Climate Risks of the Transition to a Renewable Energy Society: The Need for Extending the Research Agenda

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ABSTRACT: To reach the 1.5°–2° goal of the Paris Agreement, the speed of transition to a renewable energy society must increase significantly. Applying Perrow's theory of societal risk, we argue that switching from a fossil-based energy system to a future 100% renewable energy system may increase climate risks. Reviewing policy and research literature, and interviewing key energy policy actors in Norway, we find that there is limited knowledge on this topic and that the knowledge that does exist suffers from several shortcomings. Climate risks are generally discussed by applying future climate to the current energy system and thus failing to consider climate vulnerabilities caused by the ongoing energy transition. Also, discussions are frequently limited to subsystem reflections as opposed to system reflections and mostly present supply-side perspectives as opposed to demand-side perspectives. Most of the policy actors conclude that a future 100% renewable energy system will mainly benefit from climate change and reduce rather than increase climate risks. A research agenda is proposed to gain a better understanding of how the ongoing energy transitions can affect climate risks, especially to address the potential that reducing the level of energy consumption, diversifying energy sources, and prioritizing short-traveled energy can have to reduce climate risk in high-consuming countries.

SIGNIFICANCE STATEMENT: Switching from a fossil-based to a mostly "climate driven" renewable energy system may increase climate risks, and rapid transitions may increase risks even more. Still, knowledge of such risks is limited and suffers from several shortcomings. Studies are generally applying future climate to current energy system conditions and thus failing to consider vulnerabilities caused by the ongoing transformation of the energy system. Studies so far are also often limited to analyzing only parts of the system and not the energy system as a whole, and they are aiming at the production side rather than the consumption side. Thus, they tend to conclude that the energy system will mainly benefit from climate change. To reduce climate risks, we claim the need to focus on energy consumption and short-traveled energy.

KEYWORDS: Social Science; Europe; Adaptation

1. Introduction

An increasing number of studies suggest a complex interrelation between climate change mitigation and adaptation, indicating that they should therefore be handled in context rather than separately. If treated separately, there is a danger that adaptation policies may trigger increases in greenhouse gas (GHG) emissions, whereas mitigating policies may lead to increased physical climate risks (Bizikova et al. 2007; Klein et al. 2007; Corfee-Morlot et al. 2010; Warren 2011; IPCC 2014; Aall et al. 2016).

A growing literature explores climate change adaptation and mitigation synergies and trade-offs within different societal sectors, such as agriculture (Jarvis et al. 2011), forestry (Locatelli et al. 2015), tourism (Aall et al. 2016), development policy (Thornton and Comberti 2017), and urban development (McEvoy et al. 2006). In their systematic literature review, Landauer et al. (2015) identified "urban," "agriculture," "spatial planning," and "forestry" as the most frequently cited research terms addressing this issue, whereas "energy" was among the least cited. Furthermore, the task of integrating adaptation and mitigation efforts seems to have gained more weight in local rather than national policy-making levels (Schreurs 2008).

According to a special report on renewable energy sources and climate change by the Intergovernmental Panel on Climate Change (IPCC), increasing capacity for producing renewable energy is a key to mitigating climate change (Moomaw et al. 2011). To achieve the 1.5°–2° goal of the Paris Agreement, renewable energy within the total primary energy supply will need to exceed 60% by 2050 (Gielen et al. 2019).

It appears fair to assume that switching from predominantly fossil-based energy to a renewable energy largely "climate-

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TABLE 1. Proposed typology of climate risks relating to the energy system.

	Producer-related risks	Consumer-related risks
Physical climate risks	E.g., reduction of hydroenergy production capacity because of drought	E.g., loss of electricity-supply because of extreme weather events
Transition climate risks	E.g., bankruptcy in the energy-sector because of climate policy regulations	E.g., reduction in standard of living because of increased energy costs

driven" (e.g., sourced by wind, precipitation, or sunlight) means that such a future energy system may be more prone to climate risks. By "climate risk," we adhere to the IPCC's definition that " the potential for adverse consequences of a climate-related hazard, or of adaptation or mitigation responses to such a hazard, on lives, livelihoods, health and well-being, ecosystems and species, economic, social, and cultural assets, services (including ecosystem services), and infrastructure" (IPCC 2018, p. 557). Given that time is running out to reach the 1.5°–2° goal of the Paris Agreement, the speed of transition to a renewable-energy-based society must increase significantly. Consequently, it appears also fair to assume that if this transition occurs at a high pace, all other factors being equal this would imply climate risks to increase even more.

Norway is ranked the second highest country globally with respect to its proportion of primary energy coming from renewables during 2019 (66%), second only to Iceland (79%) (https://ourworldindata.org/renewable-energy). Norway also leads globally in the transition to electric vehicles, with the highest global share of electric vehicles (Saele and Petersen 2018). Thus, in the paper we have used a combination of criteria developed by Flyvbjerg (1992) to generalize findings from Norway as a case study, treating it both as an extreme case (i.e., one that can be considered particularly successful or unsuccessful—in this context, the former), and a critical case (i.e., one that allows the criterion that if it applies/does not apply to this case, then it applies/does not apply to all cases). In other words, countries aiming at where Norway is situated currently with respect to share of renewables, can hopefully learn something about how the ongoing transition to a renewable energy system may influence climate risks.

Herein, we address three research questions: 1) How do the policy and research literature address climate risks associated with a transition to a future 100% renewable energy system? 2) How do Norwegian energy system stakeholders reflect on climate risks associated with a transition to a future 100% renewable energy system? 3) What—if any—knowledge gaps should be filled with respect to climate risks associated with the transition to a future 100% renewable energy system?

2. The concept of "climate risk" and how it can be applied to the energy system

There are many competing taxonomies in the literature on climate risk, applying concepts such as physical risks, transition risks, liability risks, transborder risks, and political risks. The IPCC special report "Global Warming of 1.5°C" glossary points out that, in addition to physical impacts of climate change, risks stemming from adaptation and mitigation responses should also be included when assessing potential climate risks (IPCC 2018). In 2017, the Task Force on Climate-related Financial Disclosures established by the G20 Finance Ministers and Central Bank Governors, presented a review of how the financial sector can take account of climate-related issues (Task Force on Climate-related Financial Disclosures 2017). They divided climate-related risks into two main categories: risks related to the physical impacts of climate change, and risks related to the transition to a lower carbon economy. This dichotomy was also used by a Norwegian government green paper on climate risks and the Norwegian economy (Norges Offentlige Utredninger 2018b). Herein, we use a combination of the above-mentioned climate risk taxonomies, in which we differ between physical climate risk and transition climate risk, with the latter limited to risks from transforming to a system based entirely on renewable energy. The main attention in the following will be on the physical climate risks.

The IPCC Fifth Assessment Report (AR5) defines physical climate risk as the sum effect of climate hazards, exposure, and vulnerability. Exposure for the case of energy systems is the energy services society expects to attain (i.e., a sufficient, accessible, affordable, and secure energy supply), whereas vulnerability will include all societal factors and drivers that may influence "the propensity or predisposition [of the energy system] to be adversely affected" (IPCC 2014, p. 717).

The AR5 defines an energy system as "all components related to the production, conversion, delivery, and use of energy" (IPCC 2014, p. 1261). Thus, when analyzing climate risks in relation to the energy system, we may differentiate between supply- and demand-side-related physical climate risks. The former affects the production sites and is experienced by energy producers, for instance, changes in hydroelectricity production due to changes in precipitation, with consequent economic impacts on the energy company, or changes in wind patterns influencing windmill production. By contrast, the latter affects the consumers, or energy end users, for instance, with temporary energy supply failure or price fluctuations. The distinction between supply- and demand-side (cf. Table 1) should not be interpreted as a dichotomy, but rather as a continuum; the physical connection between the two (i.e., transmission grid) illustrates this point. Thus, the purpose of Table 1 is to guide the lens that should be used to analyze texts and statements about climate risks of transforming toward a system based entirely on renewable energy. As previously described, climate risks can relate to the transformation process toward a net zero-emission society by 2100, to

TABLE 2. System elements and characteristics that determine the degree of societal vulnerability (adapted from Perrow 2007).

System category and elements	System characterization	
	Resilient	Vulnerable
Interactiveness	*Simple*	*Complex*
Relationships between system elements	Linear	Nonlinear
System elements	Loose-spaced unique elements	Tight-spaced common mode elements
System stability	Stable	Growing
Interactions and risk of unintended feedback loops	In expected sequence, low risk	In unexpected sequence, high risk
Coupling	*Loose*	*Tight*
Delays in processing	High	Low
Slack in input factors	High	Low
Buffers and redundancies	High	Low
Substitution of input factors	High	Low

the transformation process endpoint, or to both the process and endpoint. The supply- and demand-side and physical/transition climate risk divisions can be applied to both the transformation process and endpoint. Finally, we can also differentiate between analyzing risks at a holistic system level or apply it to parts or elements within the energy system. The rationale for differing between the two levels is the notion that analyzing climate risks at the system level represents "more" than the mere sum of risks for each energy system element.

3. Applying "risk society" to the energy system

The idea that societal change—beyond leading to GHG emissions—co-creates climate risks is captured by the notion of vulnerability and is strongly related to the idea of "risk society" (Beck 1992; Jasanoff 2010). Works on "risk society" by the American sociologist C. Perrow (Perrow 1984, 2007) stand out as particularly relevant to our topic, insofar as it particularly addresses risks associated with industrial processes and industrial sites and includes risks related to natural hazard events.

Perrow (1984) introduced two dichotomies across two dimensions for analyzing societal risks: The interactiveness dimension, differing between linear and complex, and the coupling dimension, differing between tight and loose. Herein, linear systems are surveyable components sequentially arranged. As systems grow in functions, operating them becomes more complex and demanding (i.e., their interactiveness increases). Ties to other systems will add to the complexity, as will operating in hostile environments. In systems characterized by complex interactions, unexpected outcomes are more likely to occur. Complex systems differ from those that are linear in that they have tight spacing of equipment, many common mode connections, limited options for substitution of supplies and materials, and unfamiliar or unintended feedback loops.

The concepts of "tight" and "loose" couplings originate from engineering and denote the degree of "slack" or "buffer" between items. These terms have also been used to describe connections within and between organizations. In both engineering and organizations, loosely coupled systems inherit flexibility that, in comparison with tightly coupled systems, make them more likely to "incorporate shocks and pressures for change without destabilization" (Perrow 1984, p. 92). This resembles the well-known resilience concept, that is, a system's ability to "bounce back" to its original state after having experienced external stress (Nelson and Palmer 2007; Folke et al. 2010). Resilience is partly explained by how loosely coupled systems ensure delivery; the system's aim can be reached in many ways. This can be seen in manufacturing plants, which are typically organized in ways that make them suitable for a variety of production processes, allowing substitution of raw materials, assembling methods and final outputs, as opposed to tightly coupled systems (e.g., power grids), which are characterized by being "unidirectional" in which there is only one way to reach the goal. Tightly coupled systems' lack of flexibility also implies that sequences must follow each other in a specific order, and that processes are time dependent in the sense that there is no room for delay. Perrow suggested that the systems with the largest catastrophe potential are those in which complexity is combined with tight couplings.

The concepts summarized in Table 2 deal with the system architecture, such as system borders, levels, and nomenclature. In a later book, in which he examined organizational, executive, and regulatory sources of failure, Perrow concluded that a society that relies on tight couplings and a complex system is also inherently more vulnerable to natural hazards (Perrow 2007). Thus, Perrow's approach—according to his own assessment—should also apply to climate risks. There are also good arguments in support of Perrow's approach being applicable to the energy system. His approach was initially developed to understand industrial processes by means of terms such as "nodes" and "links," which are also highly relevant for understanding the energy system.

In the next section, we apply both concepts presented above—"climate risks" as outlined by the IPCC and the distinction between a supply and demand aspect, and "risk society" as outlined by Perrow—to structure our discussion and analyzes of how the literature and relevant energy system actors address the issue of climate risks associated with transition to a future renewable energy system, and as a theoretical basis for the concluding part.

4. The research literature on climate risks and the transition to a renewable energy society

Schaeffer et al. (2012) were the first to attempt an overview of climate risk research related to the transition to a renewable energy system. They pointed out that, at the time of their study, very few strategic studies, research workshops, development forums, or international conferences had addressed this issue. Their study focused on better understanding the possible impacts on the energy system from the projected increased intensity of extreme weather events, emphasizing the weaknesses in current energy scenarios and the need to change how these are conducted (Schaeffer et al. 2012, p. 1): "the majority of current methodologies rely on past experience but this may not be a sufficiently good guide for planning and operational activities in the coming decades . . . [therefore] climate impact assessments on energy planning and operation need to take into account a greater number of scenarios, as well as investigate impacts on particular energy segments." These investigators summarized the previous energy sector studies (e.g., thermoelectric power generation, biomass, hydropower, wind power, solar energy, geothermal energy, and wave energy), covering each energy chain stage from energy resources, conversion, and transportation to final use—though to varying degrees within each energy sector and with a clear emphasis on the supply-side (Schaeffer et al. 2012).

The general view emerging from the research literature is that climate change will positively affect hydropower capacity (see, e.g., Arnell 2004), while for other renewable energy systems (e.g., wind power, biofuels, solar energy, and marine energy) the future prospects are less certain and will likely vary strongly from positive to negative by region (Schaeffer et al. 2012). Demand-side studies cited by Schaeffer and colleagues dealt with either increased demand for air conditioning from increased summer temperatures, or reduced demand for heating due to increased winter temperatures (Schaeffer et al. 2012). Schaeffer et al. summary of existing research per energy sector illustrated an important lack of comprehensive, holistic energy system analysis. Thus, no cited study addressed the sum effects on climate risks of a future renewable energy system (Schaeffer et al. 2012). Most, if not all, cited studies concentrated on isolated impacts of climate change, overlooking the systematic sum effect of climate and societal changes. These studies also paid little attention to transition risks.

Two additional recent studies, both of which used a modified energy model to analyze the impact of climate change on the European energy system, concluded that demand-side impacts will be larger than supply-side impacts (Dowling 2013; Mima and Criqui 2015). As described above, the demand-side studies have only considered changes in heating and cooling demands; on the supply-side, efficiency of thermal power plants and changes in hydropower, wind power, and solar photovoltaic (PV) electricity output have been addressed.

In their recent literature review on current energy systems, Yalew et al. (2020) analyzed 220 studies assessing projected climate change-induced challenges to energy systems, presenting an overview of both supply- and demand-side challenges from climate change. Concerning the prior, the authors suggest that climate change will influence renewable energy systems due to changes in the regularity of precipitation, sun, and wind, and may impact turbine efficiency and cooling systems in thermal power plants. They suggest that a mix of technologies may reduce overall vulnerability to these changes. With concern to hydropower, these investigators specifically pointed to the case of Norway, indicating that there might be a lesser need for investments in the hydro energy sector as runoff is projected to increase.

Consistent with this, we found few articles that discuss posttransformation risk. For example, Lo et al. (2019) aimed, with reference to Pelling et al. (2014), to identify new risks and social or economic uncertainties emanating from a "sustainable" development pathway, and to indicate where they matter posttransition. Still—and we find this to be typical of the literature on climate change-induced risks—they did not focus on the energy sector specifically, but rather on climate change-induced physical threats to society more broadly, and thus appear more concerned with the current system's adaptive capacity (or at least a modified version of it) than with risks created by a specific system's transformation. Indeed, the authors conclude that few published articles assess the impacts of climate change on overall energy systems. They also argue that as energy systems are deeply intertwined with food and water production—as well as influencing and being influenced by variables such as biodiversity, sea level rise, permafrost deterioration, and their combined effects on infrastructure and markets (and thus energy consumption)—the need for intersectoral approaches is apparent (Pelling et al. 2014). Sovacool et al. (2019) referred to energy and social justice concerns stemming from decarbonization, "while low carbon transitions may well represent normative "goods" in the sense that they contribute to reductions in carbon dioxide, they may also generate new—or worsen pre-existing—inequalities in society" (Sovacool et al. 2019, p. 582). They also expressed concerns over what they see as a lack of focus on the potential injustices produced by decarbonization: "Numerous studies have already estimated and analyzed the litany of co-benefits offered by low-carbon transitions, but very few (if any at all) have carefully calculated the injustices, or the dis-benefits" (Sovacool et al. 2019, p. 583).

The risk to which they refer obviously relates to those vulnerable to these injustices, but also unarguably to the political regime that initiates and guides transformation. It is well documented that initiatives for decarbonization, green energy production, and climate change mitigation efforts spur resentment and discontent—and sometimes even outright defiance—and can have severe political effects such as reversing much-needed policy changes (Dale and Hovelsrud 2022, manuscript submitted to *Sustainability Sci.*).

Much of the energy transition research literature is dealing with large-scale issues, that is, the question on how to substitute the current fossil energy system with a 100% renewable energy system. Small-scale issues have attended lesser attention, such as the issue of household-managed renewable energy systems. Landauer et al. (2015) refer to this type of research, when they conclude that promoting distributed and decentralized renewable energy systems in cities, that is, small-scale wind and solar, can reduce large-scale system dependency, thereby increasing resilience toward power system failures that can be caused by climate events.

Overall, our general impression from the research literature is that the focus on climate risks and adaptation needs in the energy system has been limited. This impression is supported by a recent review of urban energy systems, which referenced more than 100 studies (Nik et al. 2020). Nik et al. described a major limitation: inadequacy in designing and preparing urban energy systems to satisfactorily address plausible extreme climate events; they further noted that few studies have focused on the design and operation of urban energy infrastructure, in terms of climate resilience. Considering the occurrence of extreme climate events and increasing demand for implementing climate adaptation strategies, their study highlighted the importance of improving energy system models and considered future climate variations, including extreme events, to identify climate-resilient energy transition pathways.

5. The policy literature on climate risks and the transition to a renewable energy society

In 2019, the European Environment Agency (EEA) presented a report stating that although most European countries have assessed their energy sector's climate vulnerability and climate change adaptation, these issues have only been assessed to a limited extent in national energy plans and strategies (EEA 2019). Of particular interest is the report's fourth chapter, which is concerned with building a climate-resilient energy system, which includes some aspects of potential risks to future energy systems. Therein, the responsibility for securing a resilient energy system is divided between policy and business, indicating that incentives and regulations will be vital (Majone et al. 2016). Accordingly, the importance of avoiding maladaptation for future resilience is highlighted (EEA 2019, p. 5), as such development would lead to "solutions that are worse than the problem" (EEA 2019, p. 5). Thus, we do find that this discussion of future resilience matches the theme herein, although it remains to be described how the stated concerns might be transformed into concrete policy measures and development plans for future energy systems. A key message in the report highlights that "(m)any extreme weather events, including heat waves, heavy precipitation events, storms and extreme sea levels, are projected to increase in frequency and/or magnitude as a result of climate change. Without appropriate adaptation measures, direct economic losses to the European energy system could amount to billions of euros per year by the end of the century, with much larger indirect costs" (EEA 2019, p. 6), a point further elaborated on in their concern about the threats to hydropower from "changes in rainfall, snowfall, and snow and glacier melt" (EEA 2019, p. 38). Similar descriptions of how extreme events such as fires, heavy precipitation, storms, flooding, and heat waves can threaten the electrical grid's future stability are discussed, and that measures to minimize these risks are needed. In other words, the focus exists—yet the question of how to mitigate these threats has been discussed less.

An International Energy Agency (IEA) report on energy transitions within the oil and gas industry (IEA 2020) discussed how companies will be affected by the clean energy transition. An interesting vulnerability is thus identified, in that industry investments in areas outside their core business were less than 1% of their total capital expenditure when the report was published. In other words, the industry is deeply path-dependent and ill-equipped for the transition. The report takes a starting point that electricity alone will not meet future energy demands, and that thus "[a] commitment by oil and gas companies to provide clean fuels to the world's consumers is critical for the prospects of reducing emissions" (IEA 2020, p. 9), and that "the oil and gas industry will be critical for some key capital-intensive clean energy technologies to reach maturely" (IEA 2020, p. 10), such as carbon capture, utilization, and storage. The vulnerability in this instance, that industry survival depends on future technologies yet to be invented, is both obvious and serves to remind us that—if the IEA prospect for the future is correct—a cleaner, posttransition energy system will be not fossil-free, but emission-free, but that this future is highly insecure given its dependence on nonexistent technology. The report does not, however, reflect on possible physical climate risks involved in a close-to-renewable energy system.

Although we also assessed Norwegian green and white papers, and business and industry gray literature of varying degrees of relevance, we found few examples of relevant concerns about the energy system's future vulnerability to climate change. For example, a series of government green papers dealt with the consequences of climate change to a variety of businesses and sectors. Some of these, such as the government green paper on access to capital in transitional times (Norges Offentlige Utredninger 2018a), only reflect on future vulnerability in passing, while others, such as those addressing the business sector's importance for sustainable development of communities (Norges Offentlige Utredninger 2020), refer more concretely to both present and future risks from climate change, albeit prioritizing the former. Another government green paper, on climate risks to the Norwegian economy, published in 2018, also focused mainly on the consequences of temperature rise for current systems, though it also included limited reference to handling excessive future risks (see part 3 chapters 6 and 7). In a 2016 Norwegian government white paper on energy, the concept of climate risk itself is not mentioned, but challenges from climate change are mentioned briefly—on 4 of its 230 pages—in relation to only the current Norwegian energy system (Olje- og Energidepartementet 2016). The main messages are that climate change may prove beneficial for the Norwegian energy system, by the combined effects of increasing hydro energy production capacity (with greater precipitation) and lowering energy use for heating (with increased temperatures). However, the report also points to possible negative impacts of climate change, most importantly reduced power supply security (due to increased likelihoods of various extreme weather events) and increased variations in power production (due to increased climate variability). A special report in 2019 by the Norwegian Water Resources and Energy Directorate [Norges Vassdrags-og Energidirektorat (NVE)] on the effect of climate change on Norway's hydro energy capacity underlines the point made above about analyzing future climate in relation to the current energy system. The report's first summary paragraph states that "In our analyzes, we have taken as our starting point the current hydropower system with the climate of the future" (NVE 2019a, p. 15, our translation). This perspective is primarily optimistic, concluding that the actual increase in hydropower production over the past decade was higher than predicted by climate change models, and that current capacity will meet future needs. This optimistic perspective was echoed in long-term power market analysis for 2019–40 done by NVE (2019c), a perspective reflected even in the report's subtitle: "More ambitious climate policy is reflected in the price of power" (our translation). Possible negative climate risks were not introduced. An accompanying NVE report on Nordic production capacity toward 2040 presents estimates of expected increases in water energy production from climate change (in the range of 5%) and presents a single reference to possible negative physical climate risks (NVE 2019b, p. 8): "Climate change can also lead to larger and more frequent floods that can present challenges for hydropower plants. This is not considered in the production projections."

Those outside government have also considered our transitional needs and challenges. The Norwegian Climate Foundation (Norsk Klimastiftelse), along with World Wildlife Fund Norway, and think tank Civita, produced the report "Rapid transition, reduced risk" (Norsk Klimastiftelse 2020) in which future challenges are described. However, the focus—as we have seen throughout most of the reviewed gray literature—is on incentives for change itself and less on potential risks to systems from climate change beyond transformation. Such themes are reiterated by central Norwegian energy sector stakeholders, which is addressed in the next section.

Overall, the policy literature appears to have a somewhat wider and more open approach to the question on what climate risks may accompany the transition to a 100% renewable energy system. On the one hand, there is a coincidence when it comes to emphasizing a production in favor of a consumption perspective, and a tendency to assess future climate risk based on the current energy system. On the other hand, there is an expressed need, at least on the part of the European Union (EU), to take a holistic systems approach and invest greater resources in mapping any negative consequences on vulnerability to climate change from the ongoing energy transition.

6. Reflections by Norwegian energy policy actors on climate risks and the renewable energy society

Although Norway already has a record-high proportion of primary energy coming from renewables in comparison with all other countries, energy transition in the face of climate change is high on the political agenda in Norway. To shed light on the ongoing Norwegian energy sector transition, we conducted 16 semistructured interviews with core sector stakeholder representatives from two environmental organizations, two state-owned infrastructural agencies, three regulatory bodies, four energy producer interest groups, and one financial support apparatus. Selection of interviewees was based on the following criterion and snowball sampling: all stakeholders having an important role within the public debates about the energy system as well as systems operations. Initial stakeholder selection was based on two ongoing research centers funded by the Norwegian Research Council in which the two of the three authors are directly involved: The Norwegian Centre for Energy Transition Strategies (https://www.ntnu.no/ntrans; Western Norway Research Institute is one of the partners) and Climate Futures led by Norce (https://www.norceresearch.no/en/projects/climate-futures).

Because of coronavirus disease 2019 (COVID-19), we were forced to conduct all interviews online. The chosen software facilitated interview recording and transcription but hampered some of the finer qualitative characteristics of semistructured interviews, such as informal conversation before and after the interview. The interviews were administered following written consent, in accordance with the Norwegian Centre for Research data guidelines. The interview guide was based on the literature review, previous research projects on climate risk and energy, and a joint workshop with some of the interviewees and the authors [see the recording of the webinar (dated 24 February 2021): https://klimatilpassingssenter.no/noradapttimen]. The interview data were compiled, categorized, and semistructurally coded to fit into broad categories of "adaptive technologies," "risk and vulnerability understanding," and "system for risk monitoring and evaluation" (see also the interview guide in the online supplemental material).

a. Future sources of energy

The first question presented to Norwegian energy system stakeholder representatives was which kind of renewable energy sources they believe will dominate the future Norwegian energy market. Most respondents agreed on offshore wind and upgrading and expansion of hydropower, both in combination with green hydrogen as a secondary source of energy (i.e., hydrogen produced by renewable energy sources) and as an energy carrier. All respondents revealed a strong market focus, mainly domestic, and some underscored less export-friendly characteristics of future energy production. Reoccurring points were in line with statements like "access to power will not be a problem, it is the infrastructure and distribution that will be of importance."

b. Future energy systems and energy risk

Second, we asked whether stakeholders generally thought that a future system based completely on renewable energy would be subject to increased or decreased physical climate risks in comparison with the current situation. Their main response reflected the latter, though a few informants phrased their responses from a holistic system perspective. According to our informants, this is more a matter of highlighting separate elements in the energy system and reflecting on how physical climate risks might decrease (mostly) or increase, with a clear emphasis on looking at the situation from a production perspective. The representative from The Norwegian Directorate for Civil Protection formulated this view clearly: "I believe that risk and vulnerability will increase somewhat in the short term, but then decrease as we reach 100 percent renewable energy production."

c. Different types of climate risks

When talking about climate risks, informants were more concerned with risks associated with the transformation process, rather than transformation outcomes. Although they did not frame their answers as "transformation risks," several statements revealed a strong preoccupation with transition processes, particularly related to policy implementation: "If everything proceeds in the right direction, and political processes go smoothly, then we have a fairly good chance of reaching the 2-degree target." Several interviewees pointed to vulnerabilities of political processes of transformation, such as, "Politically it will be easier to develop renewable than to phase out fossil fuels. Thus, this will be our biggest risk that we cannot do anything about" and "with vigorous politicians brave enough to withstand popular protest, we would have made [the transformed energy system] in 10 years." At the same time, their statements indicated that society has a strong ability to cope with the transformation process.

d. National versus international perspectives

To the extent that an international perspective was present, it was linked directly to power exchanges between Norway and abroad. The future perspective here was weak, and several informants downplayed Norway's export capacity for future energy production. Informants did not directly reflect on cross-border climate risks (financial, economic, supply and demand) associated with the transition to a renewable energy system. However, there are some clear traces of the EU taxonomy's growing influence on sustainable energy production and consumption. This manifests in a somewhat skeptical attitude toward carbon capture and storage (CCS), most importantly in relation to "blue hydrogen" as an energy carrier (i.e., hydrogen produced from natural gas). Several informants underscored the challenges surfacing about financing major investments in blue hydrogen due to negative signals from the EU taxonomy process. Responses like "CCS is not coming" and "CCS is the biggest joker in the deck today" pointed to this skepticism.

e. Perceived climate risks

We also asked more specifically about the types of climate related risks informants perceived. The most frequently mentioned were the possible upscaling of hydrogen as an energy carrier and safety challenges related to hydrogen transport and storage. Other risks mentioned were power supply security, extreme rainfall, and hydropower production and conflicts with biological diversity—mostly related to wind power construction on land but also at sea—and hydropower upgrading and expansion. The latter point may reflect that most sector representatives apply a radical climate change scenario [the representative concentration pathway (RCP) 8.5 business-as-usual scenario] when planning current and future production and consumption patterns, as advised by the Norwegian government in the government white paper on climate change adaptation. Still, some of the informants pointed out that envisioning such radical scenarios may lead to overadaptation and potentially to maladaptation (e.g., adapting to higher precipitation levels than what might be the situation if a lower temperature is achieved globally than what is embedded in RCP8.5), thus inflating the conflict between environmental and economic concerns and climate risk.

f. Wholistic system versus subsystem perspective

Only one example of system-level risk was mentioned, namely the situation of a completely renewable energy system being less flexible than the current fossil energy-based system. This was expressed by a representative from the major and state-owned power company Statkraft: "When everything is connected to everything, it becomes harder to find out why things happen. Simulation models, how the flow is across the fjord, prices are linked, things become more uncertain, and less predictable."

g. Understanding future risks

We asked the sector representatives whether, and how, they employed monitoring and forecasting procedures when planning for future climate risks. In addition to the precautionary procedure of applying the RCP8.5 scenario in their planning ["all IPCC scenarios are equally likely, we are applying the highest (business as usual), but I am not sure this is the right one"], there is a strong market-based bias related to future planning. Hence, there was the prominence of EU taxonomy in their responses, with strong regional authorities setting standards for financial mechanisms based on sustainability objectives. The respondents' responses included discrepancies about how to deal with future climate risk. Most pointed out that the market must solve these challenges, as stated by the representative from the state-owned power line company Statnett: "The market has to solve this, not us." However, other sector stakeholders, like those from Statkraft, revealed strong trust in their own ability to deal with uncertainty and risk: "We do a lot of simulations, for 2040 we are doing hourly simulations based on temperature, wind velocity, sunlight, water availability, price fluctuations, consumption patterns, etc. The variations we employ in our simulations are far stronger than the effect of climate change (90–150 TWh). Hence, we are well prepared to deal with climate change." This attitude was echoed by several stakeholders, such as "We are dealing a lot with energy system efficiency—not climate risk as such. And we do a lot of contingency planning" (example from NVE). The interviewees demonstrated a certain complacency about their ability to cope with future climate risk: "There is no indication that we will not be able to keep the risk down to today's level."

h. A production versus consumption focus

There was a strong emphasis on the roles of government and sector-specific regulators and authorities, both in adaptation measures (i.e., contingency planning) and in matters of transition to a renewable energy production system; illustrated by the following statement "Without regulations, market actors won't respond to climate change mitigation ambitions." Given the stronghold of market-based assessments of climate risk, there was less focus on energy efficiency and reduced consumption levels. All sector players have strong stakes in continuous energy demand growth, and thus civil society complains about a lack of alternative strategies, illustrated by the representative from Friends of the Earth Norway: "It's too much focus on production and distribution—and not on reduction. This makes the transition to renewables more demanding for our society."

The main impression from the interviews can be summarized in the following five points:

1) greater awareness of climate risk related to parts of the system than the whole of the energy system,
2) a belief that the future supply of electricity will not represent a problem for Norway,
3) greater awareness of transition risks than physical climate risks,
4) greater belief that the transition to a 100% renewable energy system will reduce climate risks than increase them, and
5) greater awareness of climate risks related to production than to consumption.

The informants are divided in their views on whether increased integration of the Norwegian energy system in a European renewable energy market will increase or reduce the physical climate risk.

7. Summing up the current agenda on energy transition and climate risks

Our main impression from the international research literature, EU and Norwegian policy papers, and Norwegian energy actors is a strong support around the perception that long-term climate change will decrease rather than increase climate risks related to the energy system.

There exist many references to future climate conditions; for instance, the frequent references to, and use of, various climate change projections and climate change impact studies, with conclusions about climate risks relying heavily on experience that have influenced the current—and past—energy system. When moving from the hazard to the vulnerability aspect of the climate risk equation (i.e., the energy system), the bias toward "current" rather than "future" becomes even more evident. Although somewhat simplified, we can deduce that climate risks are generally discussed by applying expectations about future climate conditions applied to the current energy system, without considering that a future entirely renewable energy system will differ markedly from today's system.

Although the IPCC definition limits climate risks to adverse consequences, the climate change and energy transition discourse appears equally concerned with the positive and negative consequences of climate change. That is, the focus is on how the need for an energy system transformation away from fossil fuels opens a new avenue for future revenue, as green transformation is depicted as both costly and as a potential industry for economic growth. What we have delineated as an economic perspective deal with the question of whether climate risks are defined from a supply- or demand-side, with energy transmission placed literally midway between the two. Given that the energy systems supply-side is in every possible way more institutionalized than the demand-side, it is unsurprising to find that the supply-side dominates. Climate risks are first and foremost defined as challenges that affect energy producers and distributors, thus requiring adaptations by these actors—even if later risks affect end users.

Moving from a subsystem toward a holistic perspective is a key challenge in addressing any large-scale societal challenge. This situation is also evident in addressing climate risks impacting the energy system. At this juncture, we must distinguish between literature arguing for a shift from the current dependence on fossil fuels to a more sustainable energy system, and more systematic research on the challenges and opportunities from upscaling current, or switching to new, renewable energy sources. Few studies addressing the latter have looked at the energy system as a whole; attention is placed on subsystems limited by energy source (e.g., hydropower and wind power), location in the value chain (e.g., energy production and energy distribution), or compiling and summarizing individual subsystems with limited ambitions to examine the broader picture and sum effects on the energy system level.

It is also evident herein that a subsystem unlike a wholistic system approach dominates, in the sense that climate risks are understood and analyzed mainly within a national context—or (as is the case in Norway) within a Nordic or northern European context, as in the integration of Norway in a Nordic (and, indirectly, a northern European) electricity market. However, few, if any, studies address the climate risk challenges to transitioning the entire global energy system to renewable sources.

The COVID-19 pandemic can serve as an illustration of what can happen when a system (the global economy) that can be characterized by everything being connected to everything is exposed to a strong external ubiquitous global stress (infection and disease): a massive unfolding—as we write—of value-chain disruptions and breaches in global mobility and global commodity supply chains. According to theories of social risk developed by academics such as Perrow, this situation is a foretold disaster. In a figurative sense, a similar situation may prove to be the case for a future 100% renewable energy system in the face of claimed change, if we do not analyze such a risk in a good way and take the necessary precautions.

8. A proposal to expand the research agenda on energy transition and climate risks

On a practical, instrumental level, we can use our cumulative review herein to identify several specific knowledge gaps in describing different aspects of climate risks associated with transition to a future renewable energy system. However, behind the "how" question, there is a "why" question: Why do these climate risks occur—in addition to the obvious fact that we have anthropogenic GHG emissions? In other words,

TABLE 3. Proposed theoretical framework for understanding how energy system transitions may influence climate risks.

	High energy use		Low energy use	
	Low CCS/NETs capacity	High CCS/NETs capacity	Low CCS/NETs capacity	High CCS/NETs capacity
High energy supply complexity	Potentially highest climate risks			
Low energy supply complexity				Potentially lowest climate risks

which societal development entities may increase or decrease the climate vulnerability associated with transition to a future 100% renewable energy system?

Returning to Perrow's theory of societal risk, the energy system will become less resilient and more vulnerable to climate change if it moves farther in the direction of more complex interactions and tight connections. But what would such developments mean specifically for the case of the energy system? One way to answer this question is to identify major drivers of energy system development, and to relate such drivers to the system elements in Perrow's model (Table 2). We propose three possible candidates of societal drivers:

1) level of energy use,
2) level of energy supply complexity, and
3) level of implemented CCS and/or negative emissions technologies (NETs).

The *first* proposed driver—level of energy use (and, correspondingly, energy production)—applies primarily to the element "system stability" (Table 2). The idea is that energy system complexity—and therefore its vulnerability—will increase with an increase in the size and number of elements and functions.

The *second* proposed driver concerns qualitative aspects of various renewable energy sources. Sources of renewable energy are often described as being numerous, small, and scattered characteristics that are often seen as problematic by the energy producer and distributor side. Thus, many initiatives have attempted to change this situation (e.g., by upscaling wind energy with respect to both individual windmill size and the number of windmills per site, creating larger and larger windmill "farms"). The same development can be seen with solar energy, from small solar panels on individual buildings' roofs to large solar energy "farms." The result will be a mixture of "small" and "large" production facilities, ranging from very small (e.g., solar cell charging integrated within small electrical appliances) to extremely large (e.g., windmill parks like the Dogger Bank Offshore wind park in western England, which has been planned to extend approximately 8660 km^2, or 6.6% of England's land area; https://doggerbank.com/about/).

A factor that has received little attention in the energy and climate literature is the possible relation between energy quality and climate risk. Energy quality can be ranked (i.e., from high to low), for example, a division into five levels proposed by Ohta (1994): electromagnetic, mechanical, photon, chemical, and heat. Numeral alternative and competing categorization systems exist. The point is that renewable energy comes in different entropic qualities, each of which has optimal and most efficient energy use purposes. Electromagnetic energy is best used to run engines, whereas heat energy is best used to—as the name suggests—heat. Moving from the current (almost) single- and all-purpose energy source system toward multiple sources with a corresponding multiple-purpose energy system will strongly increase energy system complexity.

The *third* proposed driver—the extent of CCS and/or NETs—deals with what has been characterized (also by our interviewees) as the "ultimate joker" of climate policy (Edenhofer et al. 2005). Implementation levels of various CCS and NETs solutions serve as a balancing post for GHG emissions we are unable to cut in time, including the possibility of including some fossil energy in a future energy system compatible with the Paris Agreement. All other factors being equal, there may thus be a connection between increased energy consumption and increased need for implementing CCS and NETs. This will lead to a further increase in energy system complexity.

Possible consequences of applying the framework proposed herein to guide in reducing climate risks involved in the transition toward a more-or-less (depending on the level of implemented CCS and NETs) entirely renewable energy system could be to strengthen research and policy efforts on the following challenges:

- Reduce society-wide energy consumption (as opposed to what could arguably be described as the current priority: to improve energy efficiency and facilitate continued growth in energy consumption).
- Diversify energy consumption according to energy source quality (as opposed to maintaining the current all-purpose fossil energy source structures, which may force most renewable energy sources to be transformed into electricity).
- In addition to diversification of energy consumption described above, adopt a principle of short-traveled energy, meaning that large-scale energy consumers should be located as close as possible to their most appropriate energy source (as opposed to a principle of geographically disconnecting sources of energy production and consumption, requiring long-range power transmission).

According to the framework illustrated in Table 3 and if this theory holds, following up on providing more research on these three challenges may reduce climate risks involved in the transition toward an entirely renewable energy system.

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