Received: 4 April 2023 | Revised: 1 September 2023 | Accepted: 10 September 2023

DOI: 10.1002/bse.3580

RESEARCH ARTICLE

Business Strategy and the Environment

WILEY

Climate risks to the renewable energy sector: Assessment and adaptation within energy companies

Sirkku Juhola[1] | Anna-Greta Laurila[1] | Fanny Groundstroem[1,2] | Johannes Klein[3]

[1]Faculty of Biological and Environmental Sciences, University of Helsinki, Helsinki, Finland

[2]Finnish Environment Institute, Helsinki, Finland

[3]Demos Helsinki Research Institute, Helsinki, Finland

Correspondence
Sirkku Juhola, PO Box 65, Biocentre 3, FI-00014, Faculty of Biological and Environmental Sciences, University of Helsinki, Helsinki, Finland.
Email: sirkku.juhola@helsinki.fi

Abstract

The importance of the renewable energy sector in mitigating climate change has received plenty of attention over the years, but climate risks to the renewable energy sector, and the need for adaptation within energy companies, have been largely overlooked. Subsequently, not much is known about the current state of climate risk assessments and adaptation measures within the renewable energy sector. This study addresses this gap by categorising different types of climate risks faced by renewable energy companies and the measures that are used to prepare and adapt to them. We summarise the existing literature on climate risks and adaptation within the renewable energy sector and carry out an interview-based qualitative case study regarding energy companies' perception and assessment of climate risks in Finland. The results show that while companies are aware of climate risks, particularly concerning the green transition, climate risks are not comprehensively assessed, and adaptation measures mainly account for direct physical risks with little regard for more systemic and complex risks, such as cross-border impacts or cascading risks.

KEYWORDS

private sector adaptation, risk management, systemic risk, transition risk

1 | INTRODUCTION

The energy sector plays a key role in mitigating climate change and the risks it brings. The expansion of clean energy technologies is a prerequisite for reducing greenhouse gas (GHG) emissions and decarbonising society (Owusu & Asumadu-Sarkodie, 2016), and the role of renewable energy companies in this regard is crucial (Bryant et al., 2020). However, as climate change impacts have already emerged and are projected to intensify even further in the future, the identification and management of climate risks in the renewable energy sector are of equal importance (Gernaat et al., 2021; Nam et al., 2021). To this end, renewable energy companies could conduct climate risk and vulnerability assessments to help identify assets and resources exposed to climate hazards, increase the resilience and adaptive capacity of the company and prepare for the risks related to the low-carbon energy transition (Adger et al., 2018; IEA, 2020).

Hitherto, climate risk and vulnerability assessments have mostly been conducted for regions or countries (Adger et al., 2018) with

Abbreviations: CSRD, Corporate Sustainability Reporting Directive; ESG, Environmental, social and governance reporting directives; EU, European Union; GHG, Greenhouse gas emissions.

relatively less emphasis on economic sectors. Additionally, adaptation efforts have mostly been led by the public sector with little or no steering of the private sector (Klein et al., 2018). Subsequently, the state of climate risk awareness and adaptation actions within private companies is less well understood (Averchenkova et al., 2016). There is a pressing need to accumulate empirical knowledge of different sectors, particularly of critical infrastructure, of which functioning is key to other economic sectors in society. A momentary or a short-term failure or collapse of the energy sector can have serious implications to societal security with cascading impacts across all activities. A longer-term failure to account for climate change impacts may undermine the capacity of the sector to reduce GHG emissions, leading to increased impacts of climate change.

There are several strands of literature pertaining to climate risks and adaptation from a private sector perspective, for example, regarding climate services and the communication and use of climate information (Porter et al., 2015; Tang & Dessai, 2012), organisational studies on perceptions of climate risks by industries (Berkhout, 2012; Klein et al., 2022; Orsato et al., 2017) and the ways in which climate disclosures shape the behaviour of firms and sectors (Tang & Demeritt, 2018). However, there is relatively little empirical work focusing on climate risk awareness within the renewable energy sector and how renewable energy companies manage and adapt to climate risks (Nam et al., 2021; Weinhofer & Busch, 2013; Yu et al., 2023). Additionally, the state of knowledge on and management of different kinds of indirect, systemic, cascading and cross-border impacts of climate change within the energy sector have not been extensively studied (Berninger et al., 2022). Overall, while previous studies have identified and analysed different climate risks to the private sector, the awareness of, attitude towards and responses to these risks within companies have not been comprehensively assessed (Sakhel, 2017).

This study addresses this gap by asking the following research question: How do renewable energy companies perceive different kinds of climate risks, and how are climate risk assessments utilised to adapt to these risks? The objectives of the paper are to appraise the existing level of knowledge on different climate risks within renewable energy companies, identify the motivations behind implementing adaptation actions and assess the utilisation of various climate risk and vulnerability assessments within the companies. We start by discussing the literature on climate risks and adaptation pertinent to the renewable energy sector and proceed by carrying out a qualitative case study through semistructured interviews to assess the perception and management of climate risks within the renewable energy sector in Finland. Our findings show that while most companies are aware of potential direct physical risks as well as transition risks, they are rarely assessed comprehensively or regularly, while more complex risks are rarely assessed at all. These findings urge energy companies to take a broader systems perspective in risk assessment and management trainings and guide the public sector towards providing more comprehensive informational steering and financial incentives for companies to engage with climate change risks.

2 | BACKGROUND AND ANALYTICAL FRAMEWORK

2.1 | Climate risks to the renewable energy sector

Various renewable energy resources—especially bioenergy and hydropower, which account for 10% and 3% of global primary energy production, respectively (IEA, 2017)—are highly vulnerable to changing climatic conditions (Edenhofer et al., 2011; Solaun & Cerdá, 2019). Other renewable energy sources, such as solar, wind, geothermal, air and ocean energy, are also susceptible to different types of climate risks (Alm, 2018; Bazyomo et al., 2016; European Parliament, 2021; Owusu & Asumadu-Sarkodie, 2016). The most well-known impacts and risks are direct physical risks induced by various weather phenomena on energy production (Schaeffer et al., 2012; Solaun & Cerdá, 2019; Wachsmuth et al., 2013). These predominantly arise through changing weather conditions, such as changes in temperature, precipitation, wind speed and extreme weather events (Emodi et al., 2019; Jerez et al., 2015; Mani & Pillai, 2010; Mukheibir, 2013; Patt et al., 2013; Poudel et al., 2011; Pryor & Barthelmie, 2010, 2013; Solaun & Cerdá, 2019). In addition, energy companies, with their oftentimes broad and international networks of operations, experience direct climate risks throughout the value chain, for example, on power plants, supply procurement, human resources (Cameron et al., 2018; Spalding-Fecher et al., 2016) and supply chains (Dahlmann & Roehrich, 2019). For instance, lower labour productivity due to heat waves may disrupt production processes, while extreme weather events may cause supply shortages of components or interrupt the delivery of products and services to customers (Fayolle et al., 2019; Steeves et al., 2016).

Climate risks are increasingly being regarded as complex phenomena that are shaped by the interactions of multiple stressors, compounding effects and nonlinear responses (Carter et al., 2021; Simpson et al., 2021), resulting in different types of indirect risks, such as systemic and cascading risks (Table 1) (Sillmann et al., 2022). Indirect risks can affect different sectors and regions in unpredictable ways through cross-sectoral and cross-border interactions (Groundstroem & Juhola, 2021; Hui Min et al., 2021). For instance, climate change-induced loss of income, reduced access to capital as investors become more climate risk aware and increased insurance premiums due to higher exposure to risk, may result in reduced financial performance of companies (Steeves et al., 2016; van Benthem et al., 2022). Overall, the global interconnectedness of the energy market—acutely highlighted, for example, by the Russian invasion of Ukraine in February 2022—predisposes energy companies to various cross-border and systemic impacts of climate change that may be difficult to foresee and prepare for (Groundstroem & Juhola, 2021).

In addition, the private sector and especially energy companies are increasingly being affected by different transition risks, which stem from societal and economic shifts towards a low-carbon society, which necessitates a shift away from fossil fuels. These may be related to, inter alia, tightening climate and energy policies that incur

TABLE 1 Risk types.

Type of risk	Definition
Direct risks	Climate change risks that directly hinder companies' ability to meet their objectives.
Physical risk	Climate change causes direct physical risks to companies by increasing the intensity or frequency of weather events such as heat waves, storms, floods or droughts (Alvarez et al., 2020) that may damage the company's assets and infrastructure, on which its operations depend. Physical risks concern not only private companies but also private financiers, because climate change negatively affects the property, income, costs and real estate values of borrowers and investors (Fayolle et al., 2019).
Indirect risks	Indirect physical climate risks affect the services and resources a company uses but does not own or control. These risks primarily impact the productive capacity of a company's assets and can affect both upstream and downstream operations (White, 2023).
Cascading risk	Direct impacts may initiate a series of other events, which cascade through interconnected systems, such as infrastructure, the economy, societal or ecological systems, creating a chain reaction of risks. The interactions can be one-way (like a domino effect) or have feedback connections (Helbing, 2013, Lawrence et al., 2020, Pescaroli & Alexander, 2018, Rocha et al., 2018).
Compound risk	Compound risks arise from the interaction of hazards, which can be characterised by single extreme events or several simultaneous or consecutive events that interact with exposed systems or sectors (IPCC, 2018).
Cross-border risk	Cross-border impacts of climate change create risks in locations distant from the initial impact, through the transmission of risks across borders via international connections (Carter et al., 2021).
Interacting risk	Combinations of hazards and their mutual effects between different factors and coincidences between environmental factors (Pescaroli & Alexander, 2018).
Interconnected risk	Complex interactions between people, the environment and technological systems with physical interdependencies that are closely related to interconnected social interactions (Pescaroli & Alexander, 2018).
Systemic risk	Individual events can trigger systemic risks in many complex systems in both natural and human-made environments. Systemic risks often arise from a direct risk, which then forms a set of indirect risks with cascading effects, affecting the structure, operation and stability of the entire system (Hochrainer-Stigler et al., 2020).
Transition risk	Transition risks affect companies' business operations through policy, legal, technology and market changes following the transition towards a low-carbon future. Transition risks include the following: **policy risks**, related to changing policy actions addressed at mitigating or adapting to climate change; **legal or litigation risks** related to the failure of companies to put in place mitigation or adaptation measures or properly disclose material climate risks; **technology risks** associated with the development of new technologies that may affect competitiveness, production and distribution costs or demand for products and services, creating winners and losers among companies; **market risks** connected to the shifts in demand for and supply of certain commodities and services as climate change is increasingly taken into account within society; **reputation risks** associated with changing perceptions of customers and communities concerning companies' actions towards mitigation or adaptation (Alvarez et al., 2020; Juntunen et al., 2021; Saada, 2020).

new regulations for companies, the development of new energy technologies that alter market conditions—resulting in, for example, price volatility, changing demand for goods or new competitors—or the company's reputation, which is affected by customers' and investors' concerns, negative media coverage or changing perceptions of civil society (Table 1) (Fayolle et al., 2019; Tsalis & Nikolaou, 2017).

2.2 | Climate change awareness, risk assessment and adaptation

Within the private sector, the understanding of physical climate risks that may emerge and the awareness of the measures that companies can take to maintain the profitability of their operations when facing climate risks have evolved in recent years (Canevari-Luzardo et al., 2020; Fayolle et al., 2019; Ngo et al., 2022; Winn et al., 2011). Subsequently, many companies have started to identify climate risks and prepare risk assessments or adaptation strategies to enhance the company's adaptive capacity. These assessments and strategies range in scope from being merely awareness raising documents to aiming at strengthening the role of employees in combating risks and climate proofing operations (Surminski, 2013). Assessments of climate risks utilise methods and processes for defining, evaluating and measuring risks—both to everyday practices as well as major strategic decisions—facilitating the comparison of different risks and enhancing the understanding of possible effects (Adger et al., 2018). Information gained through such assessments can help to reduce exposure and vulnerability to risks, transfer, share and combine risks and increase flexibility and risk tolerance, hence improving the adaptive capacity of companies (Hildén et al., 2018).

By conducting a climate risk assessment, a company can guide its own actions towards prioritising measures that reduce negative and adverse consequences (Adger et al., 2018). In short, a well-adapted company should, in principle, understand the possible effects of climate change on its business, take them into account in its strategic planning and decision-making, implement appropriate actions and undertake regular reviews and adjustments as trends and forecasts change (Surminski, 2013). However, adaptation action within the private sector is motivated by a wide range of both internal and external drivers, of which only some are directly related to climate change per se. For instance, company size, export orientation and financial performance are internal drivers that have been shown to correlate with environmental performance, while regulatory and legal requirements, corporate citizenship, stakeholder and investor pressure, as well as industry and market standards are external drivers that can incentivise adaptation actions within companies (Averchenkova et al., 2016; Gasbarro et al., 2017).

It is important to note that many actions taken by companies to improve resilience to environmental risks and shocks are part of standard risk management processes and may not be labelled as adaptation. Similarly, companies use a variety of different terms when referring to adaptation, and the distinction between mitigation and adaptation is not always clear (Agrawala et al., 2011). Additionally, while risks are commonly associated with negative consequences in climate change jargon, in economics, risks can also have positive consequences, in allowing companies to take advantage of expanding or emerging markets. Opportunities may arise, for instance, when private financiers respond to the changing needs of their customers by demanding greater incorporation of sustainability and adaptation measures (Bowyer et al., 2014; Fayolle et al., 2019). Likewise, climate change adaptation creates new business opportunities in several sectors, not least the energy sector.

Increasingly, climate risk assessments are becoming mandatory in many environmental, social and governance (ESG) reporting directives, complementing mandatory regulation on GHG emission reporting. For instance, as part of the EU Green Deal, the Corporate Sustainability Reporting Directive (the 'CSRD'), which entered into force in January 2023, strengthens the requirement for companies to disclose observed and potential climate risks to their operations within their sustainability reports and to prepare adaptation plans or strategies. The aim is to improve transparency of companies' sustainability efforts and give investors and stakeholders a way of evaluating and comparing the sustainability performance of different companies (EC, 2022).

Previous studies have shown that within private companies, especially those belonging to high-emission sectors such as energy, transition risks related to the changing regulatory environment concerning climate change tend to be regarded as more important than physical climate risks or market risks (i.e. changing customer demand or shifts in financial markets) (Sakhel, 2017). Additionally, only a few firms have been shown to engage in strategic adaptation, that is, with the main purpose of increasing the adaptive capacity of the firm to climate change (Meinel & Schüle, 2018). As a result, comprehensive climate risk assessments have not been considered a top priority for many companies.

A major challenge when conducting climate risk assessments is the high degree of complexity, due to countless interacting factors (Adger et al., 2018). Traditional risk assessment methods usually consider only one hazard at a time, which can lead to an underestimation of the risk, as the processes that cause extreme events often interact and are spatially and/or temporally dependent (Zscheischler et al., 2018). Cascading climate risks resulting from possible cascading effects through interconnected systems pose special challenges for risk assessments, especially when risks are transferred across sectors and international borders, affecting supply chains and wider markets (Challinor et al., 2018). Subsequently, many companies underestimate their exposure to climate risks (Goldstein et al., 2019). Additionally, companies often lack basic information about vulnerabilities or weaknesses in their own systems, which may exacerbate the implications of the risks (Cameron et al., 2018). Other identified barriers to properly implementing adaptation measures are managers' poor perception of climate risks, lack of financial resources or inadequate expertise within the company (Averchenkova et al., 2016; Todaro et al., 2021). Hence, few companies have been able to properly analyse all potential climate risks to their businesses in a comprehensive manner, and especially, climate risks that are projected to materialise further into the future are often neglected (Sakhel, 2017).

Adapting to climate change requires more than isolated climate risk assessments: A company's ability to deal with climate risks depends not only on its own operations but also on the resilience of customers, suppliers, and employees, and on functioning infrastructure. For instance, disruptions to transport and energy systems can have far-reaching consequences for production and access to services (Surminski, 2013). Adaptation is also important for producers who depend on private sector markets, consumers who depend on privately produced goods and services and workers whose livelihoods depend on businesses (Goldstein et al., 2019). The many ways in which the climate intersects with trends affecting other businesses and society, for example, through the availability of natural resources, changing disease patterns and migration are thus important to consider.

2.3 | Analytical concepts and framework for analysis

We rely on the literature above to answer our research question regarding how renewable energy companies perceive different kinds of climate risks and how climate risk assessments are utilised to adapt to these risks; see illustration in Figure 1. To address the first part of the question, we utilise the most recent IPCC risk definition (Pörtner et al., 2022) with a focus on how direct climate risks emerge for an entity, an energy company in this case. This definition is complemented by definitions of various indirect and transition risks as defined in the literature (Carter et al., 2021; Simpson et al., 2021; Steeves et al., 2016; van Benthem et al., 2022). When addressing the second part of the research question, we define adaptation as reactive or

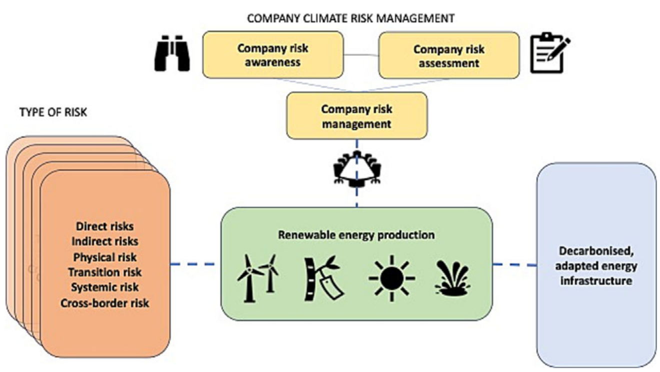

FIGURE 1 Analytical concepts.

proactive actions taken by private companies to reduce the risks from climate change and increase the adaptive capacity of the company (Hildén et al., 2018; Surminski, 2013). Adaptation actions may be prompted by a wide range of internal and external drivers, including economic and environmental performance and regulatory requirements (Averchenkova et al., 2016; Gasbarro et al., 2017). Climate risk assessments play a key role in identifying these drivers and enabling the companies to act on available information and hence adapt to emerging risks. To see how the concepts presented here are linked to the coding, see Table 2.

3 | METHODS

3.1 | Case study

Finland was chosen as a case study due to its highly ambitious goal of reaching carbon neutrality already by 2035, enshrined in the 2022 revision of the Climate Act (423/2022) (Ministry of the Environment, 2022). Since energy use is Finland's largest source of emissions (Statistics Finland, 2020), a major transformation of the energy sector—requiring various measures such as increasing the share of renewable energy, improving energy efficiency, and reducing energy demand—is crucial for reaching the goal. Despite the share of renewable energy in the Finnish energy mix having increased consistently in the past 20 years—accounting for 40% of the total energy consumption in 2020 (SVT, 2021)—the vast majority consists of bioenergy used by the forest industry in its own processes, while the most important energy sources for decarbonisation of society, that is, wind and solar, only amounted to approximately 3% of the total consumption in 2021.

This means that a substantial scale up of renewable energy production and build out of the transmission and distribution infrastructure are to be expected in the coming years. In order to ensure that the emerging low-carbon energy system is resilient and well-adapted to the future climate, risk assessments for new assets, infrastructure

TABLE 2 Coding framework.

Theme	Category	Subcategory	Code
Climate risk term/concept	Recognition and use of the term climate risk		[Climate risk term]
	IPCC-definition	Exposure, vulnerability, hazard	[IPCC-definition]
Different types of climate risks	Different types of climate risks		[Different types of risks]
		Direct risk	[Direct risk]
		Indirect risk	[Indirect risk]
		Physical risk	[Physical risk]
		Transition risk	[Transition risk]
		Systemic risk	[Systemic risk]
		Cross-border risk	[Cross-border risk]
	Identified types of risks		[Identified risks]
Climate risks to renewable energy	Climate risks to renewable energy		
		Windpower	[Windpower]
		Hydropower	[Hydropower]
		Solar power	[Solar energy]
		Bioenergy	[Bioenergy]
	Detected/identified risks		[Identified risks]
	Most significant risks		[The most significant risks]
	Climate risk preparedness		[Preparedness]
Climate risks for companies	Climate risk for different stages		[Risks in different stages]
	International connections and cross-border impacts		[Connections abroad]
	Most significant risks for companies		[The most significant risks]
Climate risk assessment	Risk assessment	How? By what means/tools?	[Risk assessment]
		Information source	[Information]
	Climate risk assessment tool	What kind of tool?	[Risk assessment tool]
	The importance of climate risk assessment		[The importance of risk assessment]

and supply networks need to be conducted. However, considering the relatively poor track record of adaptation action in the private sector, and especially in the energy sector (WEF, 2023), it is imperative to understand the level of awareness of climate change within Finnish renewable energy companies, their perception of climate risks, their adaptation strategies and plans and what is currently hindering them from mainstreaming adaptation actions across their operations.

3.2 | Data collection and analysis

A qualitative approach was considered appropriate as it allowed for exploration of a relatively new topic where there is no established knowledge base (Maxwell, 2012). Interviews were chosen as the data collection method, since a preliminary scanning of company documents did not reveal sufficient information to proceed with the study. We focused on renewable energy companies, which we consider to be publicly owned or private companies, whose business consists solely of producing renewable energy and/or related services, such as transmission, distribution, storage and retail, as well as hybrid companies that are transitioning or have transitioned away from fossil fuels into renewables. To narrow down the pool of participants, we limited our search to companies that engage in the production of renewable energy for society, that is, not only retailers or distribution operators and not companies that only produce energy for their own use (such as some forestry companies). This enabled us to focus on companies that are key drivers of the low-carbon transition and thus important for reaching the Finnish carbon neutrality goal. Based on these criteria, we identified 31 companies, which were approached with an interview invitation by email and if necessary, a reminder. Nine energy companies of different sizes agreed to take part in the study. One person from each company participated in the interviews, which lasted about 30–60 min and were conducted remotely in November 2021, via Zoom or Microsoft Teams.

The companies represented by the interviewees operate at different spatial levels ranging from regional to international; see Table 3. Accordingly, also, the size of the companies varies considerably with a yearly turnover ranging from below €10 m. to more than €20 bn. Most of the companies are energy suppliers established more than a hundred years ago, with only two newcomers established in the 1990s. All companies except one provide electricity as well as heat, and they rely on two to four different renewable energy sources, with wind being used by all nine companies and solar power by four companies. The role of the interviewees ranged from manager positions to directors.

The interviews were semistructured to allow the researcher to clarify assumptions and correct misunderstandings during the interviews. The interviews proceeded based on questions related to predetermined themes (Eskola & Suoranta, 1998, p. 87) related to renewable energy, different climate risks and climate risk assessments, in correspondence to the research question (see analytical framework in Section 2.3). The interviews were recorded for transcription to enable a thematic content analysis in line with the analytical framework (Section 2.3). Thematic analysis, which is theory driven, enables a description of the phenomenon under study in a condensed and clear form. Based on the themes, we coded the transcribed interview data using the qualitative research analysis tool Atlas.ti, for certain phenomena, things, meanings or concepts, which were compared with existing information or an analytical model (see Table 2) (Hirsjärvi & Hurme, 2008). Subsequently, we synthesised the textual material according to the research question.

3.3 | Limitations

As with any qualitative study, there are limitations to the approach and methods chosen, which affect the results of the study (Silverman, 2020). First, the sample size of our study is small, raising concerns of representation and generalisability of the study's findings. Overall, 31 possible companies were identified and contacted of which about a third responded positively. It is possible that these companies represent a positive bias due to a keen interest in the topic, thus skewing the results. Nonetheless, a third of possible respondents can still be considered a sufficient sample size in qualitative research. Second, bias can emerge when only one representative of a company is interviewed. While an effort was made to interview the most knowledgeable representative possible, the interviewees all had different roles and tasks in the companies, with various levels of subject expertise. Thus, the interviewees' roles, tasks and knowledge can influence the responses they give and thus the results and conclusions. Third, concerns can also be raised regarding the validity of the findings when it comes to coding and analysis of the data in qualitative research (Golafshani, 2003). We have aimed for transparency in terms of the analysis by explicitly showing how we use the analytical framework in the coding of the interview data. Finally, since all interviewees were promised anonymity, more detailed description of the companies interviewed is not possible.

4 | RESULTS

4.1 | Climate risk awareness

The level of climate risk awareness varied considerably within the different companies; see Table 4. Some of the companies were very familiar with climate risk as a term and topic and had been conducting climate risk assessments for some time already. However, for many companies, climate risks were either considered minor issues or their significance had only recently been acknowledged. When climate risks and their formation were viewed through three dimensions (hazard, exposure, and vulnerability), companies identified predominantly hazards, such as extreme weather events, storms and strong winds, lightning, increased temperatures, forest fires, pests, changes in ice and snow conditions, changing precipitation patterns, rising water levels and water flow fluctuations (Interviewees 1, 2, 5, 7, 8 and 9). As such, the companies were quite familiar with direct physical climate

TABLE 3 Studied companies.

Company	Number of interviewees	The role of the interviewee	Energy production/ conversion, transferring energy	Electric	Heat	Wind power	Hydroelectric	Solar energy	Bioenergy	Turnover 2021	Operational area	Day of interview
1	1	Head of the unit, electrical trade	x	x	x	x	x		x	Medium	National	19.11.2021
2	1	Senior environmental advisor	x	x	x	x	x	x	X	Major	International	19.11.2021
3	1	Environment and development manager	x	x	x	x	x	x	x	Small	Regional	22.11.2021
4	1	Production manager	x	x	x	x		x	x	Medium	Regional	23.11.2021
5	1	Director of quality and environment	x	x	x	x	x		x	Medium	Regional	26.11.2021
6	1	Development manager, wind power	x	x	x	x	x	x	x	Major	International	26.11.2021
7	1	Managing director, director of operations	x	x		x	x			Small	Regional	29.11.2021
8	1	Environment and safety manager	x	x	x	x	x		x	Medium	Regional	29.11.2021
9	1	Quality and sustainability director	x	x	x	x			x	Small	Regional	25.11.2021

Note: Date is formatted as day.month.year.

TABLE 4 Risks from climate change.

Type of renewable energy	Risks from climate change identified by the companies
Hydropower	Many **direct and physical risks** had been identified and observed for hydropower production, since hydropower is very weather-dependent. Annual water amounts and their variation have direct impacts on hydropower production. In Finland, many hydropower plants are built in small rivers, and the capacity of the power plants is rather small, which results in problems during heavy rain, runoff and flooding. Likewise, droughts affect the amount of energy that can be produced. In terms of safety, it is important to know how the weather and climate will change in the future, since changes to rainfall patterns directly affect hydropower production. Changes in winter conditions affect the creation of winter and spring floods, and also, autumn floods are projected to increase in the future. Floods are thus recognised as a clear, rapidly developing risk factor for hydropower. **Systemic risks** may emerge from the interconnectedness of the Nordic electricity market. Fluctuating weather conditions affect hydropower production also outside of Finland and thus the price of electricity on the Nordic market. Especially production conditions in Norway, where hydropower production is substantial, were perceived as very important for the whole Nordic area.
Windpower	**Direct and physical risks** may emerge from changing wind conditions; for example, storms may increase locally due to climate change. Predicting the magnitude of the change and how it will affect production were perceived as difficult. Lightning strikes have also caused damage to wind farms. Winter snow loads, freezing rain and freezing of turbines have caused problems for windpower production in the past. The risk of freezing may decrease in the future, while snowfall may increase. During strong winds and storms with wind speeds exceeding 20–25 m per second, wind turbines need to be shut down for safety reasons, affecting production. Damages and curtailment of production also cause financial losses to companies. Sea level rise was identified as a potential risk to offshore wind farms, which are built for specific sea levels.
Solar power	**Direct and physical risks** of climate change on production are still quite uncertain. Production is directly affected by the amount of solar radiation and cloudiness. A main challenge is the intermittency of solar radiation especially due to changing seasons. Additionally, with increasing temperature, the efficiency of solar panels decreases. Storms and heavy winds may cause damage to solar panels or cover them with debris.
Biomass	**Direct and physical risks** result from storms, forest fires and pest outbreaks that cause forest damage. Biomass production may increase in the future with rising temperatures, due to a longer growing season and CO_2 fertilisation, which will positively affect biomass production and biofuel availability. **Systemic risks** may arise due to increasing pressure to shift from fossil fuels to bio-based fuels, which may create competition for scarce resources, such as wood chips. This may incentivise biomass imports from abroad, questioning the sustainability of the supply chain. **Transition risks** are identified as affecting bioenergy through, for example, political decisions in Finland, at the EU level or at the local level, for instance, directed at reducing combustion-based energy production. Decisions to protect forests or strengthen sustainable forest management practices affect the availability of wood-based fuels. Biofuels may be included in the EU emissions trading system in the future, which increases costs and hence the price of the final product.

risks, since renewable energy sources are very weather-dependent (Interviewee 2), and many direct risks have already been observed: 'we are aware of the risks, but we talk about them with slightly different names than climate risk' (Interviewee 4). The companies also acknowledged that the distribution and supply networks may face physical and direct climate risks, for example, due to storms and extreme weather events.

The climate risks identified by the companies were naturally dependent on what type of renewable energy production the companies were involved in. For instance, some of the companies were partners or shareholders in wind farms but did not have their own wind power production, and hence, climate risks to wind power had not been comprehensively assessed. However, climate was still highlighted as a potential threat to wind power production by some of the interviewees: 'Freezing rain is possibly a problem for the operation of wind turbines' (Interviewee 9). Only a few companies had solar energy as part of their energy production portfolio, but many companies used solar power for providing energy to their own plants or buildings. Solar energy is still seen as an emerging form of energy production, the technology of which is in constant development.

Although the classification of climate risks based on different terms and concepts was not very familiar to most of the companies, they were still aware of different types of risks. For instance, the companies were particularly familiar with risks stemming from policies and regulations concerning the low-carbon transition, so-called transition risks, as they have already affected the companies in various ways. In fact, when asked what type of climate risks the companies believed to be the most significant for their operations and production, transition risks came to the fore, as one interviewee stated: 'the biggest risk for our business is political risk' (Interviewee 9). Political decisions stemming from many different levels (local, Finnish or European) to curb climate change or limit the use of fossil fuels were identified as significantly affecting current and future operations of the companies, through, for example, sustainability criteria, as stated by Interviewee 4: 'There will be political risk through the EU, like RED II [the recast of the EU Renewable Energy Directive]'. One interviewee (Interviewee 3) was concerned about future political regulations concerning forest management, as limits on forest logging can affect the availability of wood fuel. Hence, transition risks are constantly monitored, and efforts are made to anticipate and prepare for them.

Transition risks may also affect the financial performance of the companies. For instance, the price of carbon in the EU emissions trading system (EU-ETS) affects production costs for the companies as well as the price of end products. The possibility of assets being stranded due to new decisions or regulations was also perceived as a significant risk for companies who have already made large investments in certain production processes. For example, the availability and price of biomass for bioenergy production may change drastically in the future, a fact of which a company with large amounts of capital invested in a biofuel plant for the next 10 years was acutely aware of, particularly if the emissions trading expands to biofuels (Interviewees 4 and 8). Additionally, with increasing climate change, people's attitudes and opinions may change, which may alter the types of operations and energy production processes that are deemed acceptable in the future, creating both risks and opportunities for companies (Interviewees 1, 3, 4 and 6).

Other terms related to indirect risks, such as systemic, cascading or cross-border risks, were less familiar, and few of the companies had identified impacts stemming from such risks. This is understandable, since these risks are very complex and dynamic, which makes them difficult to understand, identify and observe. Many of the companies used indirect risk as an umbrella term to describe all risks other than direct physical risks. Nevertheless, some companies identified the increasing need for energy storage, and the importance of ensuring supply security in the face of intermittent renewable energy production, as a systemic risk. For instance, energy production capacity and energy consumption differ between winter and summer, which makes the possibility for seasonal energy storage, in which energy is stored during peak production times and utilised during peak consumption times several months later, increasingly important.

Table 5 shows risks and risk factors that the companies identified as affecting them and their operations. The formation of the risk and its impact on the company determines the classification of the risk. Risks and their effects can also arise in multiple ways. For example, the spot price of electricity in Finland is affected by the amount of weather-dependent hydropower production in Norway, classified as a cross-border impact. But the spot price can also be affected by systemic or cascading risks. For example, storms and floods can affect the availability of biofuel, by destroying forests or hindering the procurement of biomass. Subsequently, the competition for biomass may increase, leading to higher electricity production costs in biomass-based power plants.

TABLE 5 Different climate risk types identified by the companies.

Risks and risk factors affecting the company's operations	Risk type
Biofuel availability/sufficiency	
Price increase	Systemic risk
Political decisions on biofuels	Transition risk
Storms and floods that affect biofuel availability	Direct risk, physical risk
Competition for the same fuels	Systemic risk
Distribution network	Direct risk, cross-border risk
Electricity market price	Systemic risk, cross-border risk
Security of maintenance/supply/energy storage	Systemic risk
Legislation changes	Transition risk
Fossil fuel phase out	
Emission reduction mandates	
Phasing out combustion-based production	
Carbon prices	
Acceptability	Transition risk
People's perceptions and behaviour	
Social licence (e.g. wood fuels and district heating)	

4.2 | Climate risk assessments and adaptation

The assessment of climate risks varied greatly within the companies. Larger companies were generally further along in identifying and evaluating climate risks, compared with smaller companies. Several companies had been including climate risks in their general risk assessments for quite some time already, but only a few companies had conducted specific climate risk assessments. In general, the companies believed that considering climate risks in isolation was not useful, since also other factors affecting the company's operations and profitability—such as customer satisfaction, shareholder profits, and wider market forces—must be equally considered.

Many weather-related events, such as storms and floods, are already prepared for through existing risk management tools, but they have not been specifically identified as climate risks. For instance, risk assessments focusing on safety issues are routinely made for individual operations or investments, and they also take weather-related risks into account. However, the companies acknowledged that climate change may alter the frequency and intensity of these weather events, as stated by Interviewee 8, 'the climate is changing, all changes in weather are certainly not within the range of normal variations'.

Consequently, the management of these risks must be enhanced to know how to anticipate and prepare for risks with sufficient efficiency. Especially when making very large investments, for example, in a hydropower dam or a distribution system, a risk assessment including the effects of future climate change is crucial. As one interview put it:

> '[T]he most vulnerable points or operations are, e.g. electricity distribution system or hydropower. The current risks to these systems will certainly intensify in the future. I think that we can already see today the patterns that we will see in the future, but they will only get stronger'. (2)

Generally, the companies did not use specific tools or reference frameworks for climate risk assessments. Instead, they tended to analyse in a qualitative manner the risks that climate change may impose on their operations through considering various questions regarding climate change impacts. From a more day-to-day operational perspective, the companies highlighted the difficulty of understanding climate risks and predicting future events. The companies yearned for more user-friendly assessment methods that would enable climate risk assessments to be conducted more rapidly and frequently, as knowledge improves. Second, flexibility and clarity were considered important attributes of assessments to facilitate and guide the assessment process, as well as for gaining precise and unambiguous results. Third, a ranking of risks in order of severity or importance was considered useful to help prioritise adaptation actions. However, '[There are certainly many different tools out there, but they are not one-size-fits-all. You always have to choose a tool that suits your needs' (Interviewee 2). Finally, any assessment should also account for uncertainty and the implications of the risk not being realised.

A few different adaptation options were used by the companies to prepare for future climate change. One of the most frequently mentioned adaptation measures was diversification of energy production, to avoid 'putting all eggs in one basket' and as such decrease the implications from a failure in one particular power plant. In essence, '[C]limate risks are always involved in renewable energy production, and the only way to manage those risks is to bring flexible production to that side' (Interviewee 1).

Similarly, many companies considered investing in nascent and emerging energy technologies, as a strategy for adapting to transition risks and avoiding stranded assets related to fossil fuels or bioenergy in the future. For instance, geothermal heat was mentioned by several companies as an emerging form of heat production, and many companies are involved in mapping the production and usage potential of geothermal heat in Finland. 'Green hydrogen', that is, hydrogen produced from renewable electricity, has received plenty of attention in recent years—not least through the EU hydrogen strategy—and it was considered a looming opportunity by several companies, both as an energy source and as a form of energy storage (Interviewees 1 and 2). Large heat pumps were also mentioned as a promising avenue for energy storage, and their usability and profitability are currently being evaluated. Some companies also mentioned the utilisation of waste heat as a way of increasing energy efficiency in their operations, hence responding to the policy pressure of decreasing overall energy usage.

5 | DISCUSSION

This study addresses the identified research gap concerning different types of climate risks that renewable energy companies face and the measures that are in place to adapt to these risks. In particular, our findings shed light on two issues: first, company awareness and preparedness and second, the broader consideration of adaptation in the whole sector and its significance to society.

In terms of the first issue, the results show that the level of understanding and knowledge of climate risks varies between the companies. Some companies, particularly the larger ones, were very familiar with the topic in general and had identified different types of climate risks, while other companies had very little understanding of how different climate risks might affect their operations, despite the topic itself being considered important. Similarly, generic risk assessments were conducted by all the companies, but climate risks were rarely extensively covered. Only a few companies, with large enough resources to allocate, had specifically considered climate risks in their risk assessments. This means that while the awareness of climate change risks in general is high, knowledge of specific risks to a companies' own operations and possible adaptation measures is low. Additionally, adaptation measures mainly account for direct physical risks with little consideration of more complex risks. In general, the overall risk from direct climate change was considered moderate among the companies and something that is already being addressed in current risk management practices. This situation has also been highlighted in previous literature (Devis et al., 2018; Gaetani et al., 2015; Pérez et al., 2019; Solaun & Cerdá, 2019; Weinhofer & Busch, 2013).

However, the climate change risk literature is currently expanding to also consider risks arising from indirect sources, in addition to direct impacts. According to this new strand of literature, climate change creates systemic, cascading and cross-border risks in physical and ecological systems, the economy and society, and these are often interconnected, creating the conditions for irreversible threshold exceedance at multiple scales (Groundstroem & Juhola, 2021). While studies stress the importance of systemic risks caused by climate change, these studies provide little support regarding the identification or assessment of these types of risks (Hui Min et al., 2021).

Hence, the second issue that this study contributes to is the overview of adaptation across the sector and its implications for society, though admittedly with a limited view. The findings of our study show that preparing for and adapting to unpredictable, more complex future trends or sudden shocks that may arise due to climate change were largely absent in the risk strategies of the companies. Thus, current risk assessment and management practices do not account for longer-term trends or systemic impacts that span sectors and borders. This is a cause of concern, as energy infrastructure built today is meant to be operational for several decades. Furthermore, energy infrastructure and operations are considered part of the critical infrastructure of societies (Huddleston et al., 2022), meaning that a failure in the energy system may compromise other societal sectors through cascading events. However, evaluation of climate risks across sectors and scales, while maintaining the relevance for companies and decision makers, remains a major scientific challenge (Adger et al., 2018).

The lack of knowledge and available tools to assess complex risks also has implications for companies' staff and management. When comparing the significance of direct risks to systemic risks, the latter are less well-known within companies but potentially more severe if realised. This further stresses the need to address the role of energy company managers and the role their perception of climate risks plays for the resilience of the company as pointed out by Todaro et al.

(2021). Similarly, political decisions in the form of legislation and regulation affect companies' operations, accruing more costs for management, for example, in the form of developing sustainability criteria (Bryant et al., 2020). While direct physical risks are considered to some extent uncertain, transition and systemic risks are even more unpredictable and something that the companies have less control over in terms of their own management practices. This is also echoed in the call for companies to engage in more comprehensive sustainability reporting and address climate change more actively in company practices (Ngo et al., 2022).

While the findings are not particularly surprising, they further underline the need to consider the division of responsibility for adaptation between the public and the private sectors (Juhola, 2019). So far, most adaptation planning and policy have been exclusively aimed at promoting public sector actions with little direct steering of the private sector, although some examples of this are emerging (Cameron et al., 2018). In the case of the renewable energy sector, there seems to be major information needs that the sector does not have the capacity or the resources to fulfil on its own nor is it at the core of their operations. Thus, information steering for adaptation, in the form of development of different tools or information portals, is crucial (Fayolle et al., 2019; Goldstein et al., 2019). Similarly, there are some steering instruments, for example, the Adaptation Reporting Power (ARP) tool (operated by the UK government), that have been used to engage the public sector in adaptation. Though it has hitherto only been used for public companies (Dale et al., 2021), its application in private companies within sectors that are critical for society at large may be worth undertaking.

It is also clear that the ongoing energy transition is having a profound impact on energy companies, by forcing them to seek alternative methods of producing and supplying energy that does not rely on fossil fuels. Also, other sources of energy, such as bioenergy and nuclear power, are highly controversial, and their continued profitability depends on uncertain factors related to financing, technological developments, sustainability standards, people's perceptions and political will. While these types of concerns are beyond the capacity of individual companies to solve, there is clearly a need to address these questions in the sector as a whole and in collaboration with the relevant ministries. This calls for studies which account for the sector more broadly with large sample sizes, allowing for a quantitative analysis of the state of preparedness of the sector. Any new significant actions taken need to be contrasted with up-to-date climate change predictions and a systems perspective to ensure the resilience of the sector.

6 | CONCLUSION

The energy sector has predominantly been focused on the pressing need to reduce GHG emissions to mitigate climate change. However, as climate change impacts are increasingly being experienced, there is a need to examine to what extent climate risks may affect the renewable energy sector and what the sector is doing to increase adaptive capacity in the future. If climate change impacts complicate and delay the decarbonisation of the energy sector, it may lead to increasing hardship for society.

This study has shown that direct physical risks and transition risks are well-known and acknowledged within renewable energy companies, and they are often already included in existing risk assessments. More complex systemic risks are difficult to comprehend; hence, no risk assessment frameworks or tools currently exist to assess these risks, despite their potentially significant consequences. Consequently, the study shows that, in the absence of sufficient knowledge and foresight planning, adaptation measures mainly account for direct physical risks with little preparation for long-term trends. Given that most countries have net zero targets (Chen et al., 2022), combined with increasing pressure on companies to disclose climate risks, the findings of this study are of high relevance to a wide variety of renewable energy companies in different countries.

These findings are also important for the wider governance of adaptation and further highlight the need to clarify the roles of the public and the private sectors in adaptation. Steering the private sector with information and incentives may enable private companies to prepare for climate change impacts in a situation where uncertainty and lack of information are rife. It is also important to note that these steering mechanisms are largely absent at the moment. However, the success of adaptation within the energy sector is fundamental in ensuring that the level of risk to society is kept moderate.

AUTHOR CONTRIBUTIONS

Sirkku Juhola: conceptualisation, methodology, writing original draft, writing—reviewing and editing and supervision. **Anna-Greta Laurila:** conceptualisation methodology, investigation, data curation, formal analysis and writing—reviewing and editing. **Fanny Groundstroem:** conceptualisation methodology, investigation, data curation, formal analysis and writing—reviewing and editing. **Johannes Klein:** conceptualisation and writing-reviewing and editing.

ACKNOWLEDGEMENT

We want to thank all companies that participated in the research. We also thank all reviewers for their input and any remaining errors remaining are ours.

ORCID

Sirkku Juhola https://orcid.org/0000-0003-0095-2282

REFERENCES

Adger, W. N., Brown, I., & Surminski, S. (2018). Advances in risk assessment for climate change adaptation policy. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *376*(2121), 1–13. https://doi.org/10.1098/rsta.2018.0106

Agrawala, S., Carraro, M., Kingsmill, N., Lanzii, E., Mullani, M., & Prudent-Richardii, G. (2011). *Private sector engagement in adaptation to climate change: Approaches to managing climate risks*. OECD Environment Working Papers, No. 39. OECD Publishing.

Alm, M. (2018). *Sector reports—Renewable energy*. Helsinki: Motiva. https://www.motiva.fi/files/16913/Toimialaraportit_-_Uusiutuva_energia_-_TEM-julkaisu_42-2018.pdf

Alvarez, N., Cocco, A., & Patel, K. B. (2020). A new framework for assessing climate change risk in financial markets. *Chicago Fed Letter*, *448*, 1–8. https://doi.org/10.21033/cfl-2020-448

Averchenkova, A., Crick, F., Kocornik-Mina, A., Leck, H., & Surminski, S. (2016). Multinational and large national corporations and climate adaptation: Are we asking the right questions? A review of current knowledge and a new research perspective. *WIREs Climate Change*, *7*, 517–536. https://doi.org/10.1002/wcc.402

Bazyomo, S. D. Y. B., Lawin, E. A., Coulibaly, O., & Ouedraogo, A. (2016). Forecasted changes in West Africa photovoltaic energy output by 2045. *Climate*, *4*(4), 53. https://doi.org/10.3390/cli4040053

Berkhout, F. (2012). Adaptation to climate change by organizations. *WIREs Climatic Change*, *3*, 91–106. https://doi.org/10.1002/wcc.154

Berninger, K., Lager, F., Holm, T., et al. (2022). *Nordic perspectives on transboundary climate risk: Current knowledge and pathways for action*. Nordic Council of Ministers. https://doi.org/10.6027/temanord2022-531

Bowyer, P., Bender, S., Rechid, D., & Schaller, M. (2014). *Adapting to climate change: Methods and tools for climate risk management*. Climate Service Center. CSC Report, 124. https://www.climate-service-center.de/imperia/md/content/csc/csc_report17.pdf

Bryant, A., Griffin, J. J., & Perry, V. G. (2020). Mitigating climate change: A role for regulations and risk-taking. *Business Strategy and the Environment*, *29*(2), 605–618. https://doi.org/10.1002/bse.2391

Cameron, E., Harris, S., & Prattico, E. (2018). *Resilient business, resilient world: A research framework for private-sector leadership on climate adaptation*. San Fransisco: Business for a Better World. https://www.bsr.org/reports/BSR_Resilient_Business_Resilient_World_A_Research_Framework_for_Private_Sector_Leadership_on_Climate_Adaptation.pdf

Canevari-Luzardo, L. M., Berkhout, F., & Pelling, M. (2020). A relational view of climate adaptation in the private sector: How do value chain interactions shape business perceptions of climate risk and adaptive behaviours? *Business Strategy and the Environment*, *29*(2), 432–444. https://doi.org/10.1002/bse.2375

Carter, T. R., Benzie, M., Campiglio, E., Carlsen, H., Fronzek, S., Hildén, M., … West, C. (2021). A conceptual framework for cross-border impacts of climate change. *Global Environmental Change*, *69*, 102307. https://doi.org/10.1016/j.gloenvcha.2021.102307

Challinor, A. J., Adger, W. N., Benton, T. G., Conway, D., Joshi, M., & Frame, D. (2018). Transmission of climate risks across sectors and borders. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *376*, 20170301. https://doi.org/10.1098/rsta.2017.0301

Chen, L., Msigwa, G., Yang, M., Osman, A. I., Fawzy, S., Rooney, D. W., & Yap, P. S. (2022). Strategies to achieve a carbon neutral society: A review. In *Environmental chemistry letters* (Vol. 20, Issue 4) (pp. 2277–2310). Springer International Publishing. https://doi.org/10.1007/s10311-022-01435-8

Dahlmann, F., & Roehrich, J. K. (2019). Sustainable supply chain management and partner engagement to manage climate change information. *Business Strategy and the Environment*, *28*(8), 1632–1647. https://doi.org/10.1002/bse.2392

Dale, T. W., Gao, J., Kiran Avashia, V., Konrad, S., & Garg, A. (2021). *Private sector adaptation reporting as a source of input to the Global Stocktake*. UNEP DTU Partnership and Indian Institute of Management Ahmedabad. www.independentglobalstocktake.org

Devis, A., Van Lipzig, N. P. M., & Demuzere, M. (2018). Should future wind speed changes be taken into account in wind farm development? *Environmental Research Letters*, *13*(6), 064012. https://doi.org/10.1088/1748-9326/aabff7

EC. (2022). Directive (EU) 2022/2464 as regards corporate sustainability reporting. Official Journal of the European Union.

Edenhofer, O., Madruga, R. P., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., … von Stechow, C. (2011). Renewable energy sources and climate change mitigation: Special report of the intergovernmental panel on climate change. In *Renewable energy sources and climate change mitigation: Special report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Emodi, N. V., Chaiechi, T., & Rabiul Alam Beg, A. B. M. (2019). The impact of climate variability and change on the energy system: A systematic scoping review. *Science of the Total Environment*, *676*, 545–563. https://doi.org/10.1016/j.scitotenv.2019.04.294

Eskola, J., & Suoranta, J. (1998). *Johdatus laadulliseen tutkimukseen* (5th ed.). Vastapaino.

European Parliament. (2021). *Renewable energy sources* (pp. 1–6). Brussels: European Parliament.

Fayolle, V., Fouvet, C., Soundarajan, V., Nath, V., Acharya, S., Gupta, N., & Petrarulo, L. (2019). *Engaging the private sector in financing adaptation to climate change: Learning from practice. Action on climate today, February*. https://www.gcca.eu/sites/default/files/2020-03/2019 Acclimatise - Engaging the Private Sector in Financing Adaptation to Climate Change - A Learning Paper_0.pdf.

Gaetani, M., Vignati, E., Huld, T., & Dosio, A. (2015). *Science and policy report: Climate modelling and renewable energy resource assessment*. Joint Research Centre. April.

Gasbarro, F., Iraldo, F., & Daddi, T. (2017). The drivers of multinational enterprises' climate change strategies: A quantitative study on climate-related risks and opportunities. *Journal of Cleaner Production*, *160*, 8–26. https://doi.org/10.1016/j.jclepro.2017.03.018

Gernaat, D. E. H. J., de Boer, H. S., Daioglou, V., Yalew, S. G., Müller, C., & van Vuuren, D. P. (2021). Climate change impacts on renewable energy supply. *Nature Climate Change*, *11*(2), 119–125. https://doi.org/10.1038/s41558-020-00949-9

Golafshani, N. (2003). Understanding reliability and validity in qualitative research. *The Qualitative Report*, *8*(4), 597–607.

Goldstein, A., Turner, W. R., Gladstone, J., & Hole, D. G. (2019). The private sector's climate change risk and adaptation blind spots. *Nature Climate Change*, *9*(1), 18–25. https://doi.org/10.1038/s41558-018-0340-5

Groundstroem, F., & Juhola, S. (2021). Using systems thinking and causal loop diagrams to identify cascading climate change impacts on bioenergy supply systems. *Mitigation and Adaptation Strategies for Global Change*, *26*, 29. https://doi.org/10.1007/s11027-021-09967-0

Helbing, D. (2013). Globally networked risks and how to respond. *Nature*, *497*(7447), 51–59. https://doi.org/10.1038/nature12047

Hildén, M., Haavisto, R., Mäkinen, K., Parjanne, A., Pöyry, J., & Tuomenvirta, H. (2018). *Ilmastokestävä Suomi - Toimintamalli sää- ja ilmastoriskien arviointien järjestämiseksi*. Finland: The Prime Minister's Office. http://urn.fi/URN:ISBN:978-952-287-602-7

Hirsjärvi, S., & Hurme, H. (2008). *Tutkimushaastattelu: Teemahaastattelun teoria ja käytäntö*. Gaudeamus Helsinki University Press.

Hochrainer-Stigler, S., Colon, C., Boza, G., Poledna, S., Rovenskaya, E., & Dieckmann, U. (2020). Enhancing resilience of systems to individual and systemic risk: Steps toward an integrative framework. *International Journal of Disaster Risk Reduction*, *51*(January), 101868. https://doi.org/10.1016/j.ijdrr.2020.101868

Huddleston, P., Smith, T., White, I., & Elrick-Barr, C. (2022). Adapting critical infrastructure to climate change: A scoping review. *Environmental Science & Policy*, *135*, 67–76. https://doi.org/10.1016/j.envsci.2022.04.015

Hui Min, L. I., Xue Chun, W. A. N. G., Xiao Fan, Z. H. A. O., & Ye, Q. I. (2021). Understanding systemic risk induced by climate change. *Advances in Climate Change Research*, *12*, 384–394. https://doi.org/10.1016/j.accre.2021.05.006

IEA. (2017). *World energy outlook 2017*. IEA. https://www.iea.org/t&c/

IEA. (2020). *Renewables 2020* (Vol. 74, pp. 56–57). IEA.

IPCC. (2018). *IPCC, 2018: Annex I: Glossary*.

Jerez, S., Tobin, I., Vautard, R., Montávez, J. P., López-Romero, J. M., Thais, F., Bartok, B., Christensen, O. B., Colette, A. Déqué, M., & Nikulin, G. (2015). The impact of climate change on photovoltaic power generation in Europe. *Nature Communications*, *6*, 10014. https://doi.org/10.1038/ncomms10014

Juhola, S. K. (2019). Responsibility for climate change adaptation. *Wiley Interdisciplinary Reviews: Climate Change*, *10*(5), e608.

Juntunen, J., Ritvala, T., Peixoto, I., Buffart, M., 2021. *Aalto University. Department of Management Studies. Managing transition risks. Referred to: 18.4.2022*. Espoo: Aalto University. https://www.aalto.fi/en/department-of-management-studies/managing-transition-risks

Klein, J., Araos, M., Karimo, A., Heikkinen, M., Ylä-Anttila, T., & Juhola, S. (2018). The role of the private sector and citizens in urban climate change adaptation: Evidence from a global assessment of large cities. *Global Environmental Change*, *53*, 127–136. https://doi.org/10.1016/j.gloenvcha.2018.09.012

Klein, J., Käyhkö, J., Räsänen, A., Groundstroem, F., & Eilu, P. (2022). Climate risk perception, management, and adaptation in the Nordic mining sector. *The Extractive Industries and Society*, *10*, 101092. https://doi.org/10.1016/j.exis.2022.101092

Lawrence, J., Blackett, P., & Cradock-Henry, N. A. (2020). Cascading climate change impacts and implications. Climate. *Risk Management*, *29*(August 2019), 100234. https://doi.org/10.1016/j.crm.2020.100234

Mani, M., & Pillai, R. (2010). Impact of dust on solar photovoltaic (PV) performance: Research status, challenges and recommendations. *Renewable and Sustainable Energy Reviews*, *14*(9), 3124–3131. https://doi.org/10.1016/j.rser.2010.07.065

Maxwell, J. A. (2012). *Qualitative research design: An interactive approach*. Sage Publications.

Meinel, U., & Schüle, R. (2018). The difficulty of climate change adaptation in manufacturing firms: Developing an action-theoretical perspective on the causality of adaptive inaction. *Sustainability*, *10*, 569. https://doi.org/10.3390/su10020569

Ministry of the Environment. (2022). *Climate law 423/2022. Finnish legal collection* (pp. 1–9). The Government of Finland.

Mukheibir, P. (2013). Potential consequences of projected climate change impacts on hydroelectricity generation. *Climatic Change*, *121*(1), 67–78. https://doi.org/10.1007/s10584-013-0890-5

Nam, S., Shin, J., Ryu, J., & Ryu, H. (2021). Climate impacts on geographical changes in the energy industry. *Business Strategy and the Environment*, *30*(1), 478–488. https://doi.org/10.1002/bse.2632

Ngo, T., Le, T., Ullah, S., & Trinh, H. H. (2022). Climate risk disclosures and global sustainability initiatives: A conceptual analysis and agenda for future research. *Business Strategy and the Environment*, *32*, 3705–3720. https://doi.org/10.1002/bse.3323

Orsato, R. J., Barakat, S. R., & de Campos, J. G. F. (2017). Organizational adaptation to climate change: Learning to anticipate energy disruptions. *International Journal of Climate Change Strategies and Management*, *9*, 645–665. https://doi.org/10.1108/IJCCSM-09-2016-0146

Owusu, P. A., & Asumadu-Sarkodie, S. (2016). A review of renewable energy sources, sustainability issues and climate change mitigation. Cogent. *Engineering*, *3*(1), 1167990. https://doi.org/10.1080/23311916.2016.1167990

Patt, A., Pfenninger, S., & Lilliestam, J. (2013). Vulnerability of solar energy infrastructure and output to climate change. *Climatic Change*, *121*(1), 93–102. https://doi.org/10.1007/s10584-013-0887-0

Pérez, J. C., González, A., Díaz, J. P., Expósito, F. J., & Felipe, J. (2019). Climate change impact on future photovoltaic resource potential in an orographically complex archipelago, the Canary Islands. *Renewable Energy*, *133*, 749–759. https://doi.org/10.1016/j.renene.2018.10.077

Pescaroli, G., & Alexander, D. (2018). Understanding compound, interconnected, interacting, and cascading risks: A holistic framework. *Risk Analysis*, *38*(11), 2245–2257. https://doi.org/10.1111/risa.13128

Porter, J. J., Demeritt, D., & Dessai, S. (2015). The right stuff? Informing adaptation to climate change in British Local Government. *Global Environmental Change*, *35*, 411–422. https://doi.org/10.1016/j.gloenvcha.2015.10.004

Pörtner, H. O., Roberts, D. C., Poloczanska, E. S., Mintenbeck, K., Tignor, M., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., & Okem, A. (2022). *IPCC, 2022: Summary for policymakers. Intergovernmental Panel for Climate Change*. Cambridge: Cambridge University Press.

Poudel, B. C., Sathre, R., Gustavsson, L., Bergh, J., Lundström, A., & Hyvönen, R. (2011). Effects of climate change on biomass production and substitution in north-central Sweden. *Biomass and Bioenergy*, *35*(10), 4340–4355. https://doi.org/10.1016/j.biombioe.2011.08.005

Pryor, S. C., & Barthelmie, R. J. (2010). Climate change impacts on wind energy: A review. *Renewable and Sustainable Energy Reviews*, *14*(1), 430–437. https://doi.org/10.1016/j.rser.2009.07.028

Pryor, S. C., & Barthelmie, R. J. (2013). Assessing the vulnerability of wind energy to climate change and extreme events. *Climatic Change*, *121*(1), 79–91. https://doi.org/10.1007/s10584-013-0889-y

Rocha, J. C., Peterson, G., Bodin, Ö., & Levin, S. (2018). Cascading regime shifts within and across scales. *Science*, *362*(6421), 1379–1383. https://doi.org/10.1126/science.aat7850

Saada, A. (2020). Ilmastonmuutoksen siirtymäriskit globaalien arvoketjujen uhkana. *Suomen Pankki*, *1*, 1–12. https://helda.helsinki.fi/bof/handle/123456789/17766

Sakhel, A. (2017). Corporate climate risk management: Are European companies prepared? *Journal of Cleaner Production*, *165*, 103–118. https://doi.org/10.1016/j.jclepro.2017.07.056

Schaeffer, R., Szklo, A. S., de Lucena, A. F. P., Moreira Cesar Borba, B. S., Pupo Nogueira, L. P., Fleming, F. P., Troccoli, A., Harrison, M., & Boulahya, M. S. (2012). Energy sector vulnerability to climate change: A review. *Energy*, *38*(1), 1–12. https://doi.org/10.1016/j.energy.2011.11.056

Sillmann, J., Christensen, I., Hochrainer-Stigler, S., Huang-Lachmann, J., Juhola, S., Kornhuber, K., Mahecha, M., Mechler, R., Reichstein, M., Ruane, A. C., Schweizer, P.-J., & Williams, S. (2022). *ISC-UNDRR-RISK KAN briefing note on systemic risk*. International Science Council.

Silverman, D. (Ed.). (2020). *Qualitative research*. Sage Publications. 520p.

Simpson, N. P., Mach, K. J., Constable, A., Hess, J., Hogarth, R., Howden, M., Lawrence, J., Lempert, R. J., Muccione, V., Mackey, B., & New, M. G. (2021). A framework for complex climate change risk assessment. *One Earth*, *4*(4), 489–501. https://doi.org/10.1016/j.oneear.2021.03.005

Solaun, K., & Cerdá, E. (2019). Climate change impacts on renewable energy generation. A review of quantitative projections. *Renewable and Sustainable Energy Reviews*, *116*, 109415. https://doi.org/10.1016/j.rser.2019.109415

Spalding-Fecher, R., Chapman, A., Yamba, F., Walimwipi, H., Kling, H., Tembo, B., Nyambe, I., & Cuamba, B. (2016). The vulnerability of hydropower production in the Zambezi River Basin to the impacts of climate change and irrigation development. *Mitigation and Adaptation Strategies for Global Change*, *21*(5), 721–742. https://doi.org/10.1007/s11027-014-9619-7

Statistics Finland. (2020). *Suomen kasvihuonekaasupäästöt 1990-2019. Environment and natural resources*. https://www.stat.fi/static/media/uploads/tup/khkinv/yymp_kahup_1990-2019_2020.pdf

Steeves, J., Fayolle, V., Odianose, S., Rai, N., Soanes, M., Haque, M., & Mahid, Y. (2016). Building readiness of the private sector in Bangladesh for GCF accreditation. *Acclimatise, IIED and ICCCAD*, *1*, 1–45. https://cdkn.org/sites/default/files/files/Learning-Paper-from-Private-sector-readiness-in-Bangladesh.pdf

Surminski, S. (2013). Private-sector adaptation to climate risk. *Nature Climate Change*, *3*(11), 943–945. https://doi.org/10.1038/nclimate2040

SVT. (2021). *Suomen virallinen tilasto: Energian hankinta ja kulutus [online publication]*. Published: 16.4.2021. ISSN=1799-795X. 4. Vuosineljännes. Tilastokeskus. [referred to: 10.10.2021].

Tang, S., & Demeritt, D. (2018). Climate change and mandatory carbon reporting: Impacts on business process and performance. *Business Strategy and the Environment*, *27*, 437–455. https://doi.org/10.1002/bse.1985

Tang, S., & Dessai, S. (2012). Usable science? The U.K. climate projections 2009 and decision support for adaptation planning. *Weather, Climate,* *and Society*, *4*(4), 300–313. https://doi.org/10.1175/WCAS-D-12-00028.1

Todaro, N. M., Testa, F., Daddi, T., & Iraldo, F. (2021). The influence of managers' awareness of climate change, perceived climate risk exposure and risk tolerance on the adoption of corporate responses to climate change. *Business Strategy and the Environment*, *30*(2), 1232–1248. https://doi.org/10.1002/bse.2681

Tsalis, T. A., & Nikolaou, I. E. (2017). Assessing the effects of climate change regulations on the business community: A system dynamic approach. *Business Strategy and the Environment*, *26*(6), 826–843. https://doi.org/10.1002/bse.1953

van Benthem, A. A., Crooks, E., Giglio, S., Schwob, E., & Stroebel, J. (2022). The effect of climate risks on the interactions between financial markets and energy companies. *Nature Energy*, *7*, 690–697. https://doi.org/10.1038/s41560-022-01070-1

Wachsmuth, J., Blohm, A., Gößling-Reisemann, S., Eickemeier, T., Ruth, M., Gasper, R., & Stührmann, S. (2013). How will renewable power generation be affected by climate change? The case of a metropolitan region in Northwest Germany. *Energy*, *58*, 192–201. https://doi.org/10.1016/j.energy.2013.06.035

WEF. (2023). *Accelerating business action on climate change adaptation*. World Economic Forum. https://www3.weforum.org/docs/WEF_Climate_Change_Adaptation_2023.pdf

Weinhofer, G., & Busch, T. (2013). Corporate strategies for managing climate risks. *Business Strategy and the Environment*, *22*(2), 121–144. https://doi.org/10.1002/bse.1744

White, A. (2023). Capturing the direct and indirect risks of physical climate change in investment portfolios. *Sustainalytics*, *2*, 1–3. https://www.sustainalytics.com/esg-research/resource/investors-esg-blog/capturing-the-direct-and-indirect-risks-of-physical-climate-change-in-investment-portfolios

Winn, M., Kirchgeorg, M., Griffiths, A., Linnenluecke, M. K., & Günther, E. (2011). Impacts from climate change on organizations: A conceptual foundation. *Business Strategy and the Environment*, *20*(3), 157–173. https://doi.org/10.1002/bse.679

Yu, S., Zheng, Y., & Hu, X. (2023). How does climate change affect firms' investment efficiency? Evidence from China's listed renewable energy firms. *Business Strategy and the Environment*, *32*, 3977–3996. https://doi.org/10.1002/bse.3349

Zscheischler, J., Westra, S., Van Den Hurk, B. J., Seneviratne, S. I., Ward, P. J., Pitman, A., AghaKouchak, A., Bresch, D. N., Leonard, M., Wahl, T., & Zhang, X. (2018). Future climate risk from compound events. *Nature Climate Change*, *8*(6), 469–477. https://doi.org/10.1038/s41558-018-0156-3

How to cite this article: Juhola, S., Laurila, A.-G., Groundstroem, F., & Klein, J. (2024). Climate risks to the renewable energy sector: Assessment and adaptation within energy companies. *Business Strategy and the Environment*, *33*(3), 1906–1919. https://doi.org/10.1002/bse.3580