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Possible bottlenecks in clean energy transitions: Overview and modelled effects – Case Finland

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ABSTRACT

Limiting the negative effects of human-induced global warming is the focus of climate policy worldwide. In the European Union (EU), the target for reaching carbon neutrality is set to 2050, including a proposed renewable energy target of 45% for 2030. In Finland, the government has pledged to reach net-zero emissions already by 2035, which is expected to require large increases in wind and nuclear capacity, as well as sector coupling with, e.g., transport and heating. In view of these plans, this study evaluates the feasibility of attaining carbon neutrality in Finland by 2035, while considering delays from potential bottlenecks, such as limited raw material availability, fuel availability, manufacturing capacity, and import reliance. The literature review highlights the considerable dependence of renewable technologies on critical raw materials and other minerals, largely imported from non-EU countries. Modelling revealed how increased biomass usage considerably reduces the size of national carbon sinks, vital for reaching net-zero emissions in Finland in the coming decade. In light of this, current climate strategy was shown to be partially outdated and short of reaching carbon neutrality by 2035, already without including potential delays from the analyzed bottlenecks. Subsequently, alternative measures to improve sustainability and reduce emissions are presented. The findings of this paper are also relevant for other countries aiming to reach net-zero emissions, especially for those which have climate strategies emphasizing bioenergy and wind power.

1. Introduction

The negative effects of global warming accelerates the need for new and more ambitious climate targets. For instance, the European commission published its REPowerEU Plan in 2022, proposing to raise the renewable energy target of the European Union (EU) to 45% by 2030 (European Commisssion, 2022), putting the EU one step closer to becoming carbon neutral by 2050. More ambitiously, the government of Finland pledged already in 2019 to become fully carbon neutral by 2035 (Ministry of the Environment of Finland, 2020; Government of Finland, 2019), a target which was passed into national climate legislation in 2022 (Finlex, 2022a). To achieve this goal, Finland has planned to reduce its carbon emissions in all primary sectors, while increasing renewable electricity generation considerably in the coming years (Koljonen et al., 2022). These changes, combined with efforts to compensate any gross greenhouse gas (GHG) emissions through carbon sequestration, are thought to be sufficient to reach net zero emissions in Finland by 2035 (Ministry of the Environment of Finland, 2020; Koljonen et al., 2022; Lehtilä et al., 2021).

The upcoming changes to the Finnish energy system are profound. The Government strategy work estimates overall power generation in Finland to increase from 66 TWh/a in 2019 to 110 TWh/a by 2035 (Koljonen et al., 2022), which would shift Finland from a major net importer to a net exporter of electricity by 2035. Simultaneously, the total consumption of fossil fuels in power generation (incl. peat) would shrink from 12 TWh/a to only 1 TWh/a, while total renewable electricity production would increase from 31 TWh/a to 66 TWh/a. As a part of the planned energy transition, nuclear power generation is also expected to almost double from 23 TWh/a to 43 TWh/a (Koljonen et al., 2022), heavily relying on the addition of two new nuclear power plants, Olkiluoto 3 and Hanhikivi. While the 1.6 GW Olkiluoto 3 plant is scheduled to begin commercial operation in March 2023 (YLE, 2022a), the construction of the 1.2 GW Hanhikivi plant with Rosatom has been cancelled in May 2022 (Government of Finland, 2022), which makes reaching carbon neutrality a more challenging task than initially planned.

Increasing renewable capacity also poses fundamental challenges for

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Nomenclature

Abbreviations

CAES	Compressed air energy storage
CCS	Carbon capture and storage
CCUS	Carbon capture, utilization and storage
CHP	Combined heat and power
CRM	Critical raw material
DH	District heating
E-fuels	Electrofuels
EU	European Union
EV	Electric vehicle
FC	Fuel cell
GHG	Greenhouse gas
ICV	Internal combustion vehicle
IEA	International energy agency
LULUCF	Land-use, land-use change and forestry
LIB	Lithium-ion battery
NG	Natural gas
PGM	Platinum group metal
PV	Solar Photovoltaics
P2X	Power-to-X
REE	Rare earth element
SMR	Small Modular Reactor
TES	Thermal energy storage

Symbols

Al	Aluminum
Ag	Silver
Co	Cobalt
CO_2	Carbon dioxide
Cr	Chromium
Cu	Copper
In	Indium
Li	Lithium
Mn	Manganese
Mo	Molybdenum
Ni	Nickel
Te	Tellurium
Zn	Zink

Units

TWh/a	Terawatt-hours per year, unit of power
GWh	Gigawatt-hour, unit of energy
Mt	Megaton, unit of mass
Mt CO_2	Megatons of carbon dioxide
CO_2-eq	Carbon dioxide equivalent

the Finnish energy sector and electricity transmission system. Large shares of intermittent wind and solar PV generation necessitates energy storage or supply and demand flexibility to be effective, which is currently challenging as these technologies and systems are not yet in widespread use or even always cost-effective (Lehtilä et al., 2021; Koivunen et al., 2022). Simultaneously, recent geopolitical events in Europe have shown how national energy security and self-sufficiency is a vital national concern, which cannot be solved by renewables alone. As various bottlenecks, such as limitations in raw material availability, manufacturing capacity and import reliance can severely delay or hinder the implementation of many renewable energy technologies, systematic risk assessment and contingency preparation is of high importance, emphasizing the relevance and need for further research on this topic.

Past research has modelled pathways to Finnish carbon neutrality using various optimization tools (Koljonen et al., 2022; Lehtilä et al., 2021; Ministry of the Environment Finland, 2022). However, even at international level, it is rare that studies would include assessments on the impact of potential bottlenecks in modelled energy system scenarios towards carbon neutrality. In its 2021 report on the role of critical minerals in clean energy transitions (IEA, 2021), the International Energy Agency (IEA) emphasized how growth in renewable energy technologies will exponentially increase demand for critical raw materials (CRMs) in the coming decade, while also highlighting supply chain risks following a concentrated global supply of raw materials. Other studies, such as a recent report by the European Commission, support the findings of the IEA by showing the importance of CRMs in several strategic technologies as well as in the energy sector (Bobba et al., 2020; Carrara et al., 2020).

Consequently, this paper aims to identify the most significant bottlenecks and challenges that may hinder or delay the planned energy transition to a carbon neutral Finland by 2035. Based on these outcomes, this study aims to present alternative approaches to achieve carbon neutrality. As many countries plan to rely largely on similar technology combinations towards net zero carbon emissions, this study has wide relevance. The structure of this paper is as follows: Chapter 2 assesses various bottlenecks relevant for energy-sector technologies. Chapter 3 outlines the materials and methods used in this paper. Chapter 4 presents the modelling results, and Chapter 5 presents the conclusions of this study.

2. Review of bottlenecks and constraints

This chapter identifies potential bottlenecks that may hinder the planned energy transition in Finland. These bottlenecks include limitations to raw materials and fuel availability, manufacturing capacity, permitting, licensing, technological maturity, geography, and risks associated with import reliance. Notably, bottlenecks are also analyzed for a few technologies with no large-scale use as of yet, in order to assess alternative approaches for reaching carbon neutrality in Finland.

2.1. Raw material constraints

Many renewable energy technologies, including solar photovoltaics (PV), wind turbines, battery storage, and electric vehicles (EV) require substantial quantities of CRMs and other minerals to be manufactured. Most notably, these materials include lithium, cobalt, nickel, rare earth elements (REEs), platinum group metals (PGMs), chromium, zinc, copper, and aluminum (IEA, 2021; Bobba et al., 2020). As demand for many of these raw materials is predicted to increase significantly in the coming decade (IEA, 2021), sufficient mineral excavation, processing and recycling can become a serious bottleneck in the transition towards renewable energy sources.

The IEA identified in its 2021 report on the role of CRMs in clean energy transitions (IEA, 2021), that current mineral supply and investment plans fall short of what is needed to transform the energy sector. The report detailed how the consumption of many CRMs and vital minerals is predicted to skyrocket in the coming decades, with for example lithium demand predicted to increase by 42 times before 2040 to satisfy the EV and energy storage markets (IEA, 2021). Likewise, the demand for other vital minerals such as cobalt, nickel and REE is predicted to increase by 21, 19 and 7 times, respectively, by 2040. Based on this analysis, there is a high risk that raw material extraction and mineral processing becomes a limiting factor for many renewable technologies, as declining resource quality, long development lead times, high geographical concentration and water scarcity threaten the reliability of mineral extraction.

Hence, this paper identifies and assesses the importance of critical minerals used in energy-sector technologies, using the IEA report on the role of critical minerals in clean energy transitions from 2021 as a starting point (IEA, 2021). The minerals that were identified as particularly important in this assessment were Aluminium (Al), Copper (Cu), Nickel (Ni), Zink (Zn), Lithium (Li), Cobalt (Co), Chromium (Cr), Silver (Ag), Indium (In), Tellurium (Te), Manganese (Mn), Molybdenum (Mo), REEs, and PGMs. Notably, several other materials are used in the manufacture of energy-related technologies (European Commission, 2020a), but were not assessed in this study. Out of the identified minerals, Li, Co, In, REEs and PGMs were classified as CRMs by the European Commission in 2020 (European Commission, 2020b).

Table 1 shows the analysis on important minerals for energy sector technologies, including power and heat production, energy storage, and transportation. In the table, the relative importance of minerals used to manufacture energy-related technologies is indicated with different shading based on the following factors: global supply risk, European domestic supply, a criticality factor, import reliance, substitution, and recycling possibility of each technology, as presented in a foresight study on CRMs by the IEA in 2020 (IEA, 2021). In the table, data from other studies is harmonized and presented using the same format as in the IEA report (IEA, 2021; Bobba et al., 2020; Carrara et al., 2020; European Commission, 2020a; The World Bank, 2017; Grandell et al., 2016). In this analysis, some assumptions were made based on similarities in the material use between technologies. For instance, the mineral usage of thermal energy storage (TES), in this case sensible heat storage, was assessed to match that of geothermal heat production, as both technologies utilize heat pumps. Similarly, important minerals needed for the manufacture of fuel cells (FC), used in both H_2 vehicles and H_2 storage were considered equal, as were the raw materials needed for the turbines used in wind power and compressed air storage (CAES). Lastly, the CRMs needed for combustion, including the incineration of biomass, coal, and waste, were considered equivalent.

As can be observed in the table, the production of several technologies, such as Li-ion batteries (LIB) and H_2 storage, is very raw-material intensive, making the wide-scale implementation of these technologies difficult and expensive. Especially REEs, which have been identified as a group of very critical materials in prior research (IEA, 2021), are needed to manufacture several renewable technologies, including turbines for both wind power and CAES, as well as electrolysers and FCs for H_2 and Power-to-X (P2X) technologies. Additionally, nearly all of the evaluated technologies are dependent on widely used minerals such as copper and aluminum in their production, which could significantly increase the economic cost and viability of these technologies in the future. While many of the analyzed technologies also require substantial amounts of structural materials like concrete, steel, glass and polymers in their manufacture or construction, these materials were not considered as bottlenecks in this study, as they are used in large quantities in various sectors worldwide.

2.2. Fuel availability

In addition to raw materials, many technologies used in power and heat production, transportation, and industry require a variety of fuels to operate. Most commonly, these include fossil fuels, such as coal, natural gas (NG) and oil, which are used in power plants to produce heat and power, or in internal combustion vehicles (ICVs) for mobility. However, the availability of fuels can also be subject to bottlenecks, especially as geopolitical events have adjusted fossil fuel supply chains, and new low-carbon fuel alternatives are still under development. Table 2 shows an assessment on potential bottlenecks limiting the availability of fuels for power production, heat production and transportation.

As can be observed in Table 2, this paper considers there to be no critical bottlenecks in the supply of fossil fuels and uranium needed for electricity production, heat production, and transportation purposes, as the supply of these fuels is backed up by well-developed supply chains and there are sufficient reserves to meet demand in the foreseeable future (World Nuclear Association, 2022a; International Energy Agency (IEA), 2022; Shafiee and Topal, 2009). However, the availability of renewable fuels, such as biomass, waste, and electrofuels (E-fuels) are subject to various challenges in their production and acquisition (Ministry of Agriculture and Forestry, 2022; Koivunen et al., 2020).

Biomass, especially wood-derived products, is in high demand in many sectors, including construction, industry, and combined heat and power (CHP) production in Finland (Ministry of Agriculture and Forestry, 2022). Furthermore, logging could face restrictions, as forests function as a carbon sink and storage and can be used to negate greenhouse gas (GHG) emissions elsewhere. For instance, high felling volumes and slowed tree growth in 2021 caused the annual emissions

Table 1
Identified minerals with high importance for power and heat production, energy storage, transportation, and industrial applications.

Minerals with high importance for energy-sector technologies	Al	Cu	Ni	Zn	Cr	Ag	Mn	Mo	Te	In	Li	Co	REE	PGM
Power and heat production														
Solar PV (IEA, 2021; Bobba et al., 2020; Carrara et al., 2020; European Commission, 2020a; The World Bank, 2017; Grandell et al., 2016)	++	++	0	0	0	++	0	+	+	+	0	0	0	0
Wind (IEA, 2021; Bobba et al., 2020; The World Bank, 2017)	+	++	+	++	+	0	+	+	0	0	0	+	++	0
Nuclear (IEA, 2021; The World Bank, 2017)	0	+	+	0	+	+	0	+	0	+	0	0	0	0
Hydroelectric (IEA, 2021)	+	+	0	+	+	0	0	0	0	0	0	0	0	0
Combustion (IEA, 2021)	+	++	0	+	0	0	0	0	0	0	0	0	0	0
Geothermal (IEA, 2021)	+	++	0	+	0	0	0	0	0	0	0	0	0	0
Import/export (IEA, 2021; Grandell et al., 2016)	++	++	0	0	0	++	0	0	0	0	0	0	0	0
Energy storage														
LIB storage (IEA, 2021; Bobba et al., 2020; European Commission, 2020a)	++	++	++	0	0	0	0	0	0	0	++	++	++	0
H_2 storage/P2X (IEA, 2021; Bobba et al., 2020)	+	0	++	0	+	0	0	0	0	0	+	+	+	++
TES (IEA, 2021)	+	++	0	+	0	0	0	0	0	0	0	0	0	0
CAES (IEA, 2021; Bobba et al., 2020; The World Bank, 2017)	+	++	+	++	+	0	+	+	0	0	0	0	++	0
Transportation and industry														
ICVs (IEA, 2021; Grandell et al., 2016)	+	++	0	+	0	+	0	0	0	0	0	0	0	0
H_2 vehicles (IEA, 2021; Bobba et al., 2020; Grandell et al., 2016)	+	0	++	0	0	+	0	0	0	0	0	0	+	++
EVs (IEA, 2021; Bobba et al., 2020; European Commission, 2020a; The World Bank, 2017)	++	++	++	0	0	+	0	0	0	0	++	++	++	0
CCUS (The World Bank, 2017)	+	+	+	0	+	0	+	+	0	+	0	+	0	0

Notes: Marking indicates the relative importance of minerals for specific technologies in the energy sector (++ = very important, + = significant, 0 = not important or required).

Table 2
Availability of fuels for power and heat production, energy storage, transportation, and industrial applications in Finland.

Availability of fuels in energy-sector applications	Coal	Oil	NG	Peat	Biomass	Waste	Uranium	Electrofuels
Nuclear (World Nuclear Association, 2022a; International Energy Agency (IEA), 2022)	0	0	0	0	0	0	+	0
Combustion (International Energy Agency (IEA), 2022; Shafiee and Topal, 2009; Ministry of Agriculture and Forestry, 2022)	+	+	+	+	–	–	0	0
CAES (Aghahosseini and Breyer, 2018)	0	0	–	0	–	0	0	0
ICVs (International Energy Agency (IEA), 2022; Shafiee and Topal, 2009; Ministry of Agriculture and Forestry, 2022)	0	–	0	0	–	0	0	–
Gas vehicles (International Energy Agency (IEA), 2022; Shafiee and Topal, 2009)	0	0	–	0	0	0	0	0

Notes: Marking indicates limited availability of fuels for specific technologies in the energy sector.
(– = very limited, - = limited, + = available, 0 = not applicable).

from the land-use, land-use change and forestry (LULUCF) sector in Finland to change from a net carbon sink to a net emission source for the first time in recent history (Ministry of the Environment of Finland, 2022; YLE, 2022b). As Finland counts on the LULUCF sector to negate CO_2 emissions by 27 Mt annually to reach carbon neutrality in 2035 (Ministry of the Environment of Finland, 2022; YLE, 2022b), biomass availability could become the most important bottleneck limiting the Finnish energy transition (Koivunen et al., 2022).

The amount of available waste for energy utilization can be considered another bottleneck, as the scale of waste energy production is mainly determined by the waste output of different municipalities and is not expected to increase significantly in Finland in the coming years (Bröckl et al., 2021a). Comparably, the supply of E-fuels, which are carbon-based fuels produced from renewable hydrogen, will take time to develop as new supply chains and manufacturing facilities do not yet exist (Bobba et al., 2020). Thus, E-fuels were classified as a moderate bottleneck in this paper.

2.3. Manufacturing, permitting and licensing limitations

The planned transition away from fossil in Finland by 2035 will require the construction of thousands of new wind turbines, as well as considerable investments into electricity transmission capacity in the coming decade (Koljonen et al., 2022; Fingrid, 2022a). In turn, this will increase the demand for industrial capacity, funding, and human capital to be implemented, all assets which take time to acquire. As the majority of new renewable energy generation projects in Finland and Europe are funded by private investments, with varying levels of government support and involvement, increasing the capacity of renewables in time to meet ambitious climate targets can be expected to be a difficult and capital-intensive process (Wind Europe, 2020, 2022; Statistics Finland, 2022).

In order to analyze potential bottlenecks related to manufacturing, permitting and licensing, this paper estimated the total and annual capacity increase of energy-related technologies between 2019 and 2035 (Koljonen et al., 2022; Lehtilä et al., 2021; Official Statistics of Finland, 2023). The estimates were calculated based on the governmental climate strategy report (HIISI), using the WAM-H scenario with ambitious additional measures for the energy sector. Accordingly, Table 3 presents an overview of the energy sector in 2019 and as estimated for 2035 in Finland, followed by the total and annual increase in energy and fuel usage, energy storage capacity, and key transportation and industry technologies.

Table 3 highlights how the usage of nuclear, wind, and solar electricity generation is set to increase considerably between 2019 and 2035, whereas the use of coal, oil and import of electricity is expected to decrease. Oil will be completely phased out from energy production in Finland before 2035, with its only remaining use in industrial applications, such as iron and steel production. The increase in carbon free power generation is set to offset the reduction in fossil fuel usage and simultaneously push Finland to become a net exporter of electricity. Remaining emissions will be compensated through increased forest carbon sinks and storage (Koljonen et al., 2022).

Table 3
Overview of the use of key technologies in the energy sector in 2019 and as estimated for 2035, with the total and annual increase in capacity calculated for each technology between these years.

	Usage in 2019	Usage in 2035[a]	Total increase	Annual increase
Energy & fuel usage	*(TWh/a)*	*(TWh/a)*	*(%)*	*(%)*
Coal and peat	41.1	10.4	−75%	−8.23%
Oil	79.3	42.7	−46%	−3.80%
Natural gas	20.3	20.5	1%	0.06%
Nuclear	69.4	126.1	82%	3.80%
Biomass (incl. biofuels)	123.5	128.7	4%	0.26%
Wind	6.0	30.7	412%	10.74%
Solar PV	0.1[b]	3.4	2213%	21.69%
Hydroelectric	12.2	14.4	18%	1.04%
Electricity import	20	−6.7	−134%	-n/a-
Other fuels	5.7	0	−100%	-n/a-
Energy storage	*(GWh)*	*(GWh)*	*(%)*	*(%)*
LIB storage	0[c]	0	0%	0%
H2 storage	0	0	0%	0%
TES	22	22	0%	0%
CAES	0	0	0%	0%
Transportation	*(TWh/a)*	*(TWh)*	*(%)*	*(%)*
Electric vehicles	0.1	5.7	5600%	28.75%
H_2 vehicles	0	0	0%	0%
Gas vehicles (ICV)	0.2	3.5	1650%	19.15%
Carbon capture	(Mt CO_2/a)	(Mt CO_2/a)	*(%)*	*(%)*
CCS (LULUCF)	13.6	15.4	13%	0.96%
CCUS	0	0	0%	0%

[a] Estimated based on the HIISI WAM-H scenario.
[b] Annual Solar PV production was 147 GWh in 2019.
[c] Around 50 MW of LIB battery projects exist in Finland, of which 30 MW was commissioned in 2020. These LIB systems are mainly used for grid services in reserve markets, and not for large scale energy storage operations. Upcoming projects would increase this capacity to over 110 MW (Fingrid, 2021).

This transition of the energy sector will require the construction of multiple new wind power parks and additional nuclear capacity. Large scale projects such as these are susceptible to delays and potential bottlenecks in manufacturing, licensing and permitting, as they require sizable funding and resources to be realized. For instance, the construction process of a wind turbine includes detailed planning, an investment decision, permits and licensing, manufacturing, installation, and testing before being fully operational, which on average takes 4–6 years in Finland (Chang et al., 2021; Finnish Wind Power Association, 2022a). These long construction times could alone be enough to delay Finland from installing enough wind power capacity to reach its climate targets for 2035. This could also be one reason behind why the EU-27 block only installed 17 GW of new wind energy capacity in 2021, i.e., less than half what is required to meet current EU climate and energy goals for 2030 (Wind Europe, 2022). Another concern when installing additional wind power capacity is guaranteeing sufficient grid transmission capacity in time, which otherwise can delay the connection of new wind turbines to the power grid by several years (YLE, 2022c). Nevertheless, as a considerable expansion in the amount of wind turbines is already ongoing in Finland, major setbacks from manufacturing, licensing and permitting can be expected to be infrequent (Finnish Wind Power Association, 2022b, 2022c).

Likewise, the construction of new nuclear power plants also takes considerable amounts of time. Section 4 of the nuclear energy law in Finland dictates that the government and parliament of Finland need to agree on the construction of a new nuclear power plant (Finlex, 2022b), a process which can take several years. This combined with unforeseen problems in construction and testing can further postpone the operation of new nuclear power plants. For instance, the Olkiluoto 3 nuclear power plant in Finland was initially scheduled to begin operation in 2009 and was still not fully operational in 2022 after a 13-year delay (YLE, 2022d), whereas the construction of another new nuclear power plant in Hanhikivi, initially to be supplied by Rosatom, was ended in May 2022 (Government of Finland, 2022). However, as new nuclear small-modular reactors (SMR) are under active development (International Atomic Energy Agency (IAEA), 2020), nuclear construction times can be expected to shorten in the coming decade.

2.4. Technological maturity, geographical limits and import reliance

In addition to raw material, fuel, and manufacturing constraints, some energy sector technologies are also limited in their technological maturity, geographical location and from risks related to import reliance. Table 4 shows an overview of these potential bottlenecks.

As shown in Table 4, most of the technologies used for power and heat production are technologically mature and already in commercial use worldwide. However, development towards some technologies, such as nuclear small modular reactors and deep geothermal energy extraction is still ongoing, with no widespread commercial use (International Atomic Energy Agency (IAEA), 2020; Kukkonen and Pentti, 2021). The state of technological development towards energy storage systems is more widespread, with Li-ion battery systems already in use in several sectors and profitable in ancillary electricity markets, while many other technologies, such as hydrogen storage, P2X and CAES still in active development and only utilized to a limited extent (Chehade et al., 2019; Budt et al., 2016). Likewise, some of the new low-carbon technologies developed for transportation and industry, mainly E-fuels, 3rd and 4th generation biofuels, hydrogen vehicles, and CCUS, have not seen widespread use as of yet (Malico et al., 2019; Alalwan et al., 2019; Kumar et al., 2020; Ababneh and Hameed, 2022; Ajanovic and Haas, 2021; Chen et al., 2022).

Table 4
Bottlenecks in technological maturity, geographical location and import reliance for specific technologies.

Technological maturity and geographical limitations			Import reliance				
	Technical maturity	Geographical limitations	Raw materials	Processed materials	Components	Assemblies	Fuels
Power and heat production							
Solar PV (Bobba et al., 2020; The World Bank, 2020; Ritchie, 2022)	0	+	+	+	++	+	0
Wind (Bobba et al., 2020; Ritchie, 2022; Díaz and Guedes Soares, 2020; European Environment Agency, 2009)	0	+	++	+	+	0	0
Nuclear (Statistics Finland, 2022; International Atomic Energy Agency (IAEA), 2020; World Nuclear Association, 2022b; World Nuclear Association, 2022c)	+	0	0	0	0	0	+
Hydroelectric (Ritchie, 2022; Motiva, 2021; Ministry of Agriculture and Forestry of Finland, 2022)	0	++	0	0	0	0	0
Biomass (Ministry of Agriculture and Forestry, 2022; Malico et al., 2019; Fortum, 2022; Helen, 2022a; YLE, 2022e)	0	0	0	0	0	0	+
Waste (Bröckl et al., 2021b)	0	0	0	0	0	0	0
Geothermal (Kukkonen and Pentti, 2021)	+	+	0	0	0	0	0
Natural gas (Statistics Finland, 2022; Eurostat, 2022)	0	0	0	0	0	0	++
Oil (Statistics Finland, 2022; Eurostat, 2022)	0	0	0	0	0	0	++
Peat (Statistics Finland, 2022)	0	0	0	0	0	0	0
Coal (Statistics Finland, 2022; Eurostat, 2022)	0	0	0	0	0	0	++
Electricity import (Grandell et al., 2016; Fingrid, 2022a; Agency for the Cooperation of Energy Regulators (ACER), 2015)	0	+	+	0	0	0	+[a]
Energy storage							
LIB storage (Bobba et al., 2020; Dehghani-Sanij et al., 2019)	0	0	++	++	+	++	0
H_2 storage/P2X (Bobba et al., 2020; Chehade et al., 2019)	+	0	++	0	0	++	0
TES[b] (Sarbu and Sebarchievici, 2018; International Renewable Energy Agency (IRENA), 2013)	0	+	0	0	0	0	0
CAES (Bobba et al., 2020; Aghahosseini and Breyer, 2018; Chehade et al., 2019; Budt et al., 2016)	++	+	++	+	+	0	0
Transportation and industry							
Fossil fuels (Statistics Finland, 2022; Eurostat, 2022)	0	0	0	0	0	0	++
Biofuels (Malico et al., 2019; Alalwan et al., 2019; Kumar et al., 2020)	+	0	0	0	0	0	0
Electrofuels (Ababneh and Hameed, 2022)	++	0	++	0	0	0	0
EVs (Bobba et al., 2020)	0	0	++	++	++	+	0
H_2 vehicles (Bobba et al., 2020; Ajanovic and Haas, 2021)	+	0	++	++	++	++	0
CCS (LULUCF) (Ministry of Agriculture and Forestry, 2022; Ministry of the Environment of Finland, 2022; National Board of Forests Metsähallitus, 2018)	0	+	0	0	0	0	0
CCUS (Bobba et al., 2020; Chen et al., 2022; Hansen et al., 2019)	++	0	+	0	0	0	0

Notes: Marking indicates how limited energy-sector technologies are by technological maturity and geography, as well as the level of import reliance of select technologies (++ = high, + = moderate, 0 = low or not applicable).

[a] Import reliance of electricity.

[b] Sensible heat storage.

In contrast, several renewable energy technologies are limited by their need for a specific location or geographical aspects (Ritchie, 2022). Hydropower expansion is subject to a variety of regulatory and environmental concerns, which makes finding locations for the construction of new large hydropower plants unlikely in Finland (Motiva, 2021; Ministry of Agriculture and Forestry of Finland, 2022). Similarly, solar PV electricity generation is limited by the available solar irradiation in a given location (The World Bank, 2020), making geography a limiting factor for effectively increasing solar PV capacity especially in Nordic climates. Moreover, both offshore and onshore wind power turbines are limited by their access to suitable construction locations, as many factors, such as land use, visual pollution, water depth, and distance to major population centers limit the number of credible construction locations (Ritchie, 2022; Díaz and Guedes Soares, 2020; European Environment Agency, 2009).

Thermal power plants, such as fossil, biomass, and nuclear, generally use very little land per unit of produced electricity and are thus more flexible in terms of location (Ritchie, 2022). However, technologies such as geothermal energy, TES, and CAES can often require specific geological attributes to be feasible or effective. For instance, the efficiency of boreholes used for geothermal energy extraction or for TES largely depends on soil and rock compositions (Sarbu and Sebarchievici, 2018; International Renewable Energy Agency (IRENA), 2013), whereas large scale CAES requires either caverns, old mine shafts or gas fields to be implemented (Aghahosseini and Breyer, 2018; Budt et al., 2016). Moreover, increasing land-use, land-use change and forestry (LULUCF) carbon sinks to offset national CO_2 emissions can compete with and impede biomass utilization (Ministry of Agriculture and Forestry, 2022; Ministry of the Environment of Finland, 2022; National Board of Forests Metsähallitus, 2018). Also, building new transmission lines is typically both costly and time-consuming (Fingrid, 2022a; Agency for the Cooperation of Energy Regulators (ACER), 2015).

As globalization has increased the interdependence of the world's economies significantly in the last decade (Ortiz-Ospina and Beltekian, 2018), the importance of ensuring a reliable supply of essential products, raw materials and energy has grown. Hence, Table 4 also illustrates the import reliance of specific technologies and highlights the dependence of Finland on non-EU countries for raw materials, processed materials, components, assemblies, and fuels. For instance, the manufacture of Solar PV systems is highly concentrated in China, with 89% of solar PV components and 70% of solar PV assemblies located in the country (Bobba et al., 2020). Similarly, the supply chain for wind turbines is largely located outside Europe, with China having the largest global market share in the production of raw materials, processed materials, and component manufacturing (Bobba et al., 2020).

LIB storage is another technology that is highly reliant on imports from non-EU countries, with China retaining a leading market share in all manufacturing phases of LIB systems, as 32% of raw materials, 52% of processed materials and components, and 66% of assemblies are located in China (Bobba et al., 2020). Likewise, many other energy storage and P2X technologies are also highly import reliant, as 48% of raw materials used in FCs are extracted in Africa, and component manufacture and assemblies largely concentrated outside Europe (Bobba et al., 2020). The high import reliance of LIB and FC supply chains also affect the transportation sector, as these technologies are needed in the manufacturing of electric, hydrogen, and hybrid vehicles (Bobba et al., 2020). However, sensible TES, utilizing either water tanks, boreholes or caverns in combination with heat pump systems, are not particularly reliant on imports (Sarbu and Sebarchievici, 2018; International Renewable Energy Agency (IRENA), 2013).

Furthermore, Finland is also reliant on the import of fuels. In 2021, 2.4 million tons of coal, 13.8 million tons of oil and petroleum products, and 2500 million m^3 of NG were imported from Russia, Norway, and Sweden, resulting in Finland having an estimated 42% energy dependence on other nations (Statistics Finland, 2022; Eurostat, 2022). While biomass and biofuels are typically produced domestically from forest industry and waste, Finland has still partly relied on biomass imports from Russia in the past (Statistics Finland, 2022; Fortum, 2022; Helen, 2022a; YLE, 2022e). Lastly, this paper found no evidence that facilities producing power and heat from fossil fuels, biomass, or waste would be noticeably reliant on imports, as these facilities rely on well-developed technologies manufactured worldwide. Similarly, even though the construction of nuclear power plants and nuclear fuel has been largely attained from outside of Finland from countries such as, France, Russia and Canada (Statistics Finland, 2022; World Nuclear Association, 2022b, 2022c), nuclear power plant development is diversified worldwide and not excessively reliant on imports from a single nation.

3. Materials and methods

3.1. Modelling approach

In order to analyze the feasibility and resilience of a carbon-neutral Finnish energy sector in 2035, this paper models the impact of the possible bottlenecks on the Finnish energy sector using the energy system analysis tool EnergyPLAN (Lund et al., 2021). The software allows for holistic energy system modelling, including simulation of power and heat production while considering energy use in industry and transportation and it has been widely used to analyze the energy systems of many countries (Østergaard, 2015). The main schematic of the EnergyPLAN model is presented in Fig. 1.

Previous studies made with EnergyPLAN on the Finnish energy system have analyzed 100% RES scenarios for 2050, the maximum amount of wind power in the Finnish system and electricity sufficiency during winter peaks (Child and Breyer, 2016; Zakeri et al., 2015; Jaaskelainen et al., 2017). However, none of the existing studies consider the impacts of resource constraints, even though they may seriously hinder achieving the targets. As changes in biomass usage can extensively impact the magnitude of LULUCF-sector carbon sinks, this paper presents the novel approach of combining dynamic carbon sink modelling with energy systems modelling by calculating the relationship between biomass usage and carbon sink volume in Finland. Biomass combustion characteristics, carbon tree content, biomass content, and optimal harvest times were identified as the most important factors determining the biomass output of forests in these calculations. The employed parameters included a pareto-optimal harvesting time of 70 years, corresponding to a forest carbon sink of 314 tonCO_2/ha annually. As Finnish boreal forests aged between 30 and 130 years have been estimated to contain around 70–200 tons of biomass per hectare (Liu, 2009), the 70-year harvesting time, modelled with a clear-cut approach, would with linear correlation result in a biomass content of 120 ton/ha. With the energy content of wooden biomass being approximately 19 MJ/kg (Clarke and Preto, 2011), this paper estimated the carbon sink potential of Finnish forests to be 0.5 Mt-CO_2/TWh of harvested biomass. The clear cut-model is further elaborated in Appendix I (Lehtonen et al., 2004; Ekholm, 2020).

3.2. Material and data

This paper applied the governmental HIISI WAM-H scenario with ambitious additional measures as the base scenario for 2035 (Koljonen et al., 2022). The values for electricity production, individual heating and transportation were calibrated between the EnergyPLAN model and the HIISI report, with remaining unavailable data estimated by the authors. The background modelling for the National climate strategy was performed with the TIMES model for Finland (Koljonen et al., 2022). For comparison, historical data for 2019 was used to validate the modelling (Official Statistics of Finland, 2023; Koivunen et al., 2023; Official Statistics of Finland, 2022). Indirect emissions and emissions caused by agriculture and waste management were not considered in detail in the modelling and is reflected in the total CO_2 - emissions allowed in the base scenario for 2035.

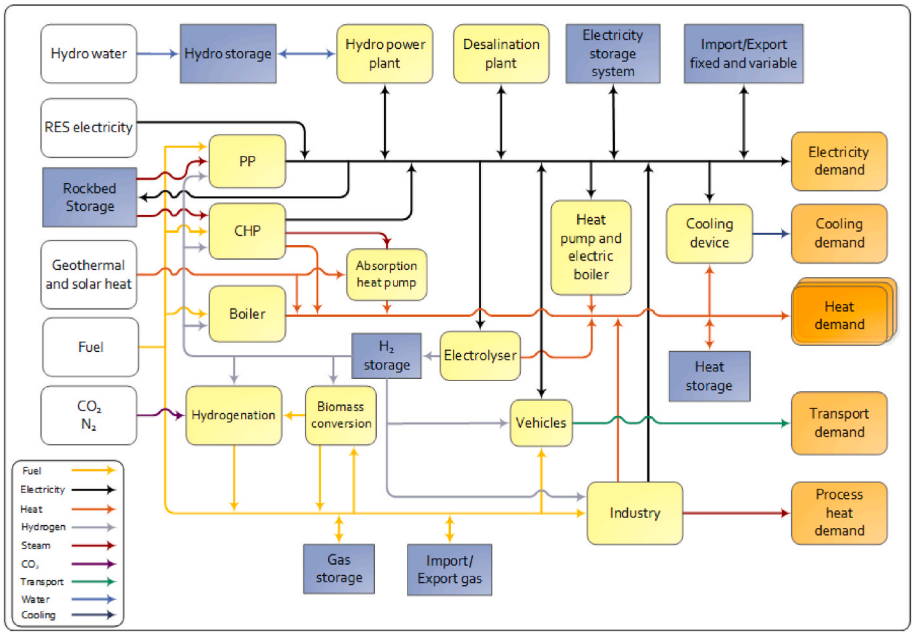

Fig. 1. Schematic and main operation of the EnergyPLAN energy system analysis tool (v16.1–15.07.2021).

In addition to source data derived for the HIISI report, this paper utilized historical hourly energy production and consumption data from 2019, originally downloaded from the Finnish TSO's open data service (Fingrid, 2022b). These datasets included electricity consumption data for Finland, hourly wind power generation data, hourly solar power generation forecasts, industrial cogeneration data, real-time hydro power production data, real-time nuclear power production data, as well as real time data showing the net import and export of electricity, as summarized in Appendix II. In addition, DH distribution profiles were acquired from the open data service of Helsinki region energy company Helen Oy (Helen, 2022b).

Furthermore, the heat demand, base electricity demand, industrial demand and transport total mileage were assumed the same in each scenario, and they were based on detailed bottom-up estimates of expected energy efficiency and other policy measures. Any missing data for specific hours was linearly interpolated in the model, whereas all additional dataset values were presented in an hourly resolution.

3.3. Modelled scenarios

In addition to the 2035 base scenario, and the 2019 reference scenario, this paper modelled the impact of the identified bottlenecks on the transition towards a carbon neutral energy sector by 2035 using four different scenarios. Scenario 1 (S1) and Scenario 2 (S2) focus on bottlenecks in fuel, raw material, and import availability, whereas Scenario 3 (S3) and Scenario 4 (S4) showcase how the energy sector could develop with realistic expectations or with even stricter climate policies. In S1, S2 and S4 it was assumed nuclear capacity would not be reduced from the base scenario, as nuclear SMR could replace lost capacity from the planned Hanhikivi nuclear power plant by 2035. Table 5 presents the most significant differences between the 2035 base scenario and each modelled scenario, with detailed values shown in Appendix III.

3.3.1. Scenario 1: Limited biomass

The first scenario modelled how limitations to biomass and biofuel usage could impact the Finnish energy sector in 2035. For instance, stricter national targets for reducing CO_2 emissions could lead to larger forest areas being preserved for carbon capture and storage, decreasing the available biomass for power and heat production, and industry. In addition, bottlenecks in biofuel availability could arise, as stagnant growth in both agricultural output and waste recovery limits biofuel production, while a higher demand for low-carbon fuels in the transportation sector increases demand.

In this scenario, total biomass usage was limited by 43% annually by reducing biomass usage in CHP plants and individual heating, while maintaining the industrial usage of biomass. Subsequently, the use of

Table 5
The modelled scenarios and their most significant differences compared to the base model of 2035.

	S1: Limited biomass	S2: Limited raw materials and imports	S3: Realistic expectations	S4: Stricter climate targets
Power and heat production	- 0.7 TWh (21%) more solar PV - 12.6 TWh (41%) more wind - 10.3 TWh electric DH added	- 2.4 TWh (−71%) less solar PV - 14.8 TWh (−48%) less wind	- 0.7 TWh (−21%) less Solar PV - 4.1 TWh (−13%) less wind - 10.1 TWh (−23%) less nuclear	- 7.1 TWh electric DH added - 2.9 TWh (−74%) less NG in power and heat production
Fuel use	- 19.8 TWh (97%) more NG - 56 TWh (−43%) less biomass - No biofuels	- 3.9 TWh (−19%) less NG - 30 TWh (23%) more biomass - 19.6 TWh (233%) more biofuels		- 10.3 TWh (−50%) less NG - 7.5 TWh of green hydrogen - 5 TWh (−32%) less oil in transport
Other changes	- 1.5 TWh (26%) more EVs - 27.7 MtCO2/a (176%) larger carbon sink - 100 GWh LIB storage added	- 4.5 TWh (−79%) less EVs - 14.5 $MtCO_2$/a (−92%) smaller carbon sink		- 100 GWh H_2 storage added

heat pumps and direct electric heating, both in individual and DH production was increased, accelerating the electrification of the heating sector. Simultaneously, biofuels were removed from the transportation sector and replaced by higher EV usage. NG was used to replace lost biomass in DH production. Furthermore, renewable energy capacity was increased significantly to avoid additional gross emissions. In addition, a 100 GWh electricity storage with a 2000 MW charge and discharge capacity was added.

3.3.2. Scenario 2: Limited raw materials and imports

The second scenario modelled how raw material, supply chain and import reliance bottlenecks could affect the energy sector. As renewable energy technologies require several important minerals and CRMs in their manufacture, high raw material demand combined with challenges in mineral extraction, processing and import could substantially limit the manufacture of technologies such as solar PV systems, wind turbines, and LIB storage. Additionally, international conflicts or regulation changes could lead to similar outcomes, especially considering how easily global supply chains can be disrupted and how reliant energy-related technologies are on imports from non-EU nations for their manufacture.

In this scenario, the expected wind and solar power capacity was reduced by 48% and 71% respectively. Expected growth in EV capacity was reduced by 79% compared to the base scenario, and then substituted with biofuels. Additionally, fossil fuel usage and imports were limited, with the exception of 8 TWh/a of domestic peat production, which was utilized to replace other fossil fuels in DH and CHP production.

3.3.3. Scenario 3: Realistic expectations

The third scenario attempted to model transition towards carbon neutrality in Finland with more realistic expectations, while holistically considering the risks and challenges posed by various bottlenecks to the energy transition. This included plausible constraints to the increase of nuclear capacity in Finland, combined with slightly lower expectations for additional capacity from upcoming wind and solar PV projects for 2035. This scenario utilized multiple technologies in varying degrees, attempting to illustrate how our future energy mix will likely be a combination of several technologies (Kyriakopoulos et al., 2022). Furthermore, this scenario attempted to critically evaluate whether reaching carbon neutrality in Finland by 2035 is credible with existing measures and the current climate strategy.

Accordingly, this scenario assumed that a nuclear power plant will neither be constructed in Hanhikivi by 2035, nor replaced by e.g., a nuclear SMR project elsewhere, which would reduce available nuclear capacity in Finland by 1200 MW. Annually, this would lower nuclear electricity production by 10.1 TWh/a. Moreover, as wind and solar PV deployment could be delayed due to various constraints, their capacities would be decreased by 15% and 20% respectively compared to the base scenario.

3.3.4. Scenario 4: Stricter emission targets

The fourth scenario assessed the effects of even stricter climate targets on the energy sector, with the main goal of attaining true carbon neutrality by or even before 2035. Stricter carbon neutrality targets could become a reality in Finland in the coming years, as the ambition mechanism in the Paris agreement requires each participating nation to increase the ambition of their climate targets every 5 years. In the Government HIISI WAM-h base scenario, it is also stated that an emission gap of 4.2 Mt-CO_2 would remain in 2035, preventing the base scenario from being fully carbon neutral. Thus, S4 also attempted to investigate what measures could be taken to negate this emission gap completely and achieve emissions reductions of at least 5 Mt-CO2 in 2035 compared to the base scenario. No changes were done to the renewable power capacity in this scenario.

To further reduce emissions in S4, 5 TWh/a of industrial grey hydrogen was replaced with green hydrogen. This would allow NG consumption in industrial applications to be reduced by 7.4 TWh/a, however, necessitating the implementation of 814 MW of electrolyzers capacity.[2] This change alone would cut emissions by 1.5 Mt-CO_2 annually, assuming the consumption and production of hydrogen would be constant. Furthermore, 5 TWh/a of diesel in heavy vehicles was replaced with 2.5 TWh/a of hydrogen in the transportation sector, increasing overall electrolysis capacity from 814 to 1220 MW, cutting emissions by 1 Mt-CO_2. Another change was the addition of 2000 MW of electrical heating capacity in DH networks, lowering emissions by 1.6 Mt-CO_2, resulting in a 0.5 TWh/a and 2 TWh/a reduction in oil and NG use respectively. Additionally, 1 TWh/a of NG was removed from power production, further reducing emissions by 0.9 Mt-CO_2/a.

4. Results and discussion

This chapter presents and discusses the results of the modelling. Figs. 2–5 present detailed information about the energy sector for each of the modelled scenarios, as well as the statistics for 2019 and as estimated in the base scenario for 2035. The results include overall electricity generation and consumption in Fig. 2, heat production and heat demand in Fig. 3, primary fuel demand in Fig. 4, and annual emissions in Fig. 5. More detailed results are shown in Appendix III, in tables A-3 1–5.

The electricity production in Finland in 2019 was mainly based on nuclear, fossil, biomass, and hydroelectricity power generation, with a relatively low annual production of wind and solar electricity, as shown in Fig. 2. Additionally, as domestic power generation in Finland was not enough to meet demand, a large share of electricity was imported from both Sweden on Russia. As shown by the base scenario for 2035, Finland is becoming a net exporter of electricity in the coming decade, with large increases to nuclear power generation and renewable capacity. Subsequently, some level of curtailment will take place in 2035, as some excess renewable production cannot be utilized especially in springtime.

Fig. 2 also shows how restrictions to biomass usage in S1 would affect electricity production. As can be observed in the figure, a reduction in biomass usage would require a significant increase in renewable electricity generation in order to avoid an increase in fossil fuel consumption and gross emissions. Yet, a considerable increase in NG would be required for both base load and balancing renewables. Additionally, limiting biomass (S1) requires a large electrification within the heating sector, increasing electricity demand significantly. Implementing large-scale energy storage instead of NG to balance renewables more effectively was deemed not technically feasible for LIB storage, and economically unfeasible for large scale hydrogen storage. Thus, signif-

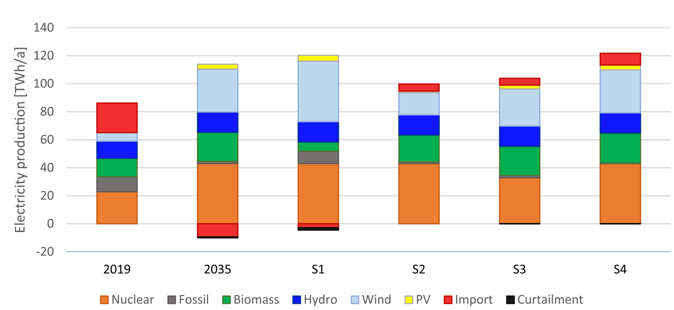

Fig. 2. Electricity production for 2019, 2035 and the modelled scenarios. Curtailment and export are presented as negative values.

[2] It is assumed, that currently hydrogen is produced from Natural gas via Steam Methane Reformation (SMR) with an efficiency of 67.6%, while the green hydrogen is produced with a 70% electrolyzers efficiency, and 20% of input heat is useable in DH.

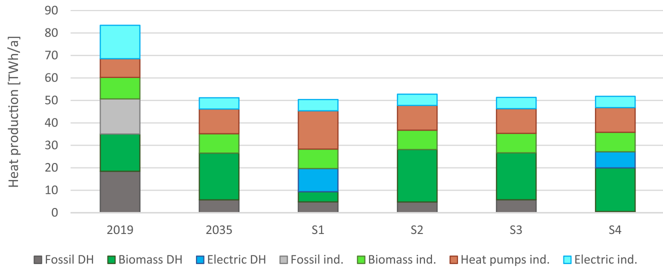

Fig. 3. Heat production for both individual heating (Ind.) and district heating (DH) for 2019, 2035 and the modelled scenarios.

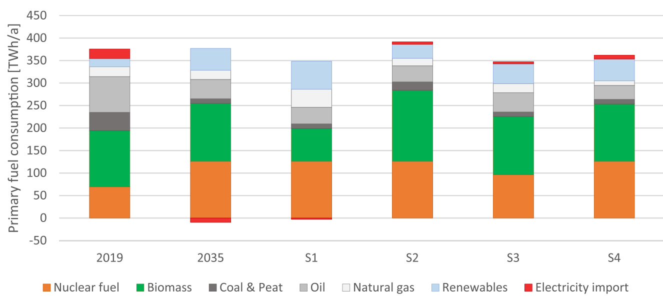

Fig. 4. Primary fuel consumption for 2019, 2035 and the modelled scenarios.

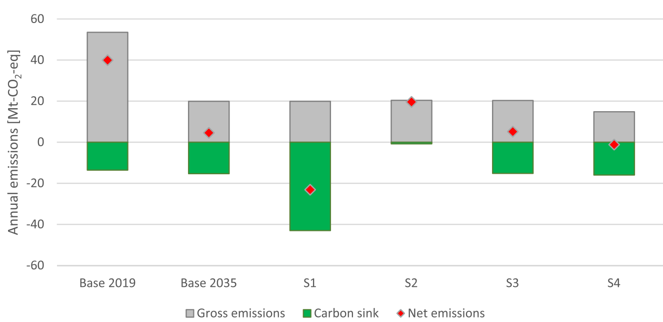

Fig. 5. Annual gross emissions, carbon sink and net emissions for 2019, 2035 and the modelled scenarios.

icant curtailment would occur in S1. In S2, biomass usage is unchanged, whereas the use of renewables and fossil fuels is reduced due to raw material and import constraints. Subsequently, total electricity generation is also lower, increasing the dependence on imported electricity. In S3, the Finnish energy sector is modelled with more realistic expectations, assuming lower nuclear base generation as construction of additional nuclear capacity in Finland by 2035 might not be realized. Renewable energy production is also marginally reduced compared to the base scenario, resulting in a slight increase in biomass production. Fig. 2 also shows how in S3 Finland remains reliant on imported electricity, instead of becoming a net exporter of electricity as predicted in the base scenario.

Moreover, S4 shows how Finland would need to rely even further on imports to meet possible stricter climate targets for 2035. Fig. 2 also illustrates how the current emission reduction targets necessitate both renewables and biomass usage to be implemented according to current plans. Other measures also play a large role in this scenario, such as green hydrogen in industry and heavy vehicles, and a partial electrification of DH networks, which would result in an increased electricity demand as can be observed in the figure.

Fig. 3 shows the heat production for each modelled scenario. It can be observed that the heating requirement in 2035 is much lower than that of 2019, as new buildings with higher energy efficiency greatly reduce the energy consumption of heating. Considering that individual oil heating will be phased out in the coming decade, the heating sector is expected to primarily utilize biomass and heat pumps in 2035, combined with a low share of electric heating in individual houses and fossil fuel in DH networks.

While the analyzed bottlenecks in S2 and S3 are expected to only have minor effects on the heating sector, limitations to biomass usage in S1 would have a substantial impact on the heating sector. The biomass limitations in S1 would force the electrification of many DH networks to not increase carbon emissions, combined with a large increase in the use of individual heat pumps for heating. Similarly, the stricter climate targets in S4 would also require some electrification of DH networks, while fossil fuels in heating would need to be completely phased out by 2035.

In addition, Fig. 4 illustrates how the modelled scenarios would impact the primary fuel consumption in Finland in 2035. Most significantly, biomass constraints in S1 would increase the share of fossil fuels in the primary fuel consumption of Finland, with the largest increase being in NG usage for electricity generation. While this increase is not desirable from an environmental viewpoint, alternative approaches would require considerable changes to the power production infrastructure. The majority of fossil fuel usage in all scenarios takes place in industry and transportation, however, with reduced transportation fossil fuel use in S4.

Fig. 5 shows the annual GHG emissions in 2019, in the 2035 base scenario, as well as in each of the modelled scenarios. As can be observed in the figure, the gross emissions are close to 20 $MtCO_2$-eq in all scenarios, whereas the annual carbon sink in the LULUCF sector varies. Notably, the limited biomass usage in scenario 1 would increase carbon sinks of forests significantly. However, restrictions on logging and biomass usage in S1 would damage the domestic forest industry and may not be financially or socially feasible. Nevertheless, S1 would simultaneously set Finland's net emissions well below current climate targets. On the contrary, raw material and import bottlenecks in S2 would instead increase biomass usage substantially, causing the net annual carbon sink in the LULUCF sector to nearly disappear.

Fig. 6 presents the electricity production and demand for the modelled scenarios for the year 2035. While both S1 and S4 had a higher annual electricity consumption compared to the base scenario, they still showed significant variation in their temporal electricity demand distribution. In S1, peaks in demand were concentrated on hours with high heat demand, while in S4, peaks in demand were more evenly spread out throughout the year. S4 included 1220 MW of H_2 electrolyzers in continuous operation throughout the year, whereas S1 only featured the electrification of heating, which caused the increased electricity demand to be focused on the winter months. On the other hand, S2 and S3 showcase a very similar electricity demand profile, whereas their electricity production differs due to S3 having a lower nuclear capacity compared to S2.

Table 6 presents the annual system costs between 2019 and 2035 for the modelled scenarios, which illustrate the need for investments and funding from the private and public sectors. As can be observed, the envisioned transition towards renewables would in total cost approximately EUR 660 million annually until 2035. Raw material and biomass constraints in S1 and S2 would only have a minor impact on the overall annual costs, whereas S3 and S4 would even have negative total annual costs relative to the base scenario, due to lower variable costs in S3 and S4. The negative variable costs are mainly due to lower fossil fuel imports compared to 2019, with especially low imports in S3 and S4. Additionally, the modelling found that the base scenario in 2035 would result in negative average electricity prices, indicating insufficient financial incentives to construct the planned nuclear and wind capacity in Finland. Detailed cost parameters can be found in Appendix IV.

Moreover, Table 7 presents the weighted significance and the effects of different electricity generation methods on coupled sectors based on the modelled scenarios. The analysis shows how the integration of

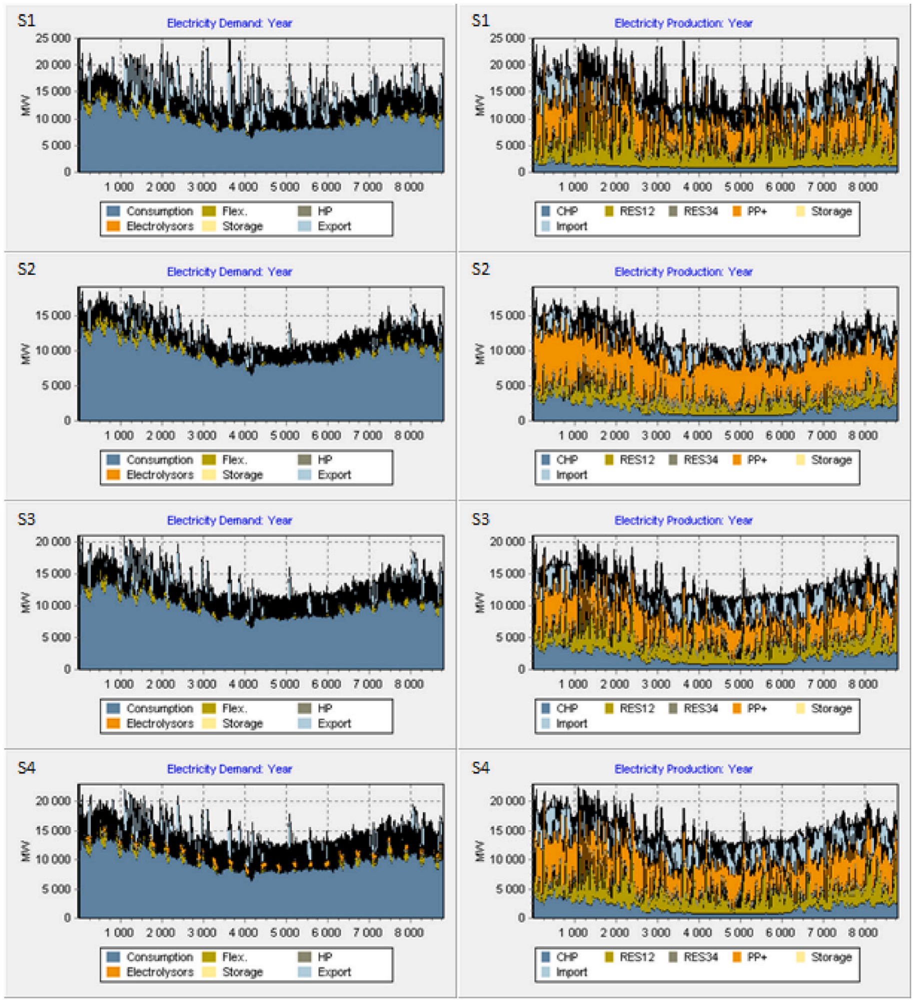

Fig. 6. Electricity demand and production during the modelled scenarios. On the left side, the electricity demand is shown, while on the right-side electricity production is presented.

Table 6
Change in annual costs between 2019 and 2035 for the modelled scenarios.

Cost and price estimates	2035	S1	S2	S3	S4
Investment costs (M€)	1771	1742	1824	1243	1975
Fixed costs (M€)	864	841	1054	576	895
Variable costs (M€)	−864	−847	−1086	−2220	−3154
Total annual costs (M€)	1771	1736	1792	−401	−284

intermittent renewables would facilitate growth in technologies such as heat pumps, electrofuels, EVs and energy storage, while, however, also increasing the need for electricity transmission capacity, trading and curtailment. In comparison, the added nuclear generation would accomplish similar effects without the resulting grid balancing challenges. The comparative findings of this paper also suggest that increased biomass or fossil fuel usage would instead incentivize continued CHP usage in the heating sector by means of combustion where applicable, decelerating electrification and the development towards renewable energy technologies. Reduced biomass usage has adverse impacts on the forest industry but positive impacts on the Land Use, Land Use Change and Forestry (LULUCF) sector. Reduced forest industry activity is generally regarded as highly undesirable from the points of view of national and regional economy and employment. Households benefit from increasing wind, solar and nuclear generation as a result of lower electricity prices. Likewise, maintaining fossil capacity would have a similar impact, depending on the amount of thermal

Table 7
Comparable findings of the modelled scenarios regarding the effects of different electricity generation methods on coupled sectors according to their weighted significance: advantageous – indifference – disadvantageous, shown as +++, ++, +, 0, -, –, —.

Sector coupling	Renewables (wind + solar)	Nuclear	Biomass	Fossil fuels
Heating				
Heat pumps	++	+	–	–
CHP	–	–	+++	+++
Transportation				
Fossil fuels	–	–	–	+++
Biofuels	–	–	++	–
Electrofuels	++	+	–	–
Electric vehicles	+++	++	–	–
Industry & agriculture				
Electricity transmission	–	++	+	++
Curtailment	–	+++	++	+++
Energy storage	++	–	–	–
Forest industry	+	–	+++	–
Agriculture	0	0	++	+
LULUCF				
Net emissions	++	++	–	–
Households	++	++	0	+

generation capacity and on fuel and CO_2 prices.

5. Conclusions

This paper presented an analysis on how various bottlenecks might delay or hinder the transition of the energy sector towards the target of carbon neutrality in Finland by 2035. Literature review highlighted how bottlenecks in CRM and mineral availability could become a considerable risk for achieving climate targets in the coming decade. Limited biomass availability and insufficient manufacturing capacity were also found to be factors that can delay or hinder the implementation of climate policy in Finland.

As many countries plan to use similar technology combinations in their national strategies towards net zero carbon emissions, this study is also applicable for several other nations. For instance, many European countries, including Sweden, Latvia, Czech Republic, Slovakia and Austria, plan to continue significant biomass utilization in their energy policies, whereas solar PV and wind power are strongly present in the energy strategies of most countries both in Europe and globally (Streimikiene et al., 2022; European Commission, 2023). National policy choices and their successful implementation also often have significant impacts on neighboring countries, as European energy markets are strongly inter-connected (Farsaei, 2022).

Modeling showed how reduced biomass usage and logging could substantially increase net carbon sinks in Finland, at the cost of increased NG usage and adverse impacts on forest industry and related economic activity. Delayed implementation of nuclear or wind power capacity or increased DH electrification may also prevent Finland from reaching its target of becoming a net exporter of electricity by 2035, as domestic electricity generation would not be sufficient to meet total demand. Modelling also illustrated how meeting or surpassing climate targets could be feasible by facilitating green hydrogen production and accelerating DH electrification, however, simultaneously increasing demand for electricity imports.

The results presented in this paper emphasize the importance of diversification in the Finnish energy sector. Modelling showed how increasing the nuclear base capacity of Finland is an effective approach to limiting electricity import reliance. Maintaining a positive net carbon sink was shown to be a critical factor for reaching present climate targets, posing limitations to biomass availability in the coming decade. Finding feasible alternatives for NG and biomass in power and heat generation is essential for transition to a more renewable and sustainable energy system.

Notably, this paper did not consider the financial or regulatory impacts of the modelled scenarios in detail, which would be a topic for further research. Additionally, the use of electrical energy storage technologies (except for S1), CAES and CCUS were excluded from the modelled scenarios in this paper, as they were not present in current government plans for reaching carbon neutrality. Finally, the use of several different system models is recommended to support the preparation of national energy strategies: energy systems are complex, and models vary in their abilities to depict different parts of the energy system. Especially model abilities to portray the behavior of interconnected electricity markets in the strong presence of wind and solar power are of growing importance.

CRediT authorship contribution statement

Johannes Hyvönen: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft. **Tero Koivunen:** Conceptualization, Formal analysis, Methodology, Software, Writing – original draft. **Sanna Syri:** Formal analysis, Funding acquisition, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendices.

APPENDIX I. Forest biomass calculation

The forest carbon content was calculated with the following formula:

$$c(t) = \alpha * v(t)$$

Where $c(t)$ is the total carbon stock, α is carbon content per stem volume, which was set at 1.36, and $v(t)$ is the stem volume.

The stem volume was assumed to be 0 at t = 0 and to change over time as follows:

$$v'(t) = v_1 * t * e^{v_2 t} + v_3 * t^3 * e^{v_4 t}$$

The coefficients $\alpha, v_1, v_2, v_3, v_4$ based on research data presented in (Lehtonen et al., 2004; Ekholm, 2020) on Norwegian Spruce were as follows:

α	1.36
v_1	0.235
v_2	−0.0153
v_3	0.00621
v_4	−0.109

Calculation was done with $t = 0.5$ steps. The forest was assumed to be cut completely at t = 70. The time t = 70 was chosen based on pareto-optimization, where both carbon sinks and the economic value of the forest were optimized. The coefficients and equations were presented in

(Ekholm, 2020), while the coefficients are based on data presented in (Lehtonen et al., 2004).

APPENDIX II. ***Fingrid open service datasets used in modelling***

- Electricity consumption in Finland
- Wind power generation – hourly data
- Solar power generation forecast – updated hourly
- Industrial cogeneration
- Hydro power production – real time data
- Nuclear power production – real time data
- Net import/export of electricity – real time data

APPENDIX III. Electricity and heat production, energy storage capacity, fuel usage and emissions in the modelled scenarios

Table A-3 1
Modelled scenarios.

	Usage in 2019	Usage in 2035[7]	Base 2035	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Electricity production	*(TWh/a)*	*(TWh/a)*	*(TWh/a)*	*(TWh/a)*	*(TWh/a)*	*(TWh/a)*	*(TWh/a)*
Nuclear electricity	22.9	43	43	43	43	32.9	43
Fossil (incl. peat)	10.7	1	1.6	8.9	1.2	1.6	0.4
Biomass	13.1	17.6	20.7	6.6	19.2	20.8	21.4
Wind electricity	6.0	30.7	30.7	43.3	15.9	26.6	30.7
PV electricity	0.2[8]	3.4	3.4	4.1	1.0	2.7	3.4
Hydro electricity	12.2	14.4	14.4	14.4	14.4	14.4	14.4
Total production	64.9	110	113.9	120.3	94.7	99	113.3
Curtailment	0	–	−0.7	−1.8	0	0	−0.1
Import/Export (−)	21.1	−6.2	−9.4	−2.6	5.1	4.8	8.5
Total electricity demand	**86.1**	**103.8**	**103.8**	**115.7**	**99.8**	**103.8**	**121.7**
Heat production	*(TWh/a)*	*(TWh/a)*	*(TWh/a)*	*(TWh/a)*	*(TWh/a)*	*(TWh/a)*	*(TWh/a)*
Fossil (DH prod.)	18.5	–	5.8	4.9	4.8	5.8	0.5
Biomass (DH prod.)	16.6	–	20.8	4.5	23.4	20.9	19.4
Electric heating of DH	0	–	0	10.3	0	0	7.2
DH network losses	−4	–	−3	−2.2	−3	−3	−3
Other DH losses[9]	−0.9	–	−1	−1	−2.6	−1.1	−1.6
DH demand	30.2	25.6	22.6	17.5	25.1	23.7	24.2
Fossil (individual heating)	15.6	0	0	0	0	0	0
Biomass (individual heating)	9.6	8.6	8.6	8.6	8.6	8.6	8.6
Heat pumps (individual heating)	8.3	–	11	17.1	11	11	11
Electric heating (individual heating)	14.9	–	5	5	5	5	5
Total heat demand[10]	**78.5**	**47.2**	**47.2**	**47.2**	**47.2**	**47.2**	**47.2**

[7] Projected usage based on the HIISI WAM-H scenario. "-" indicates an unknown value, which was estimated for the base model.
[8] Solar PV production was 147 GWh/a in 2019.
[9] The EnergyPLAN model produces more heat than needed, which is most likely due to excess heat production during summer from industrial heat, as this heat was categorized as "Biomass" DH production in the source material. This excess heat is thus considered to be other DH losses. The network losses were determined as input values in EnergyPLAN.
[10] The imbalance in footnote 9 is carried over to the total heat demand. Thus, this value indicates final heat demand, excluding all losses.

Table A-3 2
Storage, transportation, and industry fuels in different scenarios. Values are rounded to nearest 0.1 TWh/a.

	Usage in 2019	Usage in 2035[11]	Base 2035	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Energy storage capacity	*(GWh)*	*(GWh)*	*(GWh)*	*(GWh)*	*(GWh)*	*(GWh)*	*(GWh)*
LIB storage	0	–	0	100	0	0	0
H2 storage	0	–	0	0	0	0	100
TES	22	–	22	22	22	22	22
CAES	0	–	0	0	0	0	0
Transportation	*(TWh/a)*	*(TWh/a)*	*(TWh/a)*	*(TWh/a)*	*(TWh/a)*	*(TWh/a)*	*(TWh/a)*
Oil	43.6	15.8	15.8	15.8	15.8	15.8	10.8
E-fuels + H_2 for vehicles	0	0	0	0	0	0	2.5
Biofuels	5.0	8.4	8.4	0	28	8.4	8.4
Electric vehicles	0.1	5.7	5.7	7.2	1.2	5.7	5.7
Gas vehicles	0.2	3.5	3.5	3.5	3.5	3.5	3.5
Industry	*(TWh/a)*	*(TWh/a)*	*(TWh/a)*	*(TWh/a)*	*(TWh/a)*	*(TWh/a)*	*(TWh/a)*
Coal	13.2	10.4	10.4	10.4	10.4	10.4	10.4
Oil	15.7	20	20	20	20	20	20
Natural gas	8.9	13.9	13.9	13.9	13.9	13.9	6.6
Biomass	64.4	53	53	53	53	53	53
Hydrogen	0	0	0	0	0	0	5
CCUS	0	0	0	0	0	0	0

[11] Projected usage based on the HIISI WAM-H scenario. "?" indicates an unknown value, which was estimated for the base model.

Table A-3 3
Primary fuel consumption and emissions in scenarios. Values are rounded to nearest 0.1 TWh/a.

	Usage in 2019	Usage in 2035[12]	Base 2035	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Primary fuel consumption	*(TWh/a)*	*(TWh/a)*	*(TWh/a)*	*(TWh/a)*	*(TWh/a)*	*(TWh/a)*	*(TWh/a)*
Coal and peat	41.1	10.4	10.4	10.4	18.4	10.4	10.4
Oil	79.3	46.3	42.7	36.8	35.8	42.7	30.8
Natural gas	21.9	20.9	20.5	40.3	16.6	20.4	10.2
Biomass	124.5	126.5	128.8	72.8	158	129	127.4
Nuclear fuel	69.4	126.1	126.1	126.1	126.1	96.4	126.1
Renewables	18.5	45.4	48.5	61.9	31.4	43.7	48.5
Hydrogen	0	–	0	0	0	0	0
Others[13]	5.7	29.0	–	–	–	–	–
Total primary fuel consumption	**357.8**	**404.5**	**376.9**	**348.3**	**386.3**	**342.5**	**353.4**
Electricity import	21.0	−6.2	−9.4	−2.8	5.1	4.8	8.5
Total energy consumption	**378.8**	**398.3**	**367.5**	**345.5**	**381.4**	**347.4**	**361.9**
Emissions	*($MtCO_2$/a)*	*($MtCO_2$/a)*	*($MtCO_2$/a)*	*($MtCO_2$/a)*	*($MtCO_2$/a)*	*($MtCO_2$/a)*	*($MtCO_2$/a)*
Gross emissions[14]	53.5	19.6	19.9	19.9	20.4	20.3	14.8
Carbon sink	13.6	15.4	15.3	43	0.8	15.2	16.0
Net emissions	39.9	4.2	4.6	−23.1	19.6	5.1	−1.2

[12] Projected based on the HIISI WAM-H scenario. "?" indicates an unknown value, which was estimated for the base model by the authors.
[13] Not included in the fuel consumption as these fuels were not inserted into Energy Plan.
[14] Does not include the emissions from agricultural sector, except in the 2019 validation scenario. In our 2035 base and scenarios 1–4, this refers to the corrected emissions reported by EnergyPLAN. Note, that for the validation scenario, table 111k from Official Statistics of Finland was used, and not table 138v which presents slightly different values for gross emissions, but significantly different values for carbon sinks.

APPENDIX IV. Cost parameters

General cost assumptions were as follows: CO_2 price was set at 80 €/tCO_2, except in the 2019 validation scenario, where it was 25 €/tCO_2, while interest rate was set at 5%. 2019 Nord Pool system price was set as the external electricity market price.

Following technology prices were applied.

Table A-4 1
Technological parameters of used technologies

Technology	Investment cost M€/MW	Lifetime years	O&M % of inv. cost
CHP	0.82	25	3.66
Heat storage	3 €/GWh	20	0.7
Waste CHP	215.6 M€/TWh	20	7.4
Boilers	0.1	20	1.47
Electric boilers	0.1	20	1.47
Large power plants	1	30	2
Nuclear	5.5	40	3.5
Interconnection	1.2	40	1
El storage cap.	75	20	13.3
Indust. CHP Elec.	68.3	25	7.3
Wind	0.99	25	3.21
Photo Voltaic	0.83	35	1.31
Run of river hydro	2.75	50	4
Hydro power	3.3	50	1.5
Hydro storage	7.5	50	1.5
Hydrogen storage	20 M€/GWh	30	0.5
Gas storage	0.081 M€/GWh	50	1
Oil storage	0.023 M€/GWh	50	0.6

Table A-4 2
Used fuel costs.

Fuel	Price €/GJ
Coal	3.1
Fuel Oil	11.9
Diesel/Gasol	15
Petrol	16.1
Natural gas	8.33
LPG	22.1
Waste	0
Biomass	5.6
Dry biomass	5.6
Wet biomass	0
Uranium incl. handling etc.	1.5

Table A-4 3
Variable O&M costs.

Technology	Variable O&M €/MWh
Boiler	0.15
CHP	2.7
Heat pump	0.27
Electric heating	0.5
Hydro power	1.19
Condensing	2.636
Electrolyzer	0
Pump	1.19
Turbine	1.19
Hydro power pump	1.19

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