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Review of Climate Strategies in Northern Europe: Exposure to Potential Risks and Limitations

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Abstract: Several northern European countries have announced ambitious plans to become carbon neutral already before the year 2050. Recent research has, however, highlighted how potential bottlenecks in raw material and resource availability could significantly delay or hinder wind and solar photovoltaic (PV) expansion and continued biomass usage in parts of Europe. To address this issue, this paper assesses how exposed the national energy and climate plans (NECPs) of Finland, Estonia, Germany, Sweden, and Denmark are to resource limitations and techno-economic risks by reviewing and analysing 2030 NECP targets compared to statistical energy use data in these countries. The results indicate that the NECPs of Denmark and Germany are particularly exposed to risks related to global raw material availability, as Denmark plans to rapidly grow the share of wind and solar PV in electricity generation to 81% and 13% by 2030, respectively, followed by Germany, which outlines a 39% and 16% share of wind and solar PV in its national climate strategy. The NECPs of Finland and Germany are also shown to be vulnerable to limitations in biomass availability, as there is a significant disparity between the projected biomass usage and legally binding European Union (EU) targets for land use, land use change, and forestry (LULUCF) sector emissions in 2030 in these countries.

Keywords: climate policy; climate neutrality; resource adequacy; critical raw materials; biomass availability; Finland; Estonia; Germany; Sweden; Denmark

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1. Introduction

The last few years have shown how the negative effects of climate change are becoming ever more evident [1–3], leading to many countries worldwide reinforcing national climate commitments and planning measures aimed at reducing greenhouse gas (GHG) emissions [4,5]. In Europe, both the European Union (EU) and individual member states have revised their climate policies within the last few years to encompass more ambitious emission reduction targets, set to accelerate the overall implementation of renewable energy while gradually phasing out fossil fuels [6–8]. The EU is currently set on a path to reaching carbon neutrality by 2050, including a target to cut GHG emissions by at least 55% by 2030 [9]. Additionally, some member states have set out even more ambitious national climate targets, with Finland aiming to become carbon neutral already by 2035 [7], followed by countries such as Sweden, Estonia, and Germany aiming for net zero emissions by 2045 [10–12].

As Europe and the rest of the world transition towards a sustainable and carbon free society, the rapid implementation of emission reduction measures and intermittent renewable energy sources is becoming a considerable challenge across sectors [13–15]. For instance, the growing share of wind and solar generation in the energy sector is making the continuous process of balancing electricity supply with demand an increasingly difficult task, as 2.4 GW (75% increase) of new wind turbines were implemented in Finland in 2022 alone [15]. This is made even more challenging as new technologies, such as energy storage and power-to-x, are not yet adequately cost-effective to be widely implemented and solely provide sufficient flexibility to support variable renewable generation [16–18].

Furthermore, biomass has become an important part of national climate strategies as a means to achieve fast-approaching national emission reduction targets set for 2030 [19–21], as sustainable biomass is considered a renewable alternative to fossil fuels that can be utilized by many thermal power plants [22]. In 2019, biomass accounted for nearly 60% of all renewable energy in the EU, with consumption being especially high in northern and central Europe, where the forestry sector serves as the main source of biomass [21,22]. However, as the importance of utilizing forests for carbon sinks and storage grows [23,24], studies have shown that the sustainable procurement of biomass is becoming an increasing concern [25,26], which could become particularly problematic for countries overly relying on biomass in their climate strategies. For instance, prior research has highlighted how high biomass usage in the national carbon neutrality strategy of Finland could significantly reduce available carbon sinks in the land use, land use change, and forestry (LULUCF) sector [16], which plays a fundamental role in the country's plan to attain net zero emissions by 2035 [27,28].

On another front, the rapid increase in clean energy technologies is also increasing the demand for critical raw materials and other minerals at an unprecedented rate [17,18,29], with the IEA predicting the demand for lithium, cobalt, and rare earth elements (REEs) to increase by 42, 21, and 7 times by 2040, respectively, as well as lead to the demand for copper more than doubling during this time [18]. As these minerals are essential for the manufacturing of technologies such as wind turbines, solar photovoltaic (PV) systems, Li-ion batteries, electrolysers, and electricity networks [16,18], their resource adequacy and high import reliance on non-European countries is becoming an increasingly significant concern for many EU countries [29,30] which aim to extensively incorporate clean energy technologies in the coming years to attain climate and energy policy goals. The importance of resource adequacy and energy security has also been emphasized by both recent conflicts in Europe and by the 2018 trade war between the US and China, both incidents that highlight the risks related to import reliance in energy policy and national climate strategies.

Although prior research has discussed the effectiveness and future implications of the EU's climate and energy policy [13,31–35], as well as highlighted several challenges related to biomass availability, renewable energy integration, and resource adequacy in the global transition towards clean energy production [25,36–39], few studies have yet reviewed the updated climate and energy policy of EU countries nor assessed potential risks and limitations in their implementation. Thus, this paper aims to identify and assess how exposed the national climate strategies of different countries are to potential technological risks and resource adequacy limitations in northern and central Europe. For this purpose, the climate strategies of five EU countries are investigated: Finland, Sweden, Denmark, Estonia, and Germany. These countries were selected as they are all subject to EU climate and energy policy, have similarities in their climate conditions, and diversely use different technologies in their energy mix. Yet, these countries also have significant differences in their energy system designs, energy consumption, and approaches to energy policy. Additionally, alternative methods to reduce carbon emissions and potentially mitigate the negative effects of various bottlenecks in the reviewed climate strategies are discussed.

2. Materials and Methods

In order to review, assess, and compare the climate and energy policies of different countries in northern Europe, this paper conducted a literature review and analysis of the official EU national energy and climate plans (NECPs) submitted by the five studied countries [7,12,40–42]. In the analysis, future climate and energy targets were compared between countries, as well as with historical data retrieved from European and national statistics agencies. Statistical data were primarily acquired from the European statistics agency Eurostat using the Energy Balance method [43], ensuring that the national statistics data utilized remained comparable between countries. However, as not all the needed data could be retried from the Eurostat platform, national statistics were also used to supplement these data where needed [44–51]. In this work, statistical data were mainly analysed between 2010 and the latest year available, which typically was 2021 or 2022 for the assessed countries and datasets. Historical carbon sink data were utilized to analyse biomass availability in the selected countries and were downloaded from the United Nations Framework Convention on Climate Change (UNFCCC) GHG Data Interface platform [52], with values reported from 1990 onwards.

Besides historical data, future estimates for the shares of wind, biomass, and solar PV in electricity generation for 2030 were calculated with values presented in the NECPs of the assessed countries. Notably, while the NECP reports of all EU countries outline how each country aims to implement over-arching EU decarbonization and renewable energy use targets, there are distinct differences in the reporting and available data of each county. Thus, sector-specific estimates for the share of biomass in primary energy consumption were calculated and converted to comparable values based on values given in the NECPs. Emission reduction targets for 2030 for each of the studied categories were also retrieved from the NECP reports of the assessed countries, apart from 2030 carbon removal targets for the LULUCF sector, which were directly acquired from recent EU regulation, statute 2018/841 on the inclusion of GHG emissions and removals from LULUCF in the 2030 climate and energy framework [53]. In order to give an overview of the current situation and the starting point for implementing newly set climate targets, Table 1 depicts the current final energy usage of each of the assessed countries. As some countries have also published supplementary studies or revised their climate goals since the publication of the NECPs, the analysis presented in this paper also utilized information found in later publications where available. Notably, the first versions of the NECPs were formulated in 2019 and do not reflect the substantial changes in energy supply brought on by the armed conflict in Ukraine, which has especially limited Russian energy imports to EU countries.

Table 1. Current final energy usage in the electricity, heating, and transportation sectors in northern European countries (year 2021 values in TWh unless otherwise stated). Total electricity consumption values from Eurostat [43], which may also include other generation sources.

Energy Demand (TWh)	Finland	Estonia	Germany	Sweden	Denmark
Source	**[46–48,54]**	**[55]**	**[51,56,57]**	**[50]**	**[58]**
Electricity				Year 2019	
Hydro	15.6	0.0	19.4	64.9	0.0
Wind	8.2	0.7	113.5	19.8	16.1
PV	0.3	0.4	48.5	0.7	1.3
Nuclear	22.6	0.0	65.4	64.3	0.0
Thermal, fossil	9.3	4.4	204.6	3.2	6.6
Thermal, biomass	13.3	1.9	46.6	12.5	6.8
Net imports	17.8	2.6	−28.1	−26.2	4.9
Total	82.1	7.88	499.7	124.5	32.1
Heating			Year 2019	Year 2019	
Heating, fossil	18.1	0.9	544.3	25.5	11.0
Heating, biomass	37.4	3.8	130.1	52.8	25.6
Heating, electricity and others	27.5	3.8	37.3	9.4	37.2
Transportation			Year 2019	Year 2019	
Transportation, fossil	38.6	9.1	711.7	64.0	47.7
Transportation, biofuels	7.9	0.7	31.1	17.0	3.0
Transportation, electricity	0.9	0.03	11.7	3.0	0.7

3. Review of Climate and Energy Policy

3.1. European Union (EU)

Since the Paris agreement was adopted in 2015, nearly all countries worldwide have agreed to hold the increase in global average temperature to well below 2.0 °C above pre-industrial levels, as well as to pursue efforts to limit this temperature increase to 1.5 °C [59]. Signatory parties in the Paris agreement also agreed to increase the degree of ambition in their nationally determined contributions (NDCs) every five years, setting the foundations for international climate policy for years to come. Aiming to be at the forefront of global climate action, the EU has accordingly committed to reaching carbon neutrality by 2050, including a target to reduce GHG emissions by 55% by 2030 compared to 1990 levels [9].

By means of the European Green Deal announced in 2019 [60], the REPowerEU legislation proposal in 2022 [61], and the Fit for 55 package published in 2023 [19], the EU has recently introduced numerous regulatory changes aimed at reducing GHG emissions in all key sectors across member states. Most notably, the EU is aiming to increase the share of renewable energy in total energy consumption to 42.5% by 2030 [20], mainly through a rapid expansion of wind and solar PV generation. Simultaneously, the EU emission trading system (ETS) is being expanded to additional sectors in the coming years [19,62], seeking to reduce fossil fuel dependence and incentivize investments into renewable energy technologies. Moreover, biomass, nuclear power, and natural gas have all been recognized as environmentally sustainable activities in EU regulation under certain conditions [63,64], further increasing the amount of options member states have to implement adequate emission reduction measures to meet climate targets. As part of the Fit for 55 package, the EU is also aiming to improve energy efficiency across all member states, including a target of reducing final energy consumption by 11.7% in 2030 at the EU level. Several other new policies have also been introduced, attempting to improve energy performance in buildings, gradually decarbonize transportation fuels, align energy taxation with the EU's climate policy, and accelerate the integration of hydrogen to reduce the high dependence on natural gas in much of Europe [19]. Furthermore, the EU has also passed legislation to increase carbon emission removals in the LULUCF sector from 230 million tonnes of CO2eq in 2021 to 310 million tonnes of CO2eq by 2030 [23], which would significantly contribute to emission reduction targets in many EU countries. On the other hand, the EU is also currently taking action to increase and diversify its supply of critical raw materials, introducing new legislation to develop raw material extraction in Europe and reduce its import reliance on non-EU countries [65].

The implementation of EU climate and energy policy is ultimately the responsibility of the 27 EU member states, which in 2019 drafted and submitted their initial NECPs to the European Commission, with consecutive progress reports scheduled for every 2 years. The NECPs outline how individual EU countries intend to meet union-wide decarbonization and energy-use targets for 2030 and how these plans relate to and comply with the long-term climate strategy of each nation [6].

3.2. Finland

Finland has set 2035 as its target year for reaching carbon neutrality, including a sub-target of reducing GHG emissions (excluding the LULUCF sector) by 60% by 2030 [7,27]. The country is also aiming to increase the share of renewable energy in final energy consumption to at least 51% and in final energy consumption in road transport to 30% by 2030. In order to reach these targets, the Finnish energy sector is set to undergo considerable changes. Currently, the largest energy sources in electricity production are nuclear power and hydroelectric generation, followed by electricity imports [48]. However, wind power production in Finland is set to increase from 8.2 TWh to 23 TWh by 2030 [7,48], which will, in addition to the growth in solar PV generation, place intermittent renewable energy as one of the largest sources of electricity in the country. Nuclear generation has also been on the rise in Finland in the last decade, as a new nuclear power plant with a capacity of

1600 MW was commissioned in the country in 2023 [66], providing the energy sector with valuable base generation as it moves towards carbon neutrality.

Biomass is another substantial source of energy in Finland, with electricity generation and the heating sector consuming over 50 TWh of biomass annually, in addition to the 8 TWh share of biofuels in the transportation sector [46,47,54]. Overall biomass and biofuel usage is also expected to grow by 2030 [7], further increasing the significance of this renewable fuel in energy production. Notably, Finland imported a significant amount of electricity and biomass from Russia before 2022, which stopped entirely following the implementation of sanctions against the Russian federation [67]. Regardless of this interruption in energy supply, Finland has remained committed to its climate targets imposed in 2019 and even aims to become a net exporter of electricity by 2035.

Furthermore, in addition to the strong growth in renewable energy and continued reliance on biomass and nuclear energy in its energy mix, Finland is also planning to implement other changes in order to reach its emission reduction targets for 2030 and onwards. Most notably, the country aims to accelerate the progression towards electrification in the heating and transportation sectors, mainly through increased utilization of electric vehicles and heat pumps, which, in combination with energy efficiency improvements in the building stock and reduced fossil fuel usage, will lower overall heat consumption as well as help to achieve sought after emission reductions [7].

3.3. Estonia

According to its current climate strategy, Estonia is aiming to reach net zero emissions by 2050, including a sub-target of reducing GHG emissions by 70% by 2030 compared to 1990 emission levels [11]. The 2030 emission reduction measures involve increasing the overall share of renewable energy in the country to 42%, through a 40% share of renewable energy in electricity generation, 63% share in heating, and 14% share in transportation. This is estimated to be achieved by increasing wind and solar power capacity from 300 MW to 1200 MW and 100 MW to 415 MW, respectively [11,55]. Notably, solar PV generation in Estonia has been increasing rapidly since the publication of the NECP in 2019, and already exceeded its 2030 targets for solar PV electricity generation in 2021.

Nevertheless, Estonia still heavily relies on fossil fuels in its energy supply, especially in electricity generation and in the transportation sector [55]. Biomass usage is also comparatively high, having a large presence in all sectors. Thus, the 2019 NECP of Estonia outlines how the increase in renewable capacity will reduce biomass usage in electricity generation in the country by 2030, and how biomass will instead be used to displace fossil fuels in the heating sector [11]. In contrast to many other EU countries, biofuel usage is expected to decrease in Estonia by 2030, with the country focusing on the electrification of the transportation sector instead. Besides these measures, overall heat demand is also expected to decrease in Estonia, as the EU directive on energy efficiency attempts to lower overall energy consumption across the union [11].

3.4. Germany

In 2021, Germany announced that it would update its carbon neutrality target to 2045 (initially set to 2050), including revising its GHG emission reduction goal to 65% by 2030 (base level 1990) [8]. While revised sector-specific targets for emission reductions and renewable integration have yet to be announced, the German NECP planned to achieve these goals by increasing the share of renewable energy to 30% in final energy consumption, 65% in electricity generation, and 27% in the heating and transportation sectors, respectively [12].

At present, Germany has already made significant progress towards increasing renewable energy production, with wind power being the second largest source of electricity in the nation at 114 TWh annually, trailing fossil fuel consumption in electricity generation at 205 TWh [57]. Solar PV generation also contributes a considerable amount at 49 TWh, producing close to the same amount of electricity as nuclear generation (65 TWh) and thermal power plants powered by biomass (47 TWh). In the heating and transportation sectors, fossil fuels still retain their position as the most common energy source with a large margin, followed by biomass and biofuel consumption at 130 TWh and 31 TWh, respectively.

Hence, in order to reach its climate targets, Germany is planning to continue its widespread deployment of renewable energy technologies, with wind and solar power production expected to nearly double by 2030 [12]. Simultaneously, the country has finished the shutdown of nuclear power plants in 2023 following changes in policy and public opinion [68], whereas hydroelectric generation is expected to remain at a similar level. Although biomass dependence is already relatively high in the country, Germany is also planning to double the use of biomass in electricity generation, as well as pursue a huge increase in heating production using biomass. In the transportation sector, biofuel consumption is estimated to remain steady in the coming years, as Germany is planning a large-scale electrification of its vehicle fleet. Recent geopolitical events have also affected energy supply in Germany significantly, with electricity and natural gas prices rising and becoming increasingly volatile. This has led the German government to adjust its energy strategy by seeking alternatives to Russian natural gas, including the construction of new liquid natural gas (LNG) terminals and measures to accelerate the development of hydrogen infrastructure and alternative fuels [69].

3.5. Sweden

Sweden aims to cut its GHG emissions to zero by 2045, and then to achieve negative emissions [10]. This includes a 63% reduction in emission from sectors outside the EU ETS by 2030, as well as a target to reduce emissions by 70% in the transportation sector. As shown in Table 1, hydroelectric and nuclear power generation were the main sources of electricity in Sweden when the initial NECP was published in 2019, while biomass and fossil fuels had large shares in the final energy consumption of both the heating and transportation sectors [50].

While nuclear generation has been in a steady decline in Sweden over the last decades, the new elected government of Sweden has recently introduced plans to again develop and increase nuclear generation in the country, listing it as an option alongside renewable energy sources as a means to achieve national climate targets [70]. Currently, nuclear power generates between 45–50 TWh/a of electric energy in Sweden, which is close to 30% of the total generated electric energy, down from approximately 40% of electricity in the 2010s [50]. Nevertheless, according to the current climate strategy for 2030, Sweden is mainly focusing on renewable integration in order to reduce carbon emissions, planning to realize a more than threefold increase in wind power production and a sixfold increase in solar PV generation, while maintaining its remaining nuclear and hydroelectric capacity [42,50]. Biomass usage is also expected to slightly increase in electricity and heat production, while biofuel production is expected to double. Furthermore, the country is attempting to accelerate the electrification of both the heating and transportation sectors, expecting a large increase in heat pumps and electric vehicles.

3.6. Denmark

As outlined in the NECP of Denmark, this Nordic country has set its goal for reaching net zero emissions to 2050 at the latest, including a legally binding target to reduce greenhouse gases by 70% by 2030 (compared to 1990) [40,71]. In comparison to the other countries in this assessment, Denmark has set one of the highest emission reduction targets for 2030, but without yet setting an expedited goal for reaching carbon neutrality. Markedly, this could change in the coming years, as the current 2050 carbon neutrality goal is set in the Danish climate law, last amended in 2021 [72]. Looking at the current state of the Danish energy sector, wind power is already the main source of electricity in the country, generating around 16 TWh annually [58]. The heating sector is also largely based on renewable energy, with a large share of electric heating followed by biomass. However, the transportation sector still heavily relies on fossil fuels, with minor shares of biofuels and electric vehicles.

Thus, in order to reduce its climate goals for 2030, Denmark is planning further large investments into renewable electricity generation, mainly through a threefold increase in wind capacity and a tenfold increase in installed solar PV capacity [71]. This would enable the country to reduce biomass usage in electricity generation, and instead use more biomass for heat production, leading to an overall reduction in fossil fuel usage in these sectors. Simultaneously, additional emission reductions are expected to be achieved through further electrification of both the heating and transportation sectors, mainly by increased heat pump usage and electric vehicle integration.

4. Results

This chapter analyses and discusses the decarbonization strategies of northern European countries and presents a comparison of the energy use and ongoing integration of renewable energy technologies in Finland, Estonia, Germany, Sweden, and Denmark until 2030. Section 1 of this chapter analyses the development and the role of wind power, solar PV, and hydropower generation in the climate and energy policy of these countries, as several clean energy technologies have been shown to rely heavily on limited critical raw materials with potential supply bottlenecks in their procurement. Most notably, intermittent renewable energy generation and various energy storage technologies are crucially dependent on scarce minerals in their manufacture, while much of the supply chain of these technologies—from raw material extraction and processing to component production and assembly—is also highly concentrated in individual countries outside the EU [18]. Section 2 extends the analysis to renewable fuel usage and carbon sink development in the assessed countries, especially as biomass has been shown to be an important but limited resource for both energy production and industry. The main source of biomass in the EU—forestry—is also facing new limitations, as novel EU legislation aims to increase carbon emissions removal in the LULUCF sector [23], with forests becoming valuable carbon sinks substantially contributing to national emission reduction targets in northern Europe. Lastly, Section 3 of this chapter discusses potential technical, economic, and legislative risks and limitations related to nuclear energy in the climate strategies of northern European countries, as some of the assessed countries aim to increase their nuclear generation capacity in the near future.

4.1. Analysis and Comparison of Wind, Solar PV, and Hydropower Development in the Selected Countries

Although many countries already utilize renewable energy technologies to some extent, the complete decarbonization of society is estimated to require a far deeper integration of clean energy production over the coming decades. This can be seen in Figure 1a–c, which present the annual wind power, solar PV, and hydropower electricity production in Finland, Estonia, Germany, Sweden, and Denmark from 2010 until the present day, as well as a linear projection (the dashed lines) between current production values and 2030 NECP targets, illustrating how renewable energy use is expected to change in each country in the near future. Figure 1a shows how the annual wind power production of all northern European countries is expected to grow considerably over the next few years, with many countries aiming to more than double their current wind power capacity by 2030. At the forefront, Germany aims to increase its annual wind power production by nearly 100 TWh/a by 2030, followed by Sweden at around 43 TWh/a and Denmark at around 30 TWh/a. A similar trend can be seen in Figure 1b, which illustrates the planned growth in solar PV generation in the assessed countries compared to historical PV generation statistics over the last few years. As can be seen, the annual solar PV production of Germany and Denmark is expected to increase by over 44 and 14 TWh/a, respectively, equivalent to a 191% increase in solar in Germany between 2021 and 2030 and a 571% in solar in Denmark between 2022 and 2030. Furthermore, Figure 1c depicts how the annual hydropower production in the assessed countries is expected to continue at current levels until 2030, with most of the past variation stemming from annually changing weather conditions and not changes in generation capacity. Even though few changes are expected in hydropower generation in the near future, Figure 1c emphasizes how hydropower is a very important energy source in many northern European countries, with Sweden, Finland, and Germany producing around 100 TWh of electricity using hydropower every year, but also how other countries, such as Denmark and Estonia, have little to no access to domestic hydropower production.

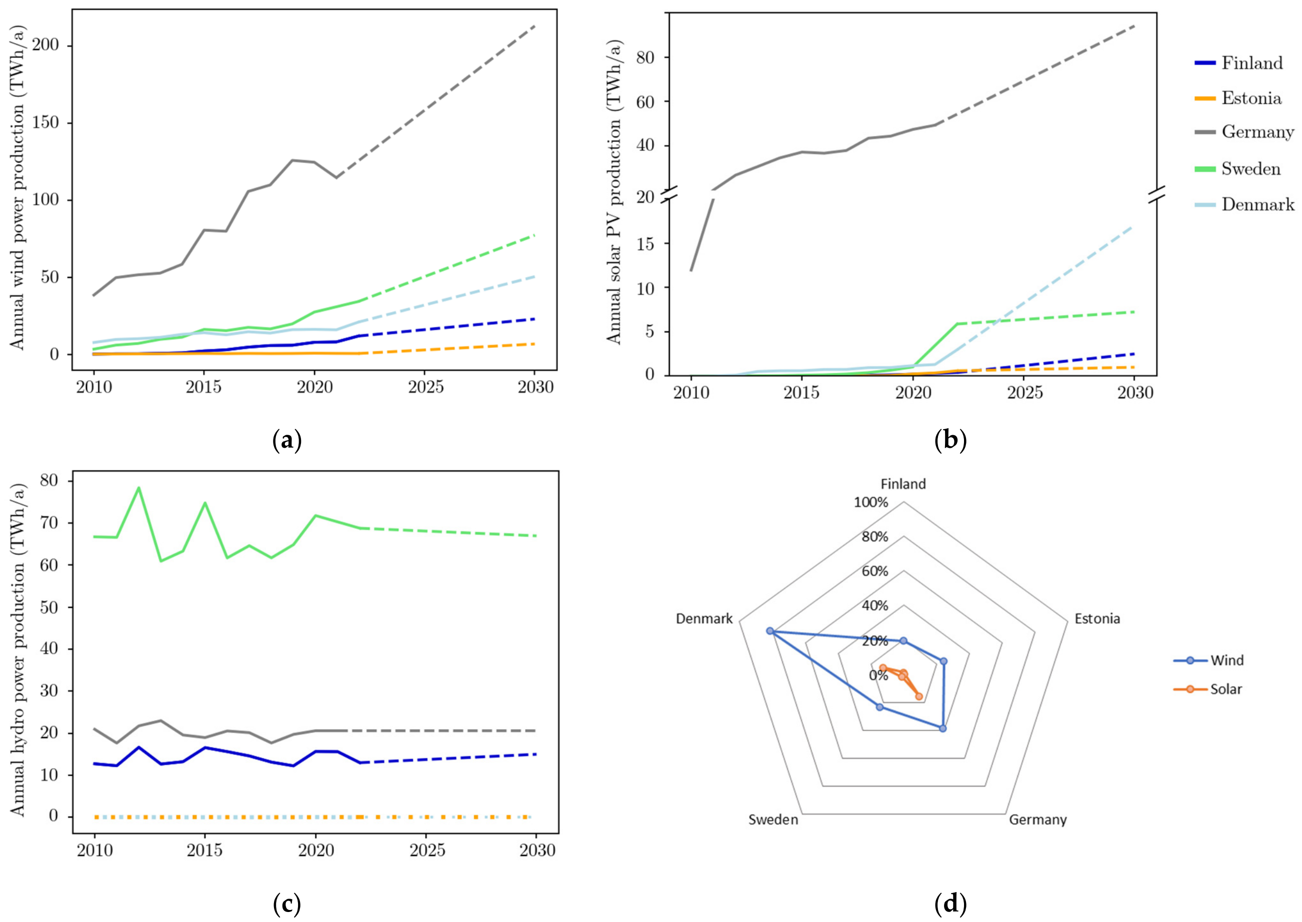


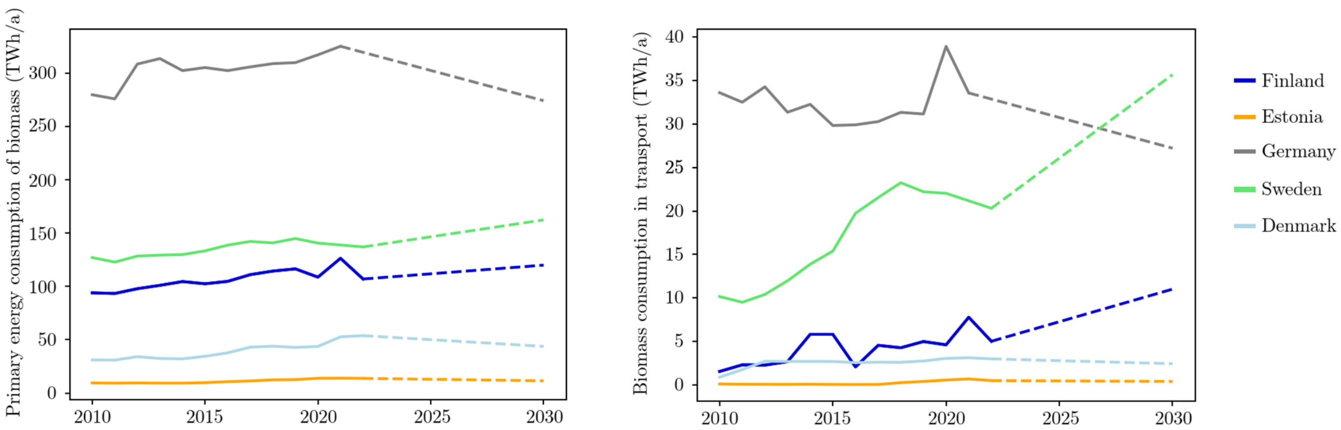
Figure 1. Historical values and NECP targets for annual (**a**) wind power, (**b**) solar PV, and (**c**) hydropower production in the selected countries, as well as (**d**) the projected share of renewable electricity in gross electricity consumption for 2030 in these countries.

Furthermore, Figure 1d illustrates the degree of reliance on wind and solar PV generation in the implementation of national climate strategies in northern Europe. As can be observed from the figure, wind power is projected to have an over 20% share in gross electricity consumption by 2030 in all countries, whereas solar PV is expected to only constitute a few percent of the total electricity demand in most countries. Figure 1d also shows how Denmark and Germany have especially high shares of intermittent renewable energy generation in their projected gross electricity consumption, with Denmark planning to utilize wind power to meet 81% of its electricity demand, followed by solar PV at a 13% share. Germany also expects wind power production to have 39% in gross electricity consumption, accompanied by a 16% share of solar PV generation, depicting how Denmark and Germany plan to rely especially on a successful expansion of wind and solar PV generation capacity to meet the emission reduction targets outlined in their national climate strategies.

4.2. Analysis and Comparison of Biomass Usage and LULUCF-Sector Carbon Removal Development in the Selected Countries

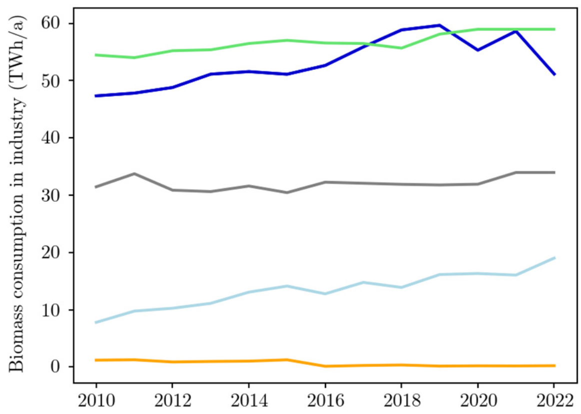
Biomass is another renewable resource with a central role in most national climate strategies in northern and central Europe. This can be observed in Figure 2, which presents the annual biomass consumption of Finland, Estonia, Germany, Sweden, and Denmark between 2010 and the present day, as well as a linear projection (the dashed lines) between current consumption values and 2030 NECP targets, illustrating how the demand for biomass is expected to change in each country in the near future. As illustrated in Figure 2a, the primary energy consumption of biomass has slowly increased over the last decade throughout northern Europe and is expected to remain at a high level in the coming years. In Finland and Sweden, total biomass consumption is expected to slightly grow by 2030, as both of these countries seek to utilize more biofuels in the transport sector to reduce GHG emissions, as can be observed from Figure 2b. In Finland, biomass consumption in transport is expected to grow from 5 TWh/a to 11 TWh/a, with Sweden planning to increase the use of biomass in the transport sector from 20 TWh/a to 35 TWh/a. On the contrary, transport-related biomass consumption in Germany is instead set to decrease from 33 to 27 TWh/a between 2020 and 2030, as the NECP of Germany outlines EVs as the primary approach to reducing transport-related emissions. Figure 2a also shows how, out of the assessed countries, Estonia and Denmark have, comparably, the lowest annual total biomass consumption, as Estonia primarily only uses biomass for heat production, and Denmark has to import most of its biomass from other countries.

Additionally, Figure 2c also illustrates how biomass is an important resource in industrial applications in many northern European countries, even though targets for biomass consumption in industry are not included in NECPs. As can be seen in Figure 2c, industrial biomass consumption has gradually increased in the selected countries since 2010, with industrial biomass demand in Denmark increasing the most in the last decade, up from 8 TWh/a in 2010 to 19 TWh/a in 2022. Notably, industrial biomass demand in Finland has fluctuated notably between 47 and 60 TWh/a in recent years due to two main factors: several factory shutdowns in the pulp and paper industry after 2018 [73] and a sharp increase in biomass prices following the cessation of biomass imports from Russia to Finland in 2022 [27]. Nevertheless, as new pulp and paper mill projects have recently been announced in Finland [74,75], industrial biomass consumption in northern Europe is likely to remain at a high level or increase in the foreseeable future.

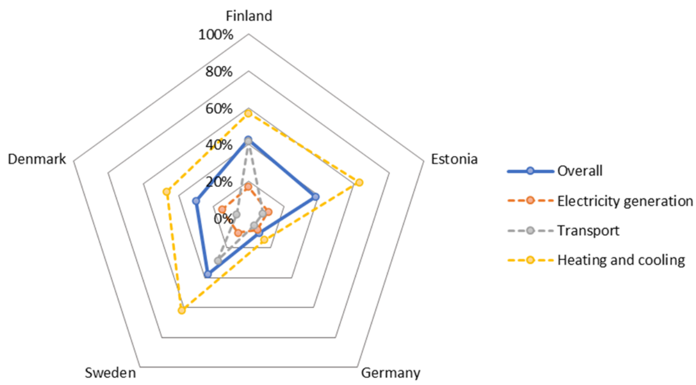


(**a**) (**b**)

Figure 2. *Cont.*



(**c**)



(**d**)

Figure 2. Historical values and NECP targets for (**a**) annual primary energy consumption of biomass, (**b**) annual final biomass consumption in transport, and (**c**) annual final biomass consumption in industry in the selected countries, as well as (**d**) the projected share of biomass in primary energy consumption for 2030 in these countries.

Lastly, Figure 2d presents the projected share of biomass in primary energy consumption of the selected countries, showing how overall biomass dependency in the energy sector varies between 10% (Germany) and 43% (Finland) in northern Europe. Notably, biomass is especially important in the heating and cooling sector in all of the assessed countries expect Germany, with biomass covering around 60% of the heating demand in Finland, Estonia, and Sweden. While biomass in Germany is currently set to have a lower share in primary energy consumption in comparison to other countries, this could also change if Germany attempts to reduce its natural gas dependence in the heating sector in the coming years, especially as the current NECP of Germany is from 2019 and does not account for energy sector changes following the war in Ukraine.

The comparison presented Figure 3 depicts the historical development of GHG emission from the LULUCF sector in the assessed countries, as well as a linear projection (the dashed lines) between current emission levels and legally binding EU emission removal targets for the LULUCF sector by 2030, illustrating how recently passed EU legislation aimed at increasing emission removals in the LULUCF sector could pose a significant challenge for forestry and biomass availability in Europe. As can be observed, GHG emissions in the LULUCF sector have been steadily increasing over the last decade, with the LULUCF sector recently becoming a net source of emissions instead of a carbon sink in most of the assessed countries. In Finland, LULUCF-sector GHG emissions have continuously increased from −38 MT CO_2-eq/a in 2009 to +1 MT CO_2-eq/a in 2021, and in Germany from–17 MT CO_2-eq/a in 2011 to +4 MT CO_2-eq/a in 2020, with LULUCF-sector GHG emissions also gradually increasing in the other assessed countries over the last decade, though to a lesser degree. The figure also shows how most countries in northern Europe will have to significantly increase emission removals in the LULUCF sector already by 2030. In Finland, LULUCF-sector emissions will have to decrease from 1 to −18 MT CO_2-eq/a by 2030; in Germany, from 4 MT CO_2-eq/a in 2020 to - −31 MT CO_2-eq/a in 2030; and Sweden and Estonia will also be required to reduce their total LULUCF-sector emissions by around 5 MT- CO_2-eq/a by 2030.

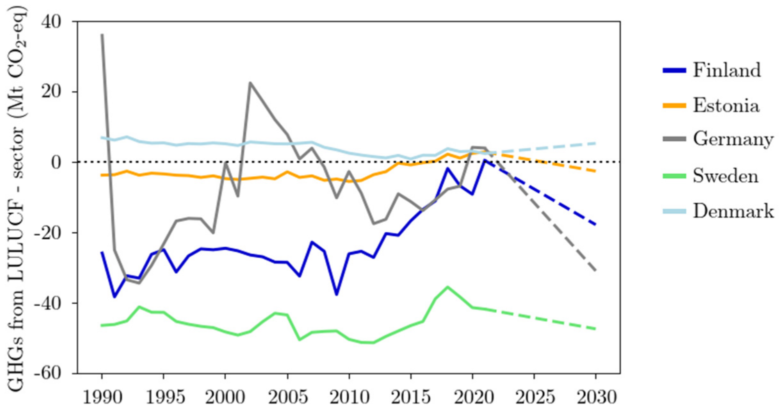


Figure 3. Historical values and EU regulation targets for GHG emissions from the LULUCF sector in northern European countries.

4.3. Analysis and Comparison of Nuclear Power Generation in the Selected Countries

Nuclear energy has been listed as another alternative clean energy source in recent EU legislation and is set to play a central role in the future energy mix of several EU countries. In northern Europe, Finland, Sweden, and Estonia have recently shown increased interest in nuclear power, whereas Germany and Denmark have excluded nuclear generation from their climate and energy policy. Out of the assessed countries, Finland is the only country that has expanded its nuclear generation capacity in recent years, with nuclear power reaching a close to 40% share in total electricity generation in 2023 following the commissioning of a new 1.6 GW nuclear power plant (Olkiluoto 3) in the country [48,66]. In Sweden, nuclear power also has an important role in electricity generation, producing approximately 30% of the electricity in Sweden in 2022, despite a gradual decline in nuclear power generation over the past decades in the country [50]. Notably, the use of nuclear power could soon grow in Sweden, as the current government has overturned nuclear energy policy in the country and announced plans to strongly expand nuclear power generation in the near future [70]. Likewise, Estonia is also currently considering introducing nuclear power to diversify its energy mix for the next decade, as the country aims to phase out domestic shale oil in electricity production by 2035 [76]. In contrast, Germany decided to completely phase out nuclear power after a shift in political opinion following the 2011 Fukushima nuclear disaster in Japan, with the last operating nuclear power plant being decommissioned in 2023 [68], despite nuclear power historically having a large role in electricity generation in the country. Similarly, Denmark has also ruled against the use of nuclear power production through a resolution in 1985 [77], with little prospect of this nuclear policy in the country being reversed anytime soon.

5. Discussion

The rapid expansion of wind and solar generation capacity illustrated in Figure 1 depicts how northern European countries depend heavily on wind power to attain 2030 renewable energy and climate targets, with Germany and Denmark planning to expand renewable generation particularly quickly over the next few years. As both wind and solar PV technologies rely on limited critical raw materials in their production, potential bottlenecks and restrictions in the supply and import of raw materials could thus significantly delay or hinder the implementation of current climate strategies in northern Europe, both for 2030 and for moving towards carbon neutrality. The national climate strategies of Denmark and Germany were also observed to be especially susceptible to these risks, as alternative generation methods, such as hydroelectric and nuclear power production, are not used in these countries.

The analysis presented in Figure 1d also emphasizes the growing reliance on weather-dependent and unpredictable electricity generation in northern Europe. Most notably, load balancing will become increasingly difficult in the coming years as we increase the share of intermittent renewable energy in our energy supply. As such, the results of this paper emphasize how the demand for cost-effective load balancing technologies is growing, with dispatchable generation using thermal power plants complementing the gradual implementation of balancing technologies, such as demand response, energy storages, and power-to-x conversion. However, as the most common battery storage and electrolyser technologies are also dependent on critical raw materials in their manufacturing, potential bottlenecks and resource constraints similar to wind power could also greatly affect the successful wide-scale implementation of balancing technologies after 2030, as these technologies are not yet present in most climate strategies. Notably, while measures to guarantee uninterrupted electricity generation and balance the increasing share of intermittent renewable energy in energy systems have been addressed on a conceptual level in many climate strategies, the need for load-balancing technologies has not yet been quantified in most countries NECP reports.

Furthermore, Figure 2 highlights how Finland, Estonia, Sweden, and Denmark will all rely on biomass to achieve the emission reduction targets set in their national climate strategies. As most of the biomass used in Europe is currently sourced through forestry, increasing carbon removals in the LULUCF sector could considerably restrict the supply of biomass in energy production, industry, and transport. Although other sources for biomass do exist, such as agricultural products and municipal waste, increasing biomass production from these sources is challenging as dedicating crops to energy production instead has a negative effect on food security, whereas the availability of municipal waste is limited by the population of a region. Although there has also been development towards other sources of biomass, including 3rd-generation biofuels from algae, these fuels are not yet widely available, and their production is frequently subject to both economic and functional difficulties. Thus, the past trends and future LULUCF-sector GHG emission reduction targets suggest that Finland, Germany, and Sweden especially will have to take significant measures to increase forestry carbon sinks in the near future in order to attain the national emission reduction targets in the LULUCF sector for 2030, which will be a considerable challenge to overcome with the existing measures. In the short term, subsequent limitations to biomass availability are also likely to make the gradual phase-out of fossil fuels more challenging, potentially leading to unanticipated emissions and delays in reaching the overall emission reduction goals set in the national climate and energy policies.

Although none of the assessed countries have yet stated intentions to increase nuclear generation in their NECPs for 2030, potential risks and limitations related to the European nuclear power industry could also become an increasingly relevant factor as EU countries aim to achieve carbon neutrality in the coming decades. While resource constraints rarely affect nuclear power production in Europe—due to the global supply of nuclear fuel being relatively diversified across several countries and the construction of nuclear power plants mainly requiring large amounts of commonly used structural materials—recent nuclear power plant projects in the EU have instead been limited by major delays and high costs. For instance, the Olkiluoto 3 plant in Finland was delayed by 14 years and significantly exceeded the budget [77]. One reason behind these problems is that the majority of European nuclear power plants were built several decades ago, with new nuclear power plants in EU countries being planned and constructed one by one. This is in contrast to the nuclear power industry in China, where multiple standardized power plants are built at once [77]. This increases the planning and construction times as well as the overall costs of European nuclear power plant projects.

Another risk which could limit or delay the construction of new nuclear power generation capacity in Europe is the out-of-date legislation and long licensing and application times of new nuclear power plant facilities. For instance, in Finland, new nuclear power plants must obtain explicit approval from the Finnish government before construction can begin [78], a process which, combined with a meticulous application process and detailed environmental assessments, can take several years. This could become especially challenging for the incorporation of nuclear small modular reactor (SMR) technology in northern

European countries over the next decades, as nuclear SMR technology aims to bring smaller, standardized, and modular nuclear reactors to the market much more rapidly and cost-effectively than conventional nuclear power plants [79], and nuclear regulation in most EU countries has not yet adapted to SMR technology. Nevertheless, new legislation in some countries could ease SMR licensing already during this decade, as, for instance, in Finland, the current government plan is to have new nuclear licensing legislation implemented by 2026 [80].

Lastly, there are also country-specific risks and limitations relevant to nuclear power utilization in northern Europe. Notably, the majority of nuclear power plants in Sweden are owned by the fully state-owned energy company Vattenfall [77], which makes nuclear energy generation in Sweden more susceptible to political changes in comparison to privately owned facilities, as the elected government has direct influence over the operation and construction of nuclear power plants. Likewise, plans to utilize nuclear power to decarbonize electricity generation in Estonia could face limitations or delays due to a lack of existing regulation and nuclear power infrastructure, as no nuclear power plants yet exist in the country. Thus, Sections 4 and 5 in this paper suggests that potential limitations related to nuclear power generation could also delay or hinder the implementation of long-term national climate strategies in northern European countries, in case that nuclear electricity generation capacity is expanded to meet future national climate and energy goals.

6. Conclusions

The main conclusions of this paper can be summarised as follows:

- Denmark and Germany rely heavily on wind and solar power in their NECPs for 2030, which exposes these countries to potential risks related to raw material availability. Denmark plans to meet 81% and 13% of total electricity demand with wind and solar energy in 2030, and Germany with 39% and 16% wind and solar, respectively. These high targets for solar and wind energy are partly due to the lower biomass resource availability and negative political attitude towards nuclear power.
- LULUCF-sector emission reduction targets and projected biomass usage have a significant disparity in northern European countries, especially in Finland and Germany. This means that the continued biomass usage threatens the achievement of the national climate strategies, and attention by policymakers is urgently needed.
- Although nuclear energy has recently been listed as an environmentally sustainable activity under certain conditions in EU legislation, nuclear energy is likely unable to further contribute to 2030 emission reduction targets in northern Europe due to the long deployment times and political uncertainty.
- The existing measures in NECPs do not adequately address resource adequacy risks, nor incorporate separate LULUCF-sector emission reduction targets, although previous studies and reports have highlighted resource adequacy as a strategic priority in climate and energy policy.
- Additional research is needed on the impact of raw material usage on the implementation of national climate strategies and the effects of LULUCF-sector carbon sinks on biomass availability in northern Europe. More detailed modelling work is also needed to quantify the amount of flexibility needed to support the rapidly growing share of intermittent renewable energy outlined in national climate strategies.

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Abbreviations

ETS	Emission trading system
EU	European Union
GHG	Greenhouse gas
LNG	Liquid natural gas
LULUCF	Land use, land use change, and forestry
NDC	Nationally determined contribution
NECP	National energy and climate plan
PV	Photovoltaic
REE	Rare earth element
SMR	Small modular reactor
UNFCCC	United Nations framework convention on climate change

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