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Cross-border impacts of climate change affect the energy transition: Insights from the Finnish energy sector

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Abstract
The world is currently in the midst of an energy transition, in which renewable and low-carbon energy is replacing the use of fossil fuels. Along the way, however, planning for and adapting to impacts of climate change is urgently needed, as these are projected to intensify in the future, despite ambitious mitigation efforts. Since the low-carbon energy transition is likely to involve many international interdependencies and connections between countries and regions, assessments of cross-border impacts of climate change, i.e., consequences of climate change that occur remotely from the location of their initial impact, are of utmost importance to ensure the decarbonisation of society is safe and sustainable. This paper utilises expert interviews and a general morphological analysis with the shared socioeconomic pathways to situate national decarbonisation efforts within a global context and identify cross-border impacts of climate change that may affect the energy transition, using the Finnish energy sector as a case study. Interestingly, many of the global development trends that were found to have a boosting effect on the Finnish energy transition, also increased the risk from cross-border climate change impacts, stressing the importance of rigorous adaptation planning. The findings affirm the need for studying national energy transitions from a global perspective and highlight the tendency of climate change impacts to be transmitted across borders via complex pathways. The study offers valuable insights into the importance of cross-border impacts for adaptation planning pertinent to any country or region currently engaged, or planning to engage, in the global low-carbon transition.

Keywords Cross-border impacts · Low-carbon transition · SSPs · GMA · Finland

1 Introduction

The world is currently in the midst of an energy transition, in which all aspects of the global energy system are being transformed away from fossil fuels towards low-carbon energy technologies. The aim of the global energy transition is to achieve net zero greenhouse gas (GHG) emissions by 2050, in order to limit the global rise in temperatures to

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1.5–2 ℃ above pre-industrial levels (IRENA 2022). The turmoil on the global energy market, induced by the COVID-19 pandemic and the Russian invasion of Ukraine, has further engrained the need to reform the energy system, for the sake of energy security and energy price stability.

It is often assumed that the energy transition will result in fewer interdependencies between countries, because of a focus on domestic energy production and the improvement of energy self-sufficiency. Subsequently, national decarbonisation strategies rarely consider the international dimensions of energy transitions and how they will evolve over time (Mikova et al. 2019). However, a low-carbon energy system is in fact likely to include many international connections, such as regional electricity grids or dependence on imported materials (Cherp et al. 2011; Scholten and Bosman 2016). Differing cost competitiveness between regions, or social resistance towards large energy infrastructure or land-use change, may also incentivise international energy trade in the future (Schmidt et al. 2019; Enserink et al. 2022).

Bridge et al. (2013) highlighted the fact that energy transitions inherently involve changes in geographical structures and international relations of economic and social activities, but studies rarely reflect on the broader implications of these changes. Sovacool et al. (2019) showed that energy transitions are embedded in a social, economic, and environmental context that spill across spatial and temporal scales, requiring a broader investigation of potential cross-border externalities and global consequences of such transitions. Thus, disregarding the dynamic global context results in national decarbonisation commitments that are based on a narrow set of plausible futures, with little wiggle room for adapting to unforeseen or unexpected developments (Walker et al. 2013).

Furthermore, despite ambitious mitigation efforts, climate change is already occurring and will intensify even further in the future, which affirms the need to identify, assess and adapt to climate change impacts also in a future low-carbon society (IPCC 2021). Considering the highly globalised nature of energy transitions, it is particularly imperative to identify and assess potential cross-border impacts of climate change that may affect the implementation of decarbonisation strategies. Cross-border impacts of climate change (hereafter referred to as CBIs), can be defined as “consequences of climate change that occur remotely from the location of their initial impact” (Carter et al. 2021), such that consequences are felt in one region, although the climatic changes took place somewhere else. The impacts are thus transmitted across borders, be they political, administrative, or natural borders, via different impact pathways related to, e.g., international trade, financial interactions, political decisions, migrations, or the spread of diseases (Moser and Hart 2015; Challinor et al. 2018; Liu et al. 2018).

As an example, the prolonged flooding event in Thailand during 2011 had global economic consequences, due to disruptions to international supply chains, affecting especially the automobile and electronics industries throughout Asia and beyond (UN-ESCAP 2012). However, research on CBIs is just emerging and therefore rarely sufficiently addressed in climate change assessments (Talebian et al. 2021) or decarbonisation strategies. Certain sectors, such as food and agriculture (see, e.g., Brás et al. 2019; Ercin et al. 2021), or impact pathways, e.g., international trade and supply chains (see, e.g., Ghadge et al. 2020; Bednar-Friedl et al. 2022), have been assessed more thoroughly with regards to CBIs. Conversely, there seems to be a lack of research concerning CBIs on the energy sector (Groundstroem and Juhola 2018, 2021; Berninger et al. 2022).

This paper seeks to expand the knowledge base regarding CBIs on the energy sector, and simultaneously advance the understanding of the dynamic global interdependencies associated with the energy transition. As guidance, the paper asks the following research questions: How could national energy transitions be affected by climate change related CBIs, and would different global socioeconomic development trends exacerbate or reduce the risk of CBIs? To help answer these questions, the Finnish energy transition was explored in a case study, in which the decarbonisation of the Finnish energy sector was linked to the global context through a systems perspective, and potential implications of CBIs were identified for a mid-term time horizon (until 2050). The study was based on expert interviews, and supported by a general morphological analysis (GMA) consisting of Finnish decarbonisation scenarios and the mitigation scenarios of the global scale shared socioeconomic pathways (SSPs). The study was confined to the energy system, comprising "all components related to the production, conversion, delivery, and use of energy" (IPCC 2014).

2 Material and methods

2.1 Case study: the Finnish energy sector

Finland is an interesting case for studying energy transitions, since the government has set the very ambitious target of achieving carbon neutrality already by 2035 and becoming carbon negative soon thereafter (Government of Finland 2020). This entails a substantial reformation of the Finnish energy sector, since ca 80% of GHG emissions can be attributed to the production and consumption of energy (MEE 2014). Additionally, the most important energy sources for decarbonisation, i.e., wind and solar (Temmes et al. 2021), only amounted to ca 3% of total energy consumption in 2021 (Motiva 2022), hence requiring a substantial scale up.

Two mid-term (until 2050) national-scale decarbonisation scenarios (called continuous growth and conserve) were developed by the Technical Research Center of Finland (VTT), to support the transition by laying out potential pathways for achieving the 2035 carbon neutrality goal (Koljonen et al. 2020). The scenarios are very similar, both assuming, inter alia, a rapid and substantial ramping up of renewable energy production, widespread electrification, a phase out of fossil fuels, increased energy efficiency and decreased energy demand, resulting in similar energy supply and consumption figures in both scenarios (Table 1). The scenarios differ in certain aspects, such as reliance on emerging technologies and international energy trade, which leads to subtle differences in energy system characteristics (see the Online Resource for additional information on the scenarios).

Despite focusing on domestic measures, the scenarios acknowledge that international policies geared towards sustainability are needed to create a supportive setting for investments, international trade, and diffusion of know-how. In fact, the scenarios hinge upon successful global climate negotiations that lead to the below 2 °C Paris Agreement target being met (Koljonen et al. 2020). Additionally, electrifying the Finnish energy sector is likely to entail major investments in new electricity production capacity as well as transmission and distribution networks, which will require expanding of cross-border transmission connections and greater dependence on international electricity markets. Moreover, Finland is a small economy, which means that new technological innovations and their diffusion to Finnish markets from abroad are needed for ramping up renewable energy production, electricity storage, energy efficiency, and prosumerism (Cherp et al. 2011).

Table 1 Elements and assumptions in the Finnish decarbonisation scenarios. Shaded boxes highlight the main differences between the scenarios. See the Online Resource for a more detailed version

Element	Current Figs. (2019)	Continuous growth	Conserve	Assumptions that affect the energy sector
Primary energy supply	1362 PJ of which 510 PJ is renewable	1200 PJ in 2050, 80% RE	1250 PJ in 2050, 80% RE	Decrease in energy supply volumes and fossil fuels phased out
Electricity consumption	86 TWh	ca 127 TWh in 2050 (54% of energy consumption), < 70% RE, rest with nuclear	ca 120 TWh in 2050 (46% of energy consumption) < 70% RE, rest with nuclear	Electricity generation is ramped up significantly
Bioenergy use	31% of energy consumption; wood-based 28%	Growth in wood-based energy use, but also other biomass	Rapid growth in bioenergy use. Biofuels used extensively in transport	Growing role for bioenergy and growth of the forest industries in Conserve
Other RE use	6 TWh wind Solar is marginal	Wind 27–33 TWh and solar 25–27 TWh, in 2050		Very significant growth for both wind and solar
Nuclear power	70 TWh	Two new plants are built (operational until at least 2070) and the lifetime of old plants are extended up to 2040–50. Modular nuclear-CHP plants are possibly built in cities	Two new plants are built (operational until at least 2070) and the lifetime of old plants are extended up to 2040–50	Nuclear power plants are operational and provide emissions-free electricity. Both scenarios assume lifetime extensions for current nuclear plants
CCS	Not commercially available	CCS not commercially available	CCS and BECCS is commercially available and in widespread use	In Conserve, CCS and BECCS are commercially available
Hydrogen, synthetic fuels, PtX	Not commercially available	Hydrogen is in widespread use. Ca 7% of light duty vehicles run on hydrogen	Hydrogen is in widespread use. Ca 14% of light duty vehicles run on hydrogen,	New and nascent technologies are widely used. Hydrogen and synthetic fuels are commercially available and cost competitive

Table 1 (continued)

Element	Current Figs. (2019)	Continuous growth	Conserve	Assumptions that affect the energy sector
Rate of technology uptake		Rapid. Electrification and digitalisation widespread. Subsidies for technology uptake and bioenergy. R&D of storage and conversion technologies, smart energy systems and demand response	Slower. Strong state control of regulations and subsidies. R&D of CCS, energy efficiency and biofuels	Rapid RE technology uptake and investments in Continuous Growth
Export market		Market for exports is thriving in all sectors and industries, making Finland competitive and fostering economic growth	Less focus on exports and more on national measures	In Continuous Growth, high economic growth (which sustains energy sector investments) is achieved through exports
Electricity trade	20 TWh/year imported	Electricity imports ca 3 TWh/year, increasing supply security in 2050	Electricity imports ca 8 TWh/year, increasing supply security in 2050	Energy self-sufficiency significantly improved
EU ETS	above 40 €/t	Price of emission allowances increases to 90€/tCO2 by 2050 (~87$ in 2005). Emissions are reduced 80% from 1990 in the EU		Regional climate negotiations are successful
International climate negotiations		The 2°C target is achieved globally		International climate negotiations are successful

2.2 Expert interviews

Finnish experts in the energy transition were consulted with the aim of (1) obtaining an overview of the current state of knowledge on CBIs, (2) identifying the impact pathways that are perceived as most relevant from a Finnish perspective, and (3) highlighting the effect of different global socioeconomic developments on the emergence of CBIs. Twenty-four experts on the Finnish energy transition were identified through institutional and stakeholder mapping (Aligica 2006) as well as snowballing, and 14 of them agreed to take part in the study. The interviews (30–60 min in duration) took place online or face-to-face in June and August 2022. The interviewees were from research institutions (9), the private sector (4), and the government (1), spanning a broad range of backgrounds in politics, economics, technology, business, humanities, and natural sciences (Table 2).

The interviews were qualitative, semi-structured, and explorative (Bogner and Menz 2009; Döringer 2020) to allow the interviewee to focus on the issues that he/she felt were most important. The interviews started with the interviewer introducing the study, explaining CBIs, the impact pathways, and the socioeconomic characteristics of the different SSPs, if needed. The questions went from more generally discussing the interviewee's perception of the Finnish energy transition and carbon neutrality goal, to exploring different aspects of the global transition and cross-border climate change implications from a Finnish energy sector perspective (Table 3). The questions were altered and tailored to the interviewee's area of expertise, with some of the interviews focusing more on the impact pathways, while some were more focused on how different SSPs may alter the manifestation of CBIs.

Expert interviews were chosen as a research method for several reasons: First, the global interconnectedness of the energy transition as well as the concept of CBIs are both fairly new areas of research, which makes the knowledge of experts a valuable source of information in an otherwise information-scarce environment. Second, since the energy transition affects a broad range of actors and industries both in the public and private sectors, expert interviews can provide insights from different perspectives. Lastly, mapping out the global interconnections and potential implications from CBIs, is a very complex endeavour that benefits from the inclusion of several viewpoints.

Expert interviews pose their own set of challenges that must be acknowledged. First, a relatively small number of interviewees, as was the case in this study, only provides a limited number of different opinions and areas of expertise that cannot be considered representative of the larger expert community. Second, the interview process is easily contaminated by the opinions of the interviewer or by misunderstandings or

Table 2 Categorisation of interviewees and their identification codes for quotations

Main group	Sub-group	Number of interviewees	Identification code
Research institutions	Political sciences	1	RPol1
	Technical sciences	2	RTech1-2
	Natural sciences	2	RNat1-2
	Social sciences	3	RSoc1-3
	Economics	1	REco1
Private sector	Business, consultancies	4	Priv1-4
Government	Energy policy	1	Gov1

Table 3 Guiding questions used in the expert interviews. The discussions differed based on the interviewees' expertise

No	Guiding question
1	How do you perceive the future of a decarbonised energy sector in Finland in general?
2	What are the main obstacles or challenges to achieving the goal of carbon neutrality by 2035 in the energy sector?
3	How connected is the Finnish energy sector to the rest of the world? How will these connections change during the unfolding of the energy transition?
4	In what way could international connections expose the decarbonising Finnish energy sector to cross-border impacts?
5	Which cross-border impact pathways are the most significant from a Finnish energy sector perspective?
6	How could different global socioeconomic development trends alter the level of exposure to cross-border impacts?
7	Will the suite of cross-border impacts be different in the transition phase vs. after decarbonisation has been achieved?

misinterpretations that may lead to incorrect coding of the material. To avoid these pitfalls, the interview results were compared to relevant literature from previous research in the field, and steering of the conversations by the interviewer was kept to a minimum. Additionally, gaps in knowledge regarding either the impact pathways or the SSPs were patched by using complementary research methods (Fig. 1).

2.3 The cross-border impact pathways approach

Since not all interviewees were familiar with different impact pathways, the interview transcripts were further analysed and coded in the content analysis software Atlas.ti based on the cross-border impact pathways (CBIP) approach (Benzie 2014; Hildén et al. 2016), in which seven pathways through which CBIs are transmitted across borders can be identified (Hildén et al. 2016; Carter et al. 2021):

- The *trade pathway* constitutes impacts that affect the movement of traded commodities on international markets, such as supply shortages or price fluctuations.
- The *finance pathway* concerns the impacts on the flow or value of private and public capital.
- The *infrastructure pathway* transmits impacts through physical links related to, e.g., transportation or electricity.
- The *people pathway* concerns the movement of people across borders, e.g., tourism or migration affected by climate change.
- The *biophysical pathway* transmits impacts brought about by changes to the natural environment, such as reduced transboundary river flows or the prevalence of pests and pathogens.
- The *geopolitical pathway* transfers effects of changing political environments or international relations, e.g., resource substitution or tightening mitigation policies, induced by climate change.

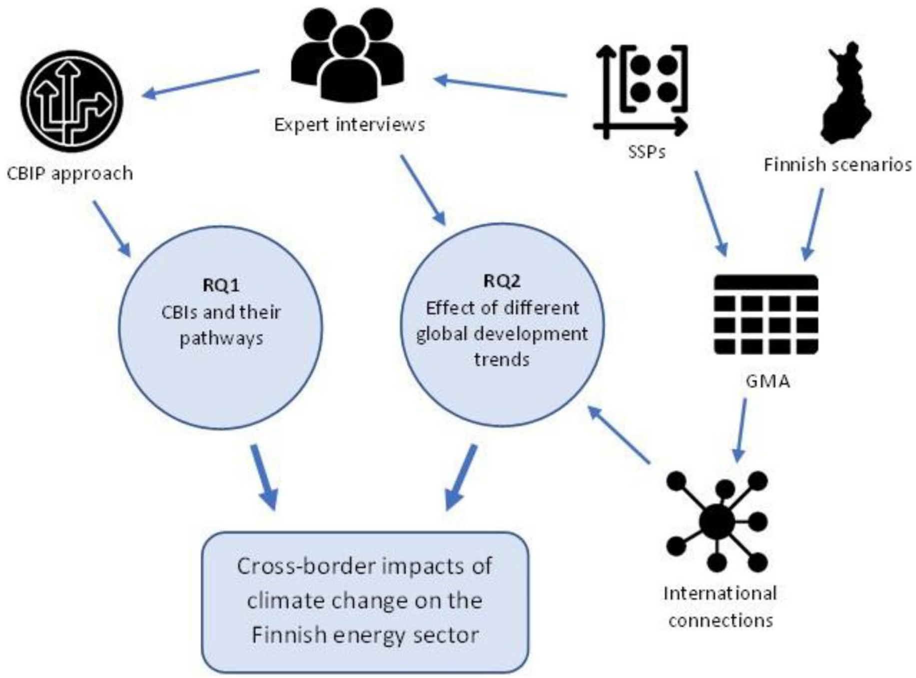

Fig. 1 Schematic of the methods used and how they were related to the two research questions. See the main text for more information

- The *psychological pathway* highlights the effects that climate change induced changes to perceptions and attitudes of different actors may have on, e.g., consumer behaviour or political engagement.

The CBIP approach has been used in previous research with the aim of bringing clarity to the different ways in which CBIs may emerge and manifest in different settings. For instance, Benzie et al. (2019) used the pathways of finance, people, trade, biophysical, and geopolitical in a study of CBIs on the EU; West et al. (2021) considered the pathways of trade, people, and finance when studying macro-scale impact transmissions between the EU and the rest of the world, while Talebian et al. (2021) conducted a CBI assessment for Kenya using the pathways of people, biophysical, trade, and finance. All seven pathways were included in this study, as the purpose was to broadly identify all potential CBIs potentially affecting the decarbonisation of the energy sector.

CBIs were considered to include both risks and opportunities, induced by either physical climate impacts abroad or transition risks stemming from actions taken outside Finland's borders — including policy, regulatory, technological, market, reputational, and legal risks arising from the energy transition itself (TCFD 2017). While not intuitively classified as CBIs, transition risks are important to include in a study of the energy system, which will be significantly affected by renewable energy policies and regulations, stranded assets and new infrastructure requirements, as well as changing perceptions of investors and consumers (Ciola et al. 2023; Hoque et al. 2023). Moreover, the term "cross-border impact" can broadly include any actions, such as international climate policies or EU energy regulations, that are a response to perceived or anticipated climate change impacts, as long as the original impact as well as the action taken originate outside Finland.

2.4 The general morphological analysis

To remedy the fact that the SSPs were not known in detail to all interviewees, a GMA was created, in which the Finnish energy transition — using the two decarbonisation scenarios — were compared to the SSPs. GMA is an effective tool for systematically structuring and analysing complex aspects of and relationships between different problem complexes, such as alternative scenarios (Ritchey 2011; Witt et al. 2018). Comparing scenarios across geographical scales has been proven useful when the processes at one scale directly depend on the processes at the other scale (Zurek and Henrichs 2007). This is true in this study, which assumes that the success of the Finnish energy transition will depend on how the rest of the world develops. Similarly, Biggs et al. (2007) emphasise the benefits of linking scenarios across scales when the purpose is to evaluate the effectiveness of local policy options in alternative world futures; a criterion that applies to this study.

The GMA was created based on the steps outlined in Johansen (2018): First, relevant SSP elements for which corresponding data were available in the Finnish scenarios, were identified based on Bauer et al. (2017) and Riahi et al. (2017). Next, the morphological field — an 11×5 matrix consisting of the SSP mitigation scenarios (explained below) on the X-axis and the identified SSP elements on the Y-axis — was filled by adding the different states for the SSP1-5 mitigation scenarios for each element. To better align with the Finnish scenarios — which assume that the 2°C target is achieved — and bring forward the effect of different socioeconomic developments rather than different levels of climate change, the SSPx-2.6 mitigation scenarios were used (Riahi et al. 2017). The SSPx-2.6 scenarios result in an end-of-century forcing level of 2.6 W/m^2 and have a high probability of meeting the 2°C target. This level can be reached in at least some modelling simulations for all the SSPs, except for SSP3 (Rogelj et al. 2018). Therefore, the most stringent SSP3 mitigation scenario available, namely SSP3-3.4 was used instead. The difference in the temperature increase between SSP3-3.4 and the SSPx-2.6 scenarios — at the most 0.2°C in 2050 and 0.5°C in 2100 (Riahi et al. 2017) — is small enough to not require any further consideration in this study, which is more focused on the effect of different socioeconomic developments. Lastly, the SSP states were compared to data in the two Finnish scenarios, and states that aligned well or partially with the scenarios were identified and highlighted with either green or yellow (Table 4). Consult the Online Resource for additional information on the SSPs and the GMA.

The resulting GMA embeds the Finnish energy transition within different global development trends and highlights the many international connections that the energy transition entails. It shows which potential development pathways — represented by different mitigation SSPs — align well with the Finnish energy transition, and which pathways are likely to cause frictions, due to them differing significantly from the assumptions in the Finnish scenarios (Table 4). The GMA also gives a sense of the level of consensus between the experts and the Finnish scenarios, regarding international interdependencies within energy systems.

Other studies that have used similar multi-scale comparing approaches when examining regional or local scenarios in the context of the SSPs, are, e.g., Palazzo et al. (2017) in a study of West African food security, Talebian et al. (2021) in an assessment of CBIs

Table 4 Concise GMA with the Finnish scenarios and mitigation SSPs

Element	SSP1-2.6	SSP2-2.6	SSP3-3.4	SSP4-2.6	SSP5-2.6
Economy and lifestyle					
International trade	Globally connected markets, regional production ***Conserve***	Imperfectly functioning global markets with entry barriers	Strongly constrained	Open markets in high-tech economy, low-tech economy left outside ***Continuous Growth***	Strong and global, with regional specialisation in production ***Continuous Growth***
Globalisation	Connected markets, regional production ***Conserve***	Semi-open globalised economy	De-globalising, regional security	Globally connected elites ***Continuous Growth***	Strongly globalised, increasingly connected ***Continuous Growth***
Policies and institutions					
International cooperation	Effective ***Continuous Growth, Conserve***	Relatively weak	Weak, uneven	Effective for globally connected economy, not for vulnerable populations	Effective for development goals, more limited for environmental goals
Institutions	Effective at national and international levels ***Continuous Growth, Conserve***	Uneven, modest effectiveness	Weak global institutions	Effective for political and business elite, not for rest of society	Increasingly effective, oriented toward competitive markets
Climate policy stringency	Early accession with global collaboration from 2020 onwards ***Continuous Growth, Conserve***	Some delays in establishing global action ***Continuous Growth, Conserve***	Slow accession	Early accession with global collaboration from 2020 onwards ***Continuous Growth, Conserve***	Some delays in establishing global action ***Continuous Growth, Conserve***
Technology					
Technological development	Relatively rapid, focused on environmentally friendly processes ***Continuous Growth, Conserve***	Medium, uneven	Very slow	Rapid in high-tech economies and sectors, slow in others ***Continuous Growth***	Rapid ***Continuous Growth***
Technological transfer	Relatively rapid ***Conserve***	Slow due to remaining legal- or property rights issues	Very slow or non-existent	Smooth transfer between high-tech countries, slow in others ***Continuous Growth***	Rapid ***Continuous Growth***
Energy technology change	High modernisation. Increased energy efficiency. Rapid electrification and introduction of hydrogen ***Continuous Growth***	Phase out of solid energy carriers. Increased electrification. Significant use of CCS	Slow tech change, directed toward domestic energy sources. Increased energy efficiency. CCS and BECCS used widely	Diversified investments in energy efficiency, CCS and BECCS. Modernisation and electrification are rapid in high income but slow in low income countries ***Conserve***	High modernisation. Substantial and rapid transformation of the energy system. Rapid and widespread electrification. BECCS is used widely, CCS to a lesser extent
Energy sector					
Energy mix (shares of fossil fuels and non-biomass renewables in 2050)	Fossil fuels 67%, 10% with CCS. Non-biomass renewables 18%	Fossil fuel 62%, 20% with CCS. Non-biomass renewables 18%	Fossil fuels 68%, 19% with CCS. Non-biomass renewables 8%	Fossil fuels 54%, 17% with CCS. Non-biomass renewables 11% ***Conserve***	Fossil fuels 61%, 10% with CCS. Non-biomass renewables 11%. ***Continuous Growth***
Use of nuclear energy	Very low, virtually phased out	High, increasing ***Continuous Growth, Conserve***	Low	Very high, increasing sharply ***Continuous Growth, Conserve***	Moderate, some increase
Use of bioenergy	High, increasing, low use of BECCS ***Continuous Growth***	Moderate, increasing	High, increasing, some use of BECCS	High, increasing, BECCS widespread ***Conserve***	High, increasing sharply, almost all with BECCS
Compatibility of assumptions in Continuous Growth	Green boxes: 3 Yellow boxes: 3	Green boxes: 1 Yellow boxes: 1	Green boxes: 0 Yellow boxes: 0	Green boxes: 2 Yellow boxes: 4	Green boxes: 3 Yellow boxes: 3
Compatibility of assumptions in Conserve	Green boxes: 6 Yellow boxes: 1	Green boxes: 1 Yellow boxes: 1	Green boxes: 0 Yellow boxes: 0	Green boxes: 3 Yellow boxes: 2	Green boxes: 0 Yellow boxes: 1

on and adaptation options in Kenya, and Frame et al. (2018) when developing policy relevant climate change impact scenarios for New Zealand. These studies have utilised the concept of extended SSPs, in which the global set of basic SSP elements are tailored to the regional or local context (van Ruijven et al. 2014). In contrast, while this study has used some extended SSP elements for Finland in the GMA (see the Online Resource), the main purpose was to embed the Finnish transition in the global context, not to extend the SSPs to the Finnish setting.

3 Results

The coding of the interview transcripts revealed that the interviewees mentioned CBIs related to international trade, geopolitics, and the international financial market the most, while cross-border infrastructure, social and behavioural factors, and the biophysical environment were mentioned less frequently (Fig. 2). In the following, these CBIs are discussed according to the CBIP approach, after which the insights from the GMA are explained and compared to the opinions of the interviewees.

3.1 Identification of CBIs according to different impact pathways

3.1.1 Geopolitical pathway

The interviewees agreed that Finland is highly affected by regional (EU) and international climate policies. A strong international commitment to climate change mitigation was

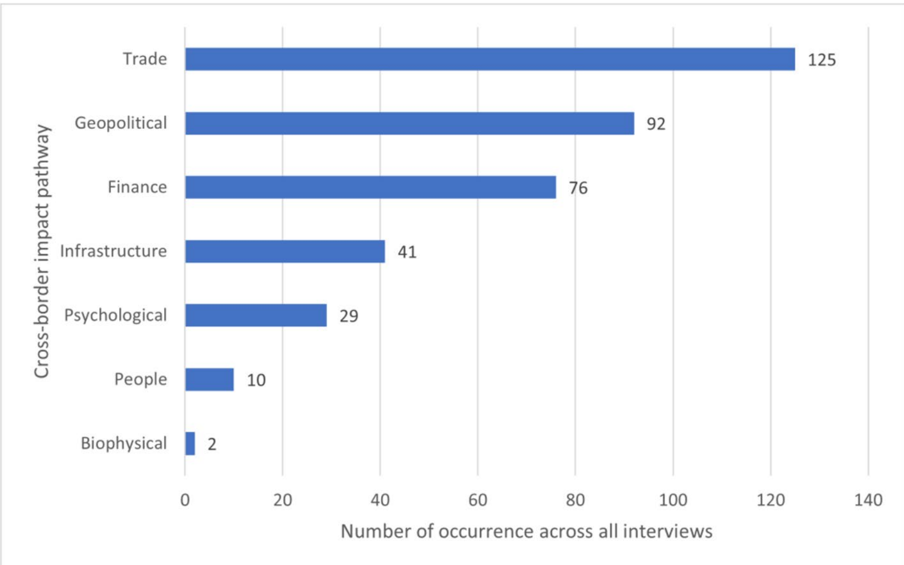

Fig. 2 The occurrence of different impact pathways in the coding process across all interviews, i.e., the number of times a statement made by an interviewee was coded according to one or several of the pathways. Note that statements could be coded according to multiple pathways, and the same aspect may have been mentioned several times

considered to have a boosting effect on the global, as well as the Finnish, energy transition through, e.g., diffusion of emission reduction mandates and low-carbon technology directives around the world. Nevertheless, one interviewee considered the commitments by individual countries or cities, and efforts made by the private sector, as more important than the stringency of global climate policies (Priv2, August 2022). Another interviewee concurred, saying that “most progress has been seen in sectors where global market forces have enabled a rapid transition, whereas sectors mainly steered by political incentives have lagged behind” (Gov1, August 2022). The reason for this, according to the interviewees, is the poor generalisability of specific political guidelines to a wide variety of different industries and processes. Hence, “businesses and industries are better off choosing the measures that work best for them through a more market-based approach” (Priv2, August 2022). Nevertheless, the underlying driver for accelerating decarbonisation efforts in private companies or local entities could still be an anticipation of stricter political regulations in the future. For instance, one interviewee considered the EU emissions trading system (EU-ETS) to be the main driver of emission reductions in the Finnish energy sector (RNat2, August 2022), a view that is supported by, e.g., Dechezleprêtre et al. (2023).

Several interviewees feared that political pressure to accelerate the energy transition too rapidly could result in increased inequality between countries, and increase the risk of the world becoming divided between fossil fuel states vs. low-carbon states, as the availability of cheap fossil fuels would be exploited by low-income countries unable to keep up with the transition pace (RSoc3, August 2022). Subsequently, global GHG emissions could rise and the risk of carbon leakage could increase. As pointed out by a few interviewees, a carbon border adjustment mechanism (CBAM) or similar measure would probably be implemented as a response, furthering the divide between the west and the rest, while raising prices and/or suppressing the availability of certain goods. The risk of the CBAM increasing social and economic inequality between rich and poor countries has also been brought forward by other studies (Magacho et al. 2023).

Several interviewees highlighted the risk of climate change induced crises and conflicts steering political focus, and hence resources, away from climate change towards solving the immediate crisis at hand, thus potentially slowing down the energy transition. Several interviewees pointed to the Russian invasion of Ukraine as an example of how geopolitical shocks can have profound impacts on the energy transition. As one interviewee pointed out, “the war has shattered the orderly planned energy transition that the world had anticipated, as we now see a deterioration of international relations and trade networks, and many countries are hastily replacing Russian gas with whatever fuel they can get their hands on, such as coal or LNG” (RSoc3, August 2022). On the other hand, the war has also pushed many countries to invest more in renewables and low-carbon options (Steffen and Patt 2022). In the longer run, according to the interviews, the war could very well speed up the transition as the quest for energy security is aligned with the aim of carbon neutrality.

3.1.2 Trade pathway

A stable geopolitical environment was considered a prerequisite for smooth and cooperative international markets. All the interviewees agreed that Finland is very much dependent on international trade in energy technology and related components, since the potential to produce goods domestically is limited in a small country like Finland. The level of energy self-sufficiency could even drop, according to some interviewees, contrary to the prevailing perception amongst policy makers that the energy transition will increase self-sufficiency. The Nordic countries as well as the EU will remain the most important trade partners for energy-related goods, according to the interviewees. However, it was agreed that new production and supply centres will emerge, as exemplified by China, which has become a major trade partner for many components and raw materials needed in the energy transition.

Several interviewees pointed out that, the more extensive the supply network becomes, the higher the risk of climate change impacts affecting vulnerable nodes in the network. On the other hand, several interviewees pointed out that international trade can reduce the impact from disruptions, if it induces diversification of supply chains. Nevertheless, the increase in systemic risks affecting international supply chains is an imminent threat to many companies, who tend to be insufficiently prepared to tackle such complex phenomena (Colon and Hochrainer-Stigler 2022).

Many interviewees were concerned about the price tag of decarbonisation if the energy transition is pushed too fast and supply of materials and components is not able to keep up with demand. Especially the availability of critical minerals and metals was considered by all interviewees as a potential bottleneck that may hinder a rapid global energy transition, as some studies suggest that current reserves may not be enough to cover global demand (IEA 2022). Additionally, new mines will be difficult to develop in many places due to social or environmental concerns. One interviewee also considered the availability of expertise as a limiting factor, as the number of professionals who can build out low-carbon energy infrastructure is in some places inadequate (Priv1, August 2022). However, undiscovered reserves, the emergence of alternative technologies that use different materials, as well as development of more efficient ways to use the materials, could alleviate the problem, according to the interviewees. Additionally, in light of new modelling exercises and viewpoints, several studies have challenged the perception that a rapid transition would be expensive (Unnerstall 2017; Victoria et al. 2020; Ives et al. 2021).

When carbon neutrality has been achieved and components for building low-carbon energy infrastructure are no longer needed to the same extent (as the infrastructure is already in place), many interdependencies will still remain, but perhaps to a lesser degree, according to some interviewees. New interdependencies will instead be created in the form of international recycling networks, negative emission and carbon removal technology supply chains, and CO_2 transportation for final storage. However, the interviewees pointed out that the interconnections, although numerous, may not be as critical in a low-carbon energy system, compared to the current fossil fuel–based energy system, because of less dependence on fuel imports, greater diversity in supply networks, combined with a ramp up of domestic energy production. Likewise, studies have argued that the current amount of internationally traded minerals, metals and components required to sustain a fossil fuel–based energy system, is much greater than the amount that will be needed in a low-carbon society (Krane and Idel 2021).

Weak or slow energy transition efforts in the rest of the world, would also induce higher prices for industries in Finland compared to other countries, with the risk of carbon leakage, according to the interviews. On the upside, an initially higher price for decarbonisation could be earned back multiple times if Finland, as a successful frontrunner, would become a major exporter of technology, products, expertise, or low-carbon energy when the transition finally takes off internationally. However, slow technological progress in the rest of the world increases the risk of unsustainable energy technology lock-ins globally, due to short economic and political cycles, slowing down the Finnish transition as well. The relatively weak direct climate change impacts projected for Finland (see, e.g., Benzie et al. 2016), was considered by some interviewees as a competitive edge in a world where many other countries are at risk of suffering from, e.g., water stress or extreme weather that could disrupt energy production. Finland has the space and the political will for building out large wind farms, for instance, which could produce excess electricity for export to Europe, or for producing green hydrogen or steel that requires large amounts of renewable electricity.

3.1.3 Finance pathway

A strong global commitment to climate change mitigation, a stable geopolitical environment, and international cooperation, were considered by several interviewees, as important enablers of effective green finance, which will be extensively needed in a global energy transition. Studies have showed that especially small economies are heavily dependent on adequate financing to enable a rapid buildout of low-carbon energy infrastructure, since many technological solutions are capital intensive, and zero-marginal-cost technologies tend to be bad investments in liberalised markets (Kraan et al. 2019; Blazquez et al. 2020; Temmes et al. 2021).

As a frontrunner in the transition, Finland could be a serious contender in the competition for international investments, although one interviewee feared that it might be too late, as other countries, such as Denmark, already have established themselves as reliable investment targets for low-carbon technology many years ago (Gov1, August 2022). In addition, disasters, crises, and conflicts may divert finance away from climate change related projects, according to the interviews, hence stalling the transition and decreasing the chances of meeting the Paris Agreement goal.

3.1.4 Infrastructure pathway

Decarbonising the energy system will require a substantial buildout of infrastructure for renewable energy production, transmission, and distribution. The interviewees believed that more cross-border transmission infrastructure in an increasingly interconnected European electricity grid will be needed to ensure security of supply amidst increasing electricity demand, considering the current inadequacy of electricity storage options. Being increasingly connected to a very wide network of European, and potentially beyond, electricity grids, increases the exposure to climate change induced damage to the network, compared to a smaller domestic grid. Furthermore, the more electrified the society becomes, the more affected it is by electricity supply disruptions.

On the other hand, more interconnections also spread out risks over a larger network of grids, which was considered by the interviewees to increase resilience, especially as more decentralised electricity production capacity is being built around Europe. One interviewee highlighted the politically challenging task of agreeing on the rules for governing an integrated European electricity system, since “many countries generally are reluctant to give EU more power, especially regarding questions of energy security” (RSoc3, August 2022). However, each country regulating its own part of an interconnected grid network was considered infeasible by the interviewee.

3.1.5 People pathway

Two interviewees regarded the social dimension of the energy transition as the most important issue, with the potential to derail the transition if not taken seriously.

Especially if the transition is pushed too fast, social and environmental dimensions are at risk of being neglected. Ensuring that social and sustainability standards are fulfilled all along the supply networks takes time, but was considered by the interviewees to be of utmost importance.

Unless properly accounted for and addressed, climate change impacts could result in a huge increase in climate refugees around the globe, with some of them reaching Finland as well. According to one interviewee, a sudden arrival of large numbers of people could alter both energy demand patterns and distribution of people, with potential challenges for the energy system, especially during peak demand hours, if not properly accounted for (RTech2, August 2022). However, the impact on the energy transition of increasing immigration of climate refugees, is difficult to assess and plan for, as studies disagree on both the effect that climate change will have on international migrations (Buhaug et al. 2022), as well as the effect of international immigration on the energy system in the destination country (Liang et al. 2020).

3.1.6 Psychological pathway

Most interviewees acknowledged the importance of the psychological pathway, as transposing the perceptions of climate change and energy transitions held by communities in other countries onto Finnish citizens, but were unable to state whether the impacts would be positive or negative, large or small. Many interviewees believed that a strong global commitment to climate change mitigation would help accelerate the energy transition in Finland, by inducing a perception of the transition as feasible and necessary in the minds of Finnish citizens, and hence incentivise domestic climate policies. Conversely, if citizens consider the transition to be unjust, due to, e.g., high prices or certain communities suffering disproportionately from EU regulations, political resistance will increase as well.

The suite of technologies that will ultimately be used in Finland was considered by some interviewees to be dependent on the acceptability of different technologies by Finnish citizens, which in turn is affected by the roll out or roll back of these technologies in the rest of the world. For instance, some interviewees believed that the role of bioenergy could rise temporarily, as it is the most logical option for replacing fossil fuels in many processes, but “because of multiple issues regarding sustainability, carbon neutrality, and impacts on biodiversity, negative public perceptions will likely diminish its use in the future” (RNat1, June 2022).

3.1.7 Biophysical pathway

Aspects relating to the biophysical pathway were rarely mentioned by the interviewees, perhaps due to biophysics being outside their areas of expertise. Some of them reflected on the urgency of the global energy transition, and the fact that the slower the transition, the more GHGs will be emitted into the atmosphere and consequently, the more the climate will change also in Finland, increasing the risk to domestic energy production and infrastructure from direct climate change impacts. One interviewee highlighted the opening up and increased utilisation of the Arctic waters, as potentially incurring risks to the sensitive Arctic ecosystems in Finland, potentially increasing further the resistance towards building wind farms in these areas (RSoc1, August 2022).

3.2 Implications of different global development trends

The interviewees agreed that the Finnish energy transition will unfold differently depending on how the rest of the world evolves, and that the suite of CBIs could differ in different SSP worlds. If current global trends (illustrated in SSP2-2.6) — such as relatively slow international climate action and persistent barriers to international trade — continue, the Finnish energy transition could be challenging to complete. This was reaffirmed in the GMA, in which only two SSP2-boxes were found compatible with the Finnish scenarios. Unsurprisingly, both the interviews and the GMA point to the fact that the Finnish transition would be aided the most by the developments outlined in SSP1-2.6, considering the common aim of moving towards a more environmentally sustainable world. Likewise, due to relatively well-functioning international markets and institutions, combined with quite rapid technological development, both SSP4-2.6 and SSP5-2.6 are advantageous especially for the continuous growth scenario, resulting in ample availability of technology, components, and raw materials needed for the energy transition. Conversely, the Finnish scenarios were not compatible with an SSP3-3.4 world characterised by a lack of international cooperation, insecurity of financial flows, ineffective trade networks, and slow technological development and diffusion, all of which are needed for a rapid energy transition (Table 4).

The GMA shows that the continuous growth scenario is potentially more adaptive than the conserve scenario, since it was found to be sufficiently compatible with SSP1-2.6, SSP4-2.6, as well as SSP5-2.6, whereas the conserve scenario was found strongly compatible only with SSP1-2.6, and to a lesser degree SSP4-2.6 (Table 4). Interestingly, the SSP characteristics that were found most beneficial for continuous growth, i.e., globalisation and booming international trade, are also to some extent unfavourable regarding CBIs, since the probability of CBIs emerging increases the more globalised and interconnected the world becomes. For instance, an expansive international power grid network is more prone to disturbances than a Nordic grid, and the risk of spillover environmental damage, such as pollution of shared watersheds, from overreliance on technological solutions or mining in neighbouring countries may increase, according to the interviews. Additionally, SSP5-2.6 is characterised by specialised production centres and complex supply networks (Kriegler et al. 2017), increasing the risk from climate change induced supply disruptions or price spikes. On the other hand, SSP5-2.6 also offers the best opportunities for exporting energy technology and securing green finance from international sources (Table 5).

Within both SSP1-2.6 and SSP4-2.6, rapidly pushing the transition through, as envisaged by the element of international climate policy stringency, increases the risk of supply shortages and price spikes, and hence social resistance, according to the interviews. However, within SSP1-2.6, this could be sufficiently mediated by strong international cooperation on aspects of social justice and equality (van Vuuren et al. 2017). Moreover, a strong international commitment increases the acceptability of stringent climate policies also in Finland, and improves the availability of international green finance. Conversely, in SSP4-2.6, inequality within and between countries and low adaptive capacity in many regions (Calvin et al. 2017) may result in a disrupting geopolitical environment and the emergence of conflicts in the face of, e.g., extreme weather events, increasing the risk of disruptions to international supply chains or grid infrastructure, as well as disorderly migrations. On the upside, in SSP4-2.6, as well as in SSP2-2.6, nuclear power is internationally accepted as an effective low-carbon solution, improving the

Table 5 Summary of the most important CBIs identified for Finland through the interviews or the GMA, and the mitigation SSP in which they are most prominent

CBI pathways	SSP1-2.6	SSP2-2.6	SSP3-3.4	SSP4-2.6	SSP5-2.6
Geopolitical	Strong global mitigation commitment pushes the transition forward	Insufficient global mitigation commitments slow down the transition	Insufficient international cooperation on mitigation. Regional conflicts cause instability on international energy markets	Low adaptive capacity in many regions increases climate change induced disasters and steers international political focus away from decarbonisation efforts	Geopolitics has a profound effect on global energy markets in a strongly globalised world
Trade	Rapid transition pace leads to increased prices for hard-to-decarbonise sectors. High international demand causes supply shortages or price spikes	Renewable energy technology prices remain high	Slow international trade hinders dissemination of energy technology to Finland, impeding the transition	Low adaptive capacity in many regions increases climate risks to production centres in these regions and to international trade networks	Increased energy export opportunities for Finland. Global dissemination of energy technology is rapid
Finance	Plenty of international green financing opportunities	Insufficient international green financing opportunities	International green financing instruments non-existent	International green financing only available for high income countries	Plenty of international green financing opportunities
Infrastructure				Low adaptive capacity in many regions increases the risk from climate change induced damage to cross-border infrastructure that Finland depends on	International power grid networks used by Finland, are prone to physical climate change impacts inducing disruptions
People				Sudden influx of immigrants causes local energy demand pressure	Globalisation increases the movement of people, with potential impacts on local energy demand
Psychological	Strong global mitigation commitment increases public acceptance for stringent mitigation efforts in Finland	Strong international acceptance of nuclear power increases acceptance for nuclear in Finland		Persistent inequality decreases acceptance of transition measures in many countries, which may spill over to Finland. International acceptance of nuclear increases acceptance in Finland	
Biophysical			The 2°C target is not met, causing more pronounced climate change impacts globally		Spillover environmental damage due to overreliance on technological solutions in many countries

outlook for nuclear also in Finland. However, in SSP2-2.6, and even more pronounced in SSP3-3.4, slow international cooperation on climate change mitigation hinders the dissemination of energy technology and financing instruments. In SSP3-3.4, climate change induced social unrest, conflicts, and migrations were considered highly probable, with potential impacts on international energy markets. In addition, SSP3-3.4 fails in achieving the 2°C target, accentuating climate change impacts globally (Table 5).

4 Discussion

This study shows that the Finnish energy transition is embedded in a global context that will shape the speed and direction of the transition. Different pathways towards decarbonisation, with differing sets of interdependencies, are possible, as illustrated by the compatibility of the Finnish decarbonisation scenarios with SSP1-2.6, SSP4-2.6, as well as SSP5-2.6. However, current development trends are not sufficient for reaching carbon neutrality (thus incompatibility with SSP2-2.6) and global cooperation is essential (thus incompatibility with SSP3-3.4).

The interviewees agreed that new international dependencies will be created in the form of mineral and raw material supply chains, global energy technology trade, global investment markets, international or regional electricity grids, international hydrogen (and perhaps bioenergy) supply infrastructure networks, and more integrated political goals. This reiterates the importance of having a system-of-systems perspective when studying energy transitions, since the energy sector is intertwined in a complex network of technological, economic, political, social, and environmental domains (Groundstroem and Juhola 2021; Oduro and Taylor 2023). In addition, interconnections between the energy and non-energy sectors, such as water, waste, and agriculture, are projected to multiply in the course of the transition (Schlosser et al. 2023), as energy producers and consumers are merged into prosumers (Cherp et al. 2011).

International interdependencies are likely to predispose the Finnish energy transition to a number of different CBIs. The current global energy transition is, in contrast to previous energy transitions, politically driven (Blazquez et al. 2020), which explains the fact that all of the interviewees emphasised CBIs transmitted via the geopolitical pathway. It also accentuates the importance of regional and international climate policies for a small open economy like Finland. The geopolitics of the global energy transition has attracted plenty of attention in recent years, and the literature in this field tends to confirm the findings of this study, i.e., that the geopolitical landscape (pertaining to, e.g., energy powers, political alliances, or international cooperation) will likely change during the transition, but its importance will remain (Vakulchuk et al. 2020; Scholten et al. 2020). The Russian invasion of Ukraine further engrained the notion of energy security within geopolitics and highlighted many vulnerabilities within the existing energy market (Steffen and Patt 2022).

The interviewees agreed that the reliance on international markets for procurement of low-carbon energy technologies and associated raw materials and components, as well as large scale buildouts of cross-border electricity transmission networks, introduce new paths for CBIs to enter Finland, in the form of, e.g., supply shortages or price spikes induced by climatic events. An internationally connected, integrated and complex energy system brings both challenges, in the form of many vulnerable nodes along the supply network, as well as opportunities in the form of greater diversity and resilience (Ratnam et al. 2020). For instance, Keles et al. (2020) showed that in tightly connected electricity market areas, electricity prices in smaller countries (such as Finland) are strongly determined by the prices in larger neighbouring countries, a market characteristic that will likely intensify in the future as more cross-border transmission capacities are developed.

This study also highlights the importance of social, cultural, and behavioural factors that may influence national energy transitions. An emerging research field has highlighted the many social dimensions, such as values, norms, knowledge, and motivations that all combine in complex and dynamic ways to define and shape the ongoing energy transition. In essence, studies show that the ever-changing nature of human behaviours and perceptions cannot be ignored when planning and executing national energy transitions, as they contain the power to either accelerate or derail the transition through the diffusion of ideas and practices across time and space (Edomah et al. 2020; Chateau et al. 2021).

Climate risks have been shown to differ between SSP mitigation scenarios due to different socioeconomic assumptions (Gambhir et al. 2022). This study finds that SSP5-2.6, SSP4-2.6, and SSP1-2.6 are the global development pathways in which the Finnish energy transition would be most susceptible to CBIs. Seeing that these are also the SSPs that are most beneficial for a smooth rollout of the energy transition, the Finnish energy sector could be faced with either an inhibiting international setting or a potentially risky set of CBIs. To that end, future research should focus on identifying appropriate adaptation options and strategies that are robust across scenarios, to ensure the timely completion of the energy transition regardless of the suite of global development trends or CBIs that may stand in its way. Currently, neither of the Finnish decarbonisation scenarios are flexible enough to offer guidance on how to achieve carbon neutrality amidst different global developments, which may lock in the Finnish decarbonisation efforts on an untenable path.

Relying on the opinions of experts when discussing inherently uncertain future developments, needs to be regarded as only one piece of the puzzle, reflecting the personal beliefs and perceptions of a few individuals and not the ultimate truth. The fact that all of the interviewees had fairly similar viewpoints, with few conflicting statements, may reflect the relatively narrow research base from which the interviewees obtain their knowledge. Moreover, due to the complex, cascading and dynamic nature of climate change impacts, climatic event are likely to induce CBIs through several pathways. Hence, the interview answers may have been distorted towards the impact pathways that were most familiar to the interviewee, artificially accentuating the importance of the trade and geopolitical pathways. Additionally, during the coding process, categorising CBIs as belonging to one particular pathway was sometimes infeasible, resulting in several statements being coded under multiple pathways. Overall, pinpointing the mitigation SSPs in which CBIs would be most likely, is hypothetical, due to uncertainty regarding the unfolding of the future.

5 Conclusions

The comparison of global mitigation SSPs to Finnish decarbonisation scenarios in the GMA offered a comprehensive view of the implications that different global development pathways may have on the realisation of Finnish decarbonisation goals and targets. Additionally, the CBIP approach based on input from expert interviews, provided valuable insights regarding CBIs on the Finnish energy sector, something that has not been sufficiently studied (Berninger et al. 2022). In essence, this study shows that the Finnish energy transition will likely be affected by international energy and climate policies, barriers to and opportunities for international trade, technology development and diffusion, supply disruptions and price spikes, as well as geopolitical and social factors, induced by physical or transition impacts of climate change originating in other countries. In addition, the suite of potential CBIs that could eventually emerge in Finland will probably differ depending on how the world evolves. Importantly, according to Groundstroem and Juhola (2018), CBIs are not sufficiently accounted for in the Finnish climate and energy strategy, despite their potentially disrupting effect.

Moreover, the study shows that the two Finnish decarbonisation scenarios that are supposed to guide the energy transition in Finland, do not account for different socioeconomic developments in the rest of the world, and the many implications they may entail for global energy markets or international climate and energy policies. For instance, the dependence on specific technologies (e.g., nuclear power or CCS) has been found problematic in both scenarios (Hyvönen et al. 2023), since the suite of energy technologies that will eventually be used in Finland, will depend on the speed and direction of technological developments in the rest of the world.

The results offer valuable insights for other countries or regions with similar characteristics as Finland (i.e., small, open economies, dependent on international or regional trade, and affected by climate and energy policies established elsewhere). In addition, regional climate and energy policy developments increasingly affect countries especially in the western world. For instance, the European Green Deal proposes a build-out of an interconnected energy system throughout Europe, including more cross-border electricity transmission capacity, as well as integrated markets for alternative fuels and infrastructure, such as hydrogen and energy storage technology (European Commission 2020). Greater interconnectivity inherently broadens the scope of CBIs that may affect a particular area and introduces new climate risks that have previously been absent. For many countries, the seemingly manageable impacts of direct climate change are significantly trumped by the wide array of CBIs that may emerge through international connections to regions more drastically affected by climate change (Hedlund et al. 2018).

Moving forward, it is imperative to build an energy system that is resilient, robust, and diversified throughout its full value chain, in order to avoid similar dependencies and bottlenecks as during the fossil fuel era. This requires national decarbonisation strategies to step out of a narrow domestic perspective, to comprehensively consider regional and global socioeconomic developments that may influence the speed and direction of the energy transition and the potentially disruptive CBIs that will affect it. This could be accomplished by better incorporating social and behavioural aspects into national transition scenarios, comparing national scenarios to global scale scenarios, such as the SSPs, and accounting for CBIs through a systems-wide climate risk assessment. Furthermore, decarbonisation policies should be developed according to a dynamic adaptive policy pathway (Mathy et al. 2016), to ensure that the decarbonisation strategies are easily adjusted and modified to reflect the continuously changing socio-technical–economic landscape. The war in Ukraine, as well as the COVID-19 pandemic, has shown that there will always remain unknown unknowns that may disrupt the energy transition profoundly. To that end, this study contributes to and improves the emerging literature in a research field that will become increasingly important as the global energy transition progresses and evolves in the coming years.

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Declarations

Ethical approval The principle of informed consent was applied in all interviews.

Competing interests The author declares no competing interests.

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