced efficiently through combined electrolysis and thermolysis from the water. Hydrogen can be utilized in generating electricity or power and heat through fuel cells. Hydrogen is a clean fuel and hydrogen combustion does not release emissions. This opportunity adds up the advantages of a DFR even further (Kowalska et al. 2018).

4.2.4 The energy output of nuclear

The energy achieved from a nuclear reactor differs depending on which plant is being discussed. For example, Finland has five reactors in two power plants under operation and each of them gives a different amount of power output. Loviisa's two units have a net electric power of 507 MWe, Olkiluoto's two units have a net electric power of 890 MWe, and the third unit has 1600 MWe (STUK 2022). Considering SMRs, the power output is going to be smaller, since a reactor's energy output is lower than 300 MW.

4.3 Nuclear power usage in Finland

As already stated, Finland has a well-built and solid nuclear industry. With a place among the top ten on the list: percent of total electricity generated by nuclear in the country in 2021. With a value of 32.8%. As a comparison, Finland's total capacity hits 4394 GW at 32.8% and Sweden's total capacity is 51426 GW at 30.8 %. Finland's reactors are among the most efficient in the world, possessing a capacity factor of over 90% (NEI 2022). The VTT Technical Research Centre of Finland is researching the potential of utilizing SMRs in Finland. Additional remarkable potential SMRs have is the ability to utilize them for district heating. Today district heating is fuelled by coal, but as going towards carbon neutrality, the outcome is to phase out the use of coal by 2029. This means new district heating technology is wanted. VTT's aim is to develop a plant that can also be used in district heating (VTT 2022).

4.4 Conclusions of EROI of nuclear development

In the previous chapters, the EROI and the factors that influence the EROI of nuclear technology were discussed. Since this paper is made within a frame time in Finland's low carbon road map 2035, the aim is to analyze the future of the nuclear industry in Finland. Most likely, the future of the nuclear energy sector is going to be utilizing SMRs (Paloneva and Takamäki 2021). However, since the SMRs are still mainly in the research and development phase, the lack of data available on the associated topic made it challenging to collect and contextualize. Yet, assumptions and raw conclusions can be made by combining research results and studies written on related to the topic. Worth noting is that the literature related to EROI of nuclear technology is pointed out as not to be settled and agreed upon. It can be observed in the large range of different values of EROI that have been calculated for nuclear. Regardless of the uncertainties, it is certain that the EROI of nuclear is among the highest of the energy technologies today (Walmsley et. al 2018). The EROI of nuclear can be calculated as anything between 30:1 to 2000:1. Most commonly it's settled a little lower or greater than 100:1. The differences vary due to several factors. It can be among other things the boundaries and limits where the study is researched, the use of old technology, and the contribution of outdated studies (King and Jones 2020).

Most commonly the EROI values are settled a little lower or greater than 100. However, these studies were made commonly to existing PWR including old and new technologies, particularly to mining and enrichment of nuclear fuel. These studies are comparable to Finnish nuclear technology today. The EROI of future nuclear could be compounded by SMR and more specifically small modular dual fluid reactor (SMDFR) which has the highest investigated values. A theoretical value of 10000 and a proven value of 2000 are presented to the newest technologies of nuclear, in this case, the DFR (Kowalska 2018).

This study gives a hum to how it could be due to developing technology. Nonetheless, the study does not provide sufficient details supporting these states.

Despite SMRs still occurring in the research and development phase and the lack of research data on EROI values, it can be assumed that the EROI of SMRs appears greater than the EROI of the conventional nuclear power plant. The assumptions of getting greater or at least somehow similar values of EROI of SMR are based on the following. The energy investments could be assumed lower since SMRs are going to be factory produced, installed more systematically, and the construction time will be notably shorter. The energy output is predicted to be more efficient and of better quality, due to its smaller size and the possibility to locate it easier. Additionally, if discussing such a reactor that possibly runs on used nuclear fuel, the fuel cycle plays a critical role in increasing EROI values (WNA 2022). These factors give a confident statement that the EROI of SMR in the future will not be lower than the EROI of nuclear power plants today. Furthermore, carefully could be stated that the EROI appears even higher when compared to the EROI of nuclear power plants today.

5 COMPARISON OF WIND AND NUCLEARDEVELOPMENT

The reason for the comparison of nuclear and wind development, despite of their dissimilarities, is the fact that they are both going to be strongly part of the energy sector in future Finland. Presumably, a combination of the two technologies is going to define the future in the power production sector including the advantages and disadvantages both present. Additionally, the possibility to produce clean energy without emissions or air pollutants is the main positive benefit of both wind and nuclear technology. Regardless of the importance, it does not have any impact on the EROI-based calculations. The next chapters will discuss further the factors that make either wind power or nuclear power worth utilizing when implementing the low-carbon roadmaps in Finland and discuss more closely what it would look like.

5.1 Comparison

By comparing the EROI analyses made of wind power and nuclear power, it can be noticed that the EROI of nuclear is ineluctably higher than the EROI of wind power. The EROI of nuclear can be set above or under 100:1 and simultaneously EROI of wind power can be set just above or under 20:1. The result and the factors that influence the result are exceptionally different from each other. Moreover, one can be assume based on the references and studies, that the EROI of wind power cannot reach the level of the EROI of nuclear power. This chapter will discuss the dissimilarities and compare the two technologies wider.

The advantages and disadvantages of both nuclear and wind power widely differ from each other. Despite of development of SMRs in the nuclear industry, the construction and operation of nuclear reactors are way more complex than wind powers. Rather, wind power may be seen as more practical, easier, and faster to both plan and construct than nuclear (IRENA 2022). Naturally, one single wind turbine's planning and construction phase takes not as long time as an NPPs planning and construction phase, which makes wind power an easy alternative if new energy sources are needed with a time limit. Moreover, if comparing 1 GW of output energy, the installation energy demand is considerably higher with wind power than nuclear power. This equals, that the installed capacity of wind power would be several times larger when gaining the same amount of energy. Furthermore, this reality lowers the EROI of wind power. The high-capacity demand issue, as well as the intermittent energy problem, could be solved with energy storage (Moriarty and Honnery 2019 pp.229-234).

A limitation of wind power is it intermittency. This factor either lowers or rises the EROI, and the main issue is excess power that the electric grid cannot accommodate. Consequently, unless further investment is included improving the flexibility of the system, this leads to curtailment, meaning a reduction of output and loss of useful energy. Undoubtedly, intermittent energy requires either energy storage or interconnectors, which may have a negative impact on the EROI values. While wind power is considered as intermittent energy, nuclear power has opposite characteristics. Nuclear power is considered as a very reliable energy source, which has the ability to produce energy any time of the day and with high full-load peak hours; theoretically ideal to supply the base load. Therefore, a combination of an intermittent energy source and a reliable energy source, such as nuclear, could be a solution (Nycander et al. 2020).

5.1.1 Energy payback time

The energy payback time (EPT) considers the time that takes to pay back the amount of energy invested from the net energy returned. Values of energy payback time are commonly associated with EROI analyses. A study by Walmsley et al. provides values of EPT for both wind and nuclear power. EPT of nuclear is considered very short with an average time of 0.12 years. While wind powers ETP varies between a range of 0.26 and 1.39, notable is that the value differs depending on the location of the turbines. Nonetheless, it gives the right direction. The stated values of ETP fail to be exact due to the lack of accounting for the energy invested for deconstruction and decommissioning (Walmsley et al. 2018). However, the study offers useful information for the comparison of wind and nuclear ETP. It is quite remarkable that nuclear ETP can be 7.5 times lower than wind power ETP, simultaneously almost the same depending on the location of wind turbines. This determines how extremely efficient as well as substantial nuclear may be and how crucial is it to outline a sufficient location for a wind turbine.

5.1.2 Primary energy factor

The primary energy factor (PEF) describes the exploitation of the resource defining the total primary energy equivalent compared to the electricity generation. Nevertheless, in PEF calculations the differences in energy quality are not accounted, which fails to qualify the resources, making, consequently, the comparison unequal. However, PEF for both wind and nuclear power is calculated to be approximately the same but occasionally wind power is just slightly higher. The average PEF value for nuclear is 3 and for wind 3.3. Notably, the closer the PEF is to unity the better the exploitation. Both technologies show roughly the same values. If compared with other energy resources, such as solar PV and geothermal, which values situate between 10 and 15 and, 10 and 45, respectively. Furthermore, the PEF of hydro is slightly above 1, with the best value (Walmsley et al.

2018). The PEF of wind and nuclear are considerably better than the PEF of solar and geothermal but not as good as hydropower.

5.1.3 Fuel and capacity factor

Fuel is considered a material that succeeds to produce useful energy through chemical or nuclear reactions. Wind power is a technology that operates without fuel while nuclear power demands fuel to operate. Fuel demand influences the EROI, which is certain. The capability of wind turbines to operate without fuel is remarkable and one of the biggest factors that speak in favor of wind power. This has, moreover, a positive effect on the economic aspect. The ability to operate without fuel, among other factors, makes wind power a very cheap utilizable energy technology and remains as cost-competitive (IRENA 2022). Simultaneously, nuclear technology demands a certain amount of fuel to operate. Regardless, the amount of fuel that it demands with respect to how great it can produce energy, is an important factor when considering it. However unmistakable, mining and enrichment of nuclear fuel cost both money and energy. Additionally, nuclear power's possible to operate in closed fuel cycles eliminates a big energy demand phase (Velikhov et al. 2020 pp. 1023).

Capacity factors: The capacity factor plays a significant role in both wind powers and nuclear powers' EROI. The differences are also significant. Wind power has uncontrolled factors that limit the capacity factor very low and simultaneously will take down the EROI values. Wind powers capacity factor varies between 0 to 47% (FWPA). Besides, the high-capacity demand and intermittent energy issues of wind power, the low-capacity factor demands energy storage facilities for wind technology (Ziemowti 2022). Simultaneously, nuclear power has a very high capacity factor of 82,5% (WNA 2019), which again speaks in favor of nuclear technology.

A study from Ziemowit (2022) provided a viewpoint; with perfect and impractical facilities of energy conversion efficiency of 75 %, the replacement of 1 GW of conventional energy installed, would require 5 GW of combined wind and solar installations and high amounts of energy storage facilities (Ziemowit 2022, p4071). The results somehow verify, the need of improvement and development of the wind power sector so that it could keep up and it would be beneficial to replace the conventional energy sources with it. Or less, the high capacity of wind power generation is not convenient enough to satisfy the demand for energy. Moreover, the comparison of renewable energy with fossil fuels is not very far-reaching. Regardless, if it continues the issues of climate change will be even harder to solve. The dominance of fossil fuels has certainly shaped our way of thinking about energy.

6 DISCUSSION AND CONCLUSION

Finland's government stated that Finland will be carbon neutral after the year 2035 (Paloneva and Takamäki 2021). To achieve this goal, Finland needs to significantly increase the share of low carbon power technologies. If climate change will be ignored in the future, the depletion of resources will force the conversion to renewable energy and nuclear. However, the sooner the conversion happens the better results.

EROI is a metric, which compares the amount of required energy to provide a certain amount of energy to society. EROI metrics are important factors to evaluate the relationship between producing a sufficient amount of electricity and energy to satisfy the societal needs in modern society. Energy ratios offer a suitable application to evaluate the sustainability of the energy source, and additionally, analyze existing and future energy applications. This paper has discussed the EROI of wind and nuclear development. As already stated, the results of EROI vary depending on the boundaries and it is important to remember that there is not only one value for each energy system, rather there are several.

The EROI of wind power is broad, varying hugely due to many factors and wind powers development has been very fast in the past decades and in all possibilities, it will also be developing in the next decades. The development of wind turbines and EROI values are seen as change in the size of the wind turbines. It is shown that an increase in rotor diameter, hub, and total turbine height influences the EROI. Commonly, greater rotor diameter and height result in better capture of energy and conversion into electricity, and further greater EROI values (Kubiszeweski et al. 2010). Siting of turbines plays also a significantly important and challenging role. The importance of the location depends upon the weather conditions and manner of the landscape. Idealistic weather conditions for efficient wind power are high wind speeds (11-20 m/s) and low air density (Awasthi 2018). The idealistic manner of the landscape is a wide-open area without barriers and obstacles. Challenging is the lack of these kinds of areas, to be able to produce enough electricity, and the space demand is significantly big. Therefore, offshore wind farms are overriding when discussing future generations of wind power (Huang et al. 2017). Additionally, factors like maintaining, constructing, and deconstructing ask for a certain amount of energy and affects the EROI. Moreover, also capacity factors, curtailment, and intermittency have a major impact on the development of wind technology, and they can be changed with the factors discussed in this chapter. However, the EROI of wind power can be analyzed realistically as anything between 10 to 50 (Kubizeweski et al. 2010). Needs to agree that the result is not precise, but it informs the level of EROI and more importantly that it is not as great as nuclear EROI. However, wind power possesses many favorable advantages, such as fuel-free operating, cheap energy technology, and easy maintenance (IRENA).

While the challenges of wind power are the low energy density, non-dispatchable, low capacity factor, and more, is nuclear quite opposite. Nuclear power is seen as reliable and with a high capacity factor. Although, the challenges are that the greatness is still in the research and development phase. Speaking of SMRs, which are promised to be made faster, with better quality of energy, easier to maintain, function with used nuclear fuel or closed fuel cycle, and located easier due to their small size. However, the research results are promising (WNA 2022). Therefore, the EROI of SMRs can only be assumed, on the base of conventional nuclear power plant EROI. NPPs EROI is usually analyzed for anything between 60 to 130, depending on the research (Walmsley et. al 2018; King and Jones 2020). Which are significantly better results than the EROI of wind power. However, when considering an SMR the EROI can be assumed greater, due to the better features mentioned above. A theoretical value of 10000 and a proven value of 2000 has been reported, however, the research fails to prove it (Kowalska 2018). Yet, the EROI of SMR and conventional NPP is higher than any kind of wind technology.

The conclusions for the analysis and comparison of the EROI for wind and nuclear development and the possibilities to enable them in the low-carbon energy system are promising and absolutely necessary. However, evidently, nuclear power possesses notably better results in EROI-based analyses and calculations than wind power. Yet, in order to get the full potential of their capabilities and the best results are possibly achieved when combining renewable energy with a reliable energy source. In other words, renewables, such as wind, are combined with nuclear power. Quite certain is that renewable sources or nuclear energy can't manage alone, due to the amount of energy that needs to be produced to satisfy societal needs.

6.1 Improvements of EROI

EROI metrics and additional sustainability metrics are important factors to evaluate the relationship between producing a sufficient amount of electricity and energy to satisfy the societal needs in modern society. Energy ratios offer a suitable application to evaluate the sustainability of the energy source, and additionally, analyse existing and future energy applications. Despite the good improvements in energy ratio research, there is a lack of attention on several aspects. To fully evaluate an electricity generation of a certain energy source, the need for economic, social, and environmental factors to be considered (Walmsley et al. 2018). During the elaboration of the thesis, the lack of exemplification and illustrations of the calculations of EROI made it challenging to rely on and understand the causations. Therefore, the need for improvement in reporting the reasons and consequences is crucial, so the overall picture is clearer and values with different boundaries are not compared with each other.

6.2 Discussion

EROI metrics are important factors to evaluate the relationship between producing a sufficient amount of electricity to satisfy the societal needs in modern society. However, one important factor, quality, is not being considered in the aspect of EROI. Basically, EROI defines the economic and quantitative impacts of certain energy development. Which definitely plays in favour of fossil fuels. The EROI of fossils is still somehow higher than the EROI of renewable energy. This tells us, that renewable energy technologies still need improvement to be able to replace the fossils of the game. However, we all know that the world is in a crisis and facing severe damage due to the use of fossil fuels. Yet, the status weighs more than actually facing the issue and solving the problem. Moreover, I think EROI as a physical metric, works when analysing the energy efficiency for variable energy technology. Nevertheless, some modifications are needed, such as the quality of the source, which needs to be taken into consideration. This could speak in a more favourable way of renewable sources, such as wind power, and focus on the sustainability of the energy source. Which indicates to be a crucial factor when fulfilling low-carbon intentions. As written in the paper, nuclear power possesses a significantly better EROI value, which in all probability will grow even further and with SMRs and especially DFSMRs likely to play an important role in a future energy production system. Wind powers capacity has grown and indeed needs to grow to be able to satisfy the societal needs. However, improvements in interconnectors and energy storage are remarkable when considering wind as an energy source. Even if, reliable energy sources, such as nuclear, are available. Yet, when considering interconnectors, it is important to bear in mind the serious damage and energy crisis today caused by the conflicts between Russia. This exemplifies the risks when relying upon uncertain factors. Additionally, it is surprising how many issues there are when implementing wind power production, such as site selection, high-capacity demand, curtailment, and icing. Still, I think the noteworthiness when applying new energy technologies is the sustainability factor and prospect of producing clean energy, which furthermore, should be taken into consideration in EROI calculations.

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