Assessing risks of low-carbon transition pathways

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Editorial

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1. Introduction to risks

Limiting climate change to well below 2 °C, as defined in the Paris Agreement, challenges current greenhouse gas (GHG) emissions trajectories of many countries. At the country level, nationally determined contributions (NDCs) require governments to specify, mitigation actions and policies to achieve the required emissions reductions. However, thus far NDCs have been conservative in their outlook and ambition. Moreover, decision makers still struggle to provide the details in achieving these pathways that are necessary to secure stakeholder by-in and participation of citizens that are vital to realizing a low-carbon transition. This special issue highlights that multiple stakeholders' perspectives at all levels of governance are required and crucial to the design of transition pathways along with the identification of associated risks.

Transition pathways consist of a set of policy instruments, strategies and technologies that contribute to promoting low carbon innovations in one or more sectors. As such they are a tool for discussing and comparing the long and uncertain roads that could lead us towards a low carbon future. Often, these low carbon transition pathways and their intended outcomes are portrayed as inherently positive; however, there are associated risks that need to be identified and managed in order to secure their social, economic, and environmental compatibility. This raises two questions: "*what are the specific risks in low carbon transition pathways?*" and "*what methods can be used to evaluate these risks across different contexts and disciplines?*".

The sixteen papers in this special issue contribute to providing the answers. A summary of each paper is provided in Table 2. Moreover, all studies featured here fulfil a set of four requirements that we consider crucial to the analysis of risks associated with transition pathways: (1) They broadly apply the same risk and uncertainty framing (Hanger-Kopp et al., 2019) to describe their findings. Eight of the studies in this collection result from the TRANSrisk project, where the risk framing was first developed and later applied in the empirical studies. The other eight papers were independent research studies outside of the TRANSrisk project where researchers primarily applied the risk framing ex-post. (2) Each paper illustrates different contexts of low carbon transition pathways within the energy, agriculture, industrial and financial sectors covering a multitude of regions, exemplary from the Global South as well as the Global North; more importantly they highlight different contextual factors that shape risks and stakeholder perceptions thereof. (3) The studies apply cross-disciplinary approaches. Finally, (4) all use a mix of qualitative (e.g. stakeholder engagement) and quantitative methods (e.g. modelling and statistical analysis) in order to draw conclusions with respect to the policy and decision-making processes required to arrive at a low carbon future.

Risk is an elusive term that is difficult to specify across disciplines, often intangible and thus either poorly or inconsistently defined. Risk is often confounded with uncertainty, but while risk always involves a level of uncertainty, an uncertainty is not necessarily a risk. We consider uncertainty as "a state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable" (Kunreuther et al., 2014, p. 155). Uncertainties, as such, may result in positive outcomes, creating opportunities and benefits. They also may have potential negative outcomes. These uncertain, potential negative outcomes are what we call risks.

In the context of low carbon transition pathways, we find two different perspectives on risk. *Implementation risk* is the potential for negative impact on the implementation of a low carbon pathway; and *consequential risk* refers to the potential for negative impacts resulting from the implementation of a potential pathway. Fig. 1 shows a framing developed in the TRANSrisk project (TRANSrisk, 2015; Hanger-Kopp et al., 2019) indicating that risks are negative outcomes of uncertainties and that risks in transition pathways can be viewed as implementation risks or barriers as well as consequential risks or negative outcomes.

The distinction between implementation and consequential risk is not always straightforward, as the knowledge of consequential risks may function as a cognitive barrier to a policy even being chosen, which also makes it an implementation risk. Finally, most risks do not occur in an isolated fashion, but are part of cause and effect chains or cascades, which often are difficult to identify. For instance, most mitigation policies support a certain technology, and in turn this technology may have negative impacts on the

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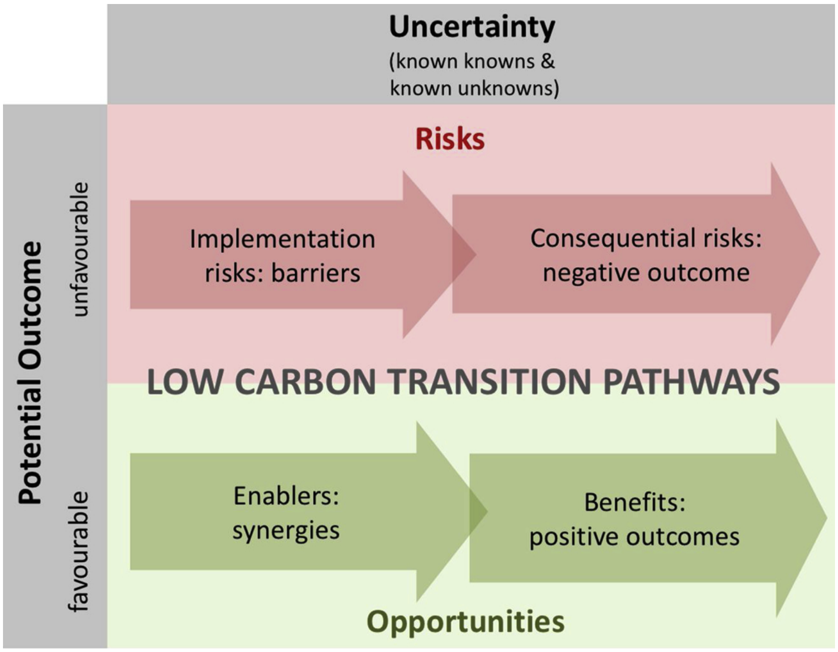

Fig. 1. Implementation and consequential risk framing.

environment, health, or other technologies in the market. An environmental impact, e.g. greenhouse gas emissions and air pollution can potentially cause a negative impact on health that can, at scale, have negative impacts on local communities.

2. Risk as a matter of context and stakeholder perceptions

In practice definitions of risks are *context specific* (Glickman and Gough, 1990), not the least, because they depend on the point of view of the person experiencing or observing the risk. What is negative for some stakeholders, may be positive for others. This can be especially extreme for climate change impacts, and mitigation where cause and effect are disproportionately distributed among different stakeholders. This special issue places a strong focus on how risk impacts different stakeholder groups – including those who influence technologies, policies and actions as well as those who do not have decision making authority but are impacted by low carbon transition pathways.

In this special issue we distinguish *environmental, social, economic, political, policy and technological* contextual factors of transition pathways (see Table 1). While they are not clearly distinct and overlap in practice, they enable us to structure our thinking on *specific* risks.

We thus summarised the key contextual factors that helped to specify the risks under investigation[1] (also see summary in Table 2). The results yield some interesting insights on risks that emerge across the contextual factors in different transition pathways. The contextual factors that appeared most frequently were *social* factors (appearing at least in 11 out of 16 papers), followed closely by *economic* and *technological* factors (≥10 papers). *Political contextual* factors also appeared quite frequently (≥8 papers) and often overlapped with *policy* (≥4 papers). Finally, *environmental* factors did not stand out as we would have expected (≥7 papers) for low carbon transition pathways.

Economic contextual factors have different implications at the economy-wide level, sectoral level, and the individual level. Incumbent technologies and their corresponding infrastructure for sectors including fossil fuels (Antosiewicz et al., 2020; Silaen et al., 2020; Skoczkowski et al., 2020), transport (Wanitschke and Hoffmann, 2020), and large/heavy industry (Bachner et al., 2020; Schneider et al., 2020; Wanitschke and Hoffmann, 2020) were often cited as crucial to the economy and could be potential barriers to low carbon innovations. At the sectoral level, businesses faced challenges within the market for low carbon innovations such as renewable energy due to their high cost (Nikas et al., 2020). This led to uncertainties for investors (Kitzing et al., 2020), needs for financing mechanisms (Bertheau et al., 2020) as well as higher investment costs of low carbon technologies (Bertheau et al., 2020; Schneider et al., 2020). At the individual level, a lack of professional and technical skills to be re-employed (Skoczkowski et al., 2020) and job losses in fossil fuel sectors (Antosiewicz et al., 2020; van Vliet et al., 2020 were highlighted as consequential risks while job gains in renewable energy (Nikas et al., 2020) and potential reskilling were opportunities.

Social contextual factors emerge when livelihoods and well-being are impacted due to unequal opportunities and rights and

[1] Note: we, the guest editors of this special issue, summarised the contextual factors that stood out to us in the papers. We have not included every contextual factor presented in each study, and therefore acknowledge some inherent biases in the selection of contextual factors.

Table 1
Contextual factors and corresponding risk descriptions.

Contextual factors	Corresponding risk examples
Environmental context: the natural resource base, biodiversity, land, water, air and overall ecological condition.	**Environmental risk:** refers to negative changes, and disturbances impacting environment systems and/or physical, chemical and biological processes and flows.
Social context: the perceptions, needs and priorities of the public which broadly consists of citizens and communities who are also consumers of goods and services.	**Social risks:** consequences such as threatening quality of life and livelihoods activities for different societal groups and/or creating inequalities among them.
Economic context: refers to the production and consumption of goods, services and materials as well as the distribution of resources within a country/region.	**Economic risks**: negative influence on the distribution of resources and adverse financial impact on part of or the entire economy.
Political context: the activities of governing institutions as well as political actors and groups within the same or different jurisdictions.	**Political risks**: decisions that cause dissent and disputes within governing bodies or mistrust with the public.
Policy context: relates to the policy instruments and corresponding policy institutions developing and implementing the policies.	**Policy risks:** policies that do not achieve its desired impact and/or conflict with the aim and objectives of policies.
Technological context: the application of scientific knowledge to serve a societal purpose, including hardware and software, and their related processes.	**Technological risks:** negative effect caused by the intrinsic complex nature and specificities of technology development and deployment.

overlap with economic, technological, political and environmental factors. For instance, employment issues were not only discussed in terms of economics, but often emerged as a social factor that impacts livelihoods. A transition into a low carbon economy can lead to unemployment, a negative outcome in high carbon sectors such as coal power. Thus, there is a need to consider re-employment into other sectors (Antosiewicz et al., 2020; Skoczkowski et al., 2020); but such mitigation cannot occur immediately and requires longer term planning across sectors (Nikas et al., 2020). The impact of low carbon technologies also raises the issues of social justice (Bachner et al., 2020), as renewable energy is often more costly (at least during the early phases) and these costs are often passed to consumers (Nikas et al., 2020). Increased cost of electricity has varying impacts on different populations, particularly for more vulnerable groups (Fell et al., 2020) as well as broader social welfare impacts (Kitzing et al., 2020), leading to potential negative impacts. The acceptance and resistance of low-carbon technologies was also brought up in several studies at the societal level (Arning et al., 2020; Bachner et al., 2020; Bertheau et al., 2020; Mayer et al., 2020; Schneider et al., 2020), as well as social unease due to a lack of policy enforcement leading to greater uncertainty (Taylor et al., 2020). Additionally, potential barriers occurred due to individual choice such as behaviour change (Bachner et al., 2020), end-user demand (Taylor et al., 2020) as well as with end-user responses for self-consumption (Nikas et al., 2020). These societal factors are also closely linked to responses of technological change.

Technological contextual factors that were highlighted in the studies primarily focused on low-carbon electricity generation technologies as a means to achieve a transition pathway (van Vliet et al., 2020). Several studies explored the readiness level (Wanitschke and Hoffmann, 2020), technological awareness (Bertheau et al., 2020), technical potential (Sharma et al., 2020; Skoczkowski et al., 2020; Arning et al., 2020;) as well as the gaps between the potential and actual installation or implementation (Mayer et al., 2020). Other studies explored barrier in deploying low carbon technologies due to energy infrastructure issues, (Bachner et al., 2020), intermittency of renewable electricity (Antosiewicz et al., 2020), and inadequate selection energy technology options for biogas energy end-users leading to unsuccessful deployment and scaling up (Silaen et al., 2020). The choice of low technologies is often impacted by other factors such as political and policy support.

Political contextual factors were closely linked to *policy contextual factors*. Politics would often dictate the extent of policy support for low carbon technologies (Mayer et al., 2020; Schneider et al., 2020; Spijker et al., 2020). The implementation of these policies would also depend on planning and coordination (Bachner et al., 2020; Bertheau et al., 2020). Barriers to adequate policy implementation included the lack of coordination between different levels of governance (Silaen et al., 2020) as well as a technology that crosses multiple policy areas and jurisdictions, leading to confusion and uncertainty (Taylor et al., 2020). Additionally, internal politics such as political agendas (Spijker et al., 2020) or political instability would result in unstable policy and regulatory frameworks (Nikas et al., 2020) or conflicting policy mixes (Mayer et al., 2020) as negative outcomes that threaten a low carbon transition.

Environmental contextual factors stood out the least in the studies even though climate change mitigation is a core premise for low carbon transitions (van Vliet et al., 2020). This could be due to the level of concern for environmental issues versus other more urgent societal or political issues. Environmental concerns were noted when a technology in a transition pathway impacts health due to poor outdoor air quality (Skoczkowski et al., 2020; Spijker et al., 2020; Arning et al., 2020;) as well as poor in-door air quality (Silaen et al., 2020). Negative impacts on the environment were discussed in terms of resource consumption (Bachner et al., 2020) and land use changes or carbon leakage where a reduction in a high carbon sector in one country is replaced by increased production in another (Spijker et al., 2020). By and large, the overall negative environmental impact did not stand out as a current risk that needed high attention. This is in line with earlier studies which reveal that environmental risk are not necessarily the key driver to implementing low carbon pathways; rather environmental factors are often secondary to other factors such as economic and societal impact (see Hanger et al. 2019; Lilliestam et al., 2014; van Vliet et al., 2012). For instance, there are synergies between addressing environmental and social issues, such as off grid technologies, which can provide electricity for community in remote locations as well as reduce emissions (Bertheau et al., 2020).

Table 2
Summary of risk discussion and methods applied in each paper of the special issue.

Paper & topic summary of country/region	Implementation risk (IR) & consequential risk (CR)	Contextual factors	Stakeholders considered	**Multi/inter/trans-disciplinary; QT° & QL°°**
Arning et al., 2020 Modelling of general and local public acceptance based on perceptions of risk and benefit for Carbon Capture and Utilization (CCU) in **Germany**	**IR**: societal acceptance can be a barrier to CCU uptake **CR**: health and environmental risks in the manufacturing process of local communities including allergies, breathing difficulties and sustainability risks on the actual CO2 emission reduction benefits	**Environmental**: CUU technology argued to save fossil resource and reduce CO2-emissions) **Social**: local acceptance depends on risk perception while general acceptance based on benefits perception **Technological**: high CUU potential for CO_2 -derived plastics products	Experts in CCU with a majority from academia and potential consumers of CCU products	**Inter-disciplinary** **QT**: on-line survey and structural equation modelling **QL**: interviews with experts and focus groups and analysed using content analysis
Antosiewicz et al., 2020* Modelling analysis and assessment of the socioeconomic implications of transitioning away from coal in **Poland**	**IR**: additional costs of investment in carbon-free source **CR**: manage impacts of decarbonisation on economy and society	**Economic**: prices of energy, market access, job losses, and overall economy growth **Political**: relations with the EU and Russia **Social**: adaptability of mining workforce **Technological**: intermittency of renewable electricity	Government agencies for political feasibility of policy instruments Industry for impacts on business and employment Environmental NGOs for potential impacts on climate change and air quality	**Inter-disciplinary** **QT**: energy system modelling, dynamic stochastic general equilibrium modelling **QL**: fuzzy cognitive maps constructed in stakeholder workshops
Bachner et al., 2020* Analysis of pathways towards climate-neutral iron and steel and electricity production in **Austria**	**IR**: (Lack of) regulation, market structures & internalized prices, coordinated climate strategy, investment in decentralized solutions **CR**: Stability of grids and flexibility of energy system (storage); impacts of energy supply, behavioural change, poor timing	**Economical**: lack of planning and investment risks **Environmental**: increasing demand of natural resources **Political**: lack coordinated political and institutional framework **Social**: societal acceptance criteria (NIMBYism). Negligence of social equity and behavioural change **Technological**: energy infrastructure	Industry experts (frontrunners) for critically reflecting on assumptions and parameters (consultation) policy, administration and scientific stakeholders (generalists)	**Multi-disciplinary** **QT**: macroeconomic modelling (computable general equilibrium with an electricity sector investment module) **QL**: Semi-structured interviews and workshops with back-casting exercises
Bertheau et al., 2020 Explore the role of electric cooperatives in small and remote islands: The example of Philippines' first off-grid, hybrid energy system **Island ofCobrador, Philippines**	**IR**: Cooperatives requiring high upfront costs; economic viability and system reliability; remoteness and delay of implementation of project **CR**: Cooperatives as stranded assets, viability of project **Societal**: skilled workers, resistance / acceptance of renewable energy	**Economical**: financing mechanisms, private sector, customer reliability **Political**: policies, lack of planning and coordination and bureaucracy **Technological**: awareness and availability of renewable energy **Geographical***: inaccessible remote islands: infrastructure & transport needs/ dependence (*author category)	Energy sector experts, electric cooperatives (EC) officers and members, island community leaders, and household heads and members for understanding the uncertainties faced by the Romblon Electric Cooperative	**Trans-disciplinary** **QT**: household survey and inventory to analyse the uncertainties and risks **QL**: focus group discussions, and expert interviews
Fell et al., 2020 approach for analysing distributional impacts of energy policies and identified mechanisms that may cause distributional injustices and explored though scenarios modelled for the **United Kingdom**	**IR**: socio-political implementation risk as it may negatively impact transition policies **CR**: Main risk explored is consequential, i.e. distributional injustices	**Social (justice)**: mechanisms that influence distributional outcomes on different population sub-groups (rural, non-switchers, low income, elderly, disability, etc.). E.g.: high costs, cold/ overheating, higher network charges, unavoidable service charges, & reduced mobility	Stakeholders consulted on mechanisms causing distributional injustices including government, regulators, advisory body, consumer advocacy organisation, university, and non-university research organisations	**Inter-disciplinary** **QT**: energy systems modelling **QL**: purposeful stakeholder/expert interviews

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Table 2 (*continued*)

Paper & topic summary of country/region	Implementation risk (IR) & consequential risk (CR)	Contextual factors	Stakeholders considered	**Multi/inter/trans-disciplinary; QT° & QL°°**
Kitzing et al., 2020 Policy price instruments for niche technologies and auction for upscaling and diffusion policies. Case of solar PV in **Germany**	**IR**: policy choices in reducing investor risk to niche innovations and accelerate deployment **CR**: manage exposure to negative outcomes (also called regulator's regret)	**Economic & policy**: financial view of risk in the market that is required for effective economic instrument selection and design **Social**: impacts of policy choices on social welfare	Investors' and entrepreneurs' perception of financial risks Policy makers' perceived risk of policy instrument choice	**Multi-disciplinary** **QT**: economic modelling **QL**: review on stakeholder perception
Mayer et al., 2020* Explore the potential impacts of scaling up solar PV via rooftops and ground mounted solar parks in **the Netherlands**	**IR**: inconsistent policy mixes, and financial constraints, grid balancing issues and infrastructure planning, spatial planning and employment **CR**: scaling up PV for electricity consumers and macroeconomic costs considering uncertainties	**Policy and politics**: Netherlands not likely to meet EU renewable energy targets thus the government announced more stringent ambitions **Technology**: large gap between technical potential and installed potential	Stakeholders consulted to explore risks for rapid PV expansion includes: public bodies, businesses, energy think tanks, academic, grid/network operators, energy cooperative, and environmental NGO	**Multi-disciplinary** **QT**: recursive- dynamic general equilibrium model **QL**: interviews with stakeholders using snowball sampling
Nikas et al., 2020* Explore benefits and risks of diffusing solar power through large scale solar and self-consumption, distributed power generation and demand flexibility in **Greece**	**IR**: poor public acceptance of residence near large scale solar and needed supporting policies **CQ**: impact of both large scale solar as well as self-consumption on the economy and households	**Economic**: ongoing economic recession, highly cost for solar **Political**: unstable political environment leading to unstable policy and regulatory frameworks **Social**: job losses may not be immediately off-set in other sectors; potential increase in electricity price due to uncertainties in self consumption and demand-side response	Expert groups to explore potential policies: representatives from renewable energy associations, energy transmission system operations, and electricity distribution network operations, policy makers, researchers, and GHG emissions industry	**Trans-disciplinary** **QT**: agent-based energy model); dynamic stochastic general equilibrium model), fuzzy cognitive mapping (qualitative inputs from stakeholders) **QL**: stakeholder workshops
Schneider et al., 2020 Explore three pathways where industry in the port of **Rotterdam, the Netherlands**, can maintain its position while reducing CO2 emissions & risks	**IR**: implement adoption of low-carbon industry clusters **CR**: reduce impacts of additional costs on viability of industry, climate change	**Economic**: investment costs, competitiveness **Political**: EU and global policies on climate change mitigation Technology: technology readiness **Social**: acceptance of new and existing technologies	Local industry, in three clusters Local authorities, including the Port Authority of Rotterdam, and environmental NGOs	**Multi-disciplinary** **QT**: scenarios analysis; energy and product flow modelling **QL**: workshops for industry and for other stakeholders
Sharma et al., 2020 Assess decarbonisation scenarios with variations across multiple dimensions, including carbon budget and technology availability in **Ireland** using a novel MCA method	**IR**: availability of technological options and resources, costs, revenues and potential market development, role of government and regulation **CR**: supply security, impacts of air quality, employment	**Economic**: part of a project focused on entrepreneurial opportunities from a low carbon transition **Technological**: energy technology portfolio selection based on low-carbon and assumed preference renewable energy - for new and more mature technologies	Stakeholders to assess risks include industry (utilities, SME, large businesses), government departments and agencies, NGOs, and lobbying groups	**Trans-disciplinary** **QT**: energy system modelling, multi-criteria analysis **QL**: workshops feeding into and using model results
Silaen et al., 2020* Explore potential for biogas an option for cooking fuel through 3 perspectives: technologies, co-	**IR**: financing and investment risk due to high costs for farmer; lack of monitoring and service and training support for biogas programmes	**Politics and policy**: national and subnational government units leading to slow implementation of policies contracting policies that promote biogas and LPG	Policy makers at local/national levels: want to explore potential to scale up biogas; key research partner Farmers as users of biogas applications	**Trans-disciplinary** **QT**: macro-economic model, Q-method (applied in stakeholder workshops to collect views on biogas) **QL**: interviews, surveys,

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Table 2 (*continued*)

Paper & topic summary of country/region	Implementation risk (IR) & consequential risk (CR)	Contextual factors	Stakeholders considered	**Multi/inter/trans-disciplinary; QT° & QL°°**
benefits and independence in **Bali, Indonesia**	**CR**: disruption of bio-digester value chain and abandonment of biogas digesters	**Social and environmental**: in-door air pollution from biomass as a health hazard **Technology**: several technological options for biofuels and not all suitable for farmers in the region	Universities, NGOs and banks: views on biogas	focus group and policy dialogues; social discourse analysis as framing
Skoczkowski et al., 2020 Explore transition stakeholders' beliefs and perception about political, economic, environmental, social and technological risks and opportunities for the coal-dependent region of **Silesia, Poland**	**IR**: challenges during a phase-out of coal mining and use **CR**: impact of coal-exit on society in mining region and electricity supply	**Environmental**: Existing air quality is poor **Political**: Power of coal mining **Social & economic**: Lack of employable skills in mining communities Technological: Low renewables potential in region	Government, trade unions, and mine management for political backing, social and economic barriers and impacts Banking & finance available capital for investment Environmental NGOs for air quality	**Inter-disciplinary** **QT**: economic and environmental analysis, risk matrix **QL**: interviews with practitioners in five sectors, and literature review of stakeholders' perspectives
Spijker et al., 2020* Assess positive and negative side effects for two pathways on reduction of cattle and integrated manure management (IMM) for the livestock sector in **the Netherlands**	**IR**: financial barriers for IMM **CR**: displacement of cattle farming to other countries leading to carbon leakage; animal welfare when keeping cattle in-doors; conversions of grass land could release soil carbon; loss of jobs	**Environment and policy**: reduce methane and improve air quality set by the EU directives; soil carbon also a concern due to land use **Political**: election programmes of several political parties promised to reduce livestock and limit nitrogen emissions	Stakeholders to identify risks include policy makers, energy industry consultants, agricultural industry associates, academic researchers	**Multi-disciplinary** **QT**: macro- econometric and atmospheric modelling **QL**: stakeholder consultations through interviews and stakeholder meetings organised by government institution
Taylor et al., 2020* Explore sustainable policies and practices for charcoal production and supply in Kitui County, **Kenya**	**IR**: regulation barriers, corruption in enforcing policies; charcoal cuts across many policy areas and jurisdictions and lead to confusion and uncertainty **CR**: overharvesting of biomass and impacts on forest resources and ecosystems, and high GHG emissions; enforcement of policy may increase cost for poorer actors in supply chain	**Policy**: increased regulation to reduce unsustainable production: previous partial logging ban; current policies to develop licensing system for producers and transporters **Society**: charcoal as main cooking fuel in urban households; demand increase partly due to urbanisation and population growth	Stakeholder includes county government, research organizations, private sector, non-governmental organizations and charcoal producer associations	**Inter-disciplinary** **QT**: agent-based model **QL**: interviews and workshop with stakeholders; stakeholder provide feedback on model outputs
van Vliet et al., 2020* Systematic analysis of the risks associated with decarbonisation pathways in 15 case studies in **12 countries**	**IR**: ex-post analysis of 145 implementation risks from an existing research project **CR**: ex-post analysis of 121 consequential risks from an existing research project	**Economic**: costs and economic impacts, particularly job losses, were the most-mentioned risks **Environmental**: all case studies were focussed on climate change mitigation **Technological**: technological innovation was an essential element in all pathways.	Domain experts (academics, practitioners) for study design Policy makers as co-designers and target audience NGOs, business, marginalised groups for being essential to a balanced and useful outcome	**Inter-disciplinary** **QT**: economic, energy systems, impact assessment, and agent-based modelling, fuzzy cognitive mapping, Q-method **QL**: literature review, social discourse analysis interviews, stakeholder workshops, policy dialogues

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Table 2 (*continued*)

Paper & topic summary of country/region	Implementation risk (IR) & consequential risk (CR)	Contextual factors	Stakeholders considered	**Multi/inter/trans-disciplinary; QT° & QL°°**
Wanitschke and Hoffmann, 2020 Identify, characterize and compare uncertainties in low carbon transition of road transport in **Germany**	**IR**: technology choices to smooth transition to low-carbon transport **CR**: manage impacts on domestic value chain and labour market	**Economic**: future demand for transport, large industry is important to national economy **Technological**: readiness and prices of fuel and vehicle technologies	Experts from the transport field for different risk aspects of drive train technology and infrastructure	**Multi-disciplinary** **QT**: economic analysis **QL**: argument mapping, literature review, expert interviews

°QT: Quantitative methods; °°QL: Qualitative methods; *TRANSrisk research projects.

3. Cross-disciplinary and mixed methods to analyse risks

Various disciplines can be applied when analysing risks across different contextual factors. All papers in this special issue are at least multidisciplinary (Bachner et al., 2020; Kitzing et al., 2020, Mayer et al., 2020; Schneider et al., 2020; Spijker et al., 2020; Wanitschke and Hoffmann, 2020) in that authors contributed approaches from two or more disciplines (Choi and Pak, 2006), to assess risk and uncertainty in transition pathways. However, more than half go beyond multidisciplinarity. Six papers (Arning et al., 2020; Antosiewicz et al., 2020; Fell et al., 2020; Skoczkowski et al., 2020; Taylor et al., 2020; van Vliet et al., 2020) can be considered interdisciplinary as their authors collaboratively joined approaches and perspectives from different disciplines to generate new knowledge and added value (Choi and Pak, 2006). Another four applied aspects of transdisciplinary methods (Bertheau et al., 2020; Nikas et al., 2020; Sharma et al., 2020; Silaen et al., 2020); they combine scientific knowledge and insight with expertise and know-how from outside academia (Polk, 2015). Multi- and inter-disciplinary research may include stakeholders in the research process, but transdisciplinary research differs in the extent to which stakeholders who have to live with pathway outcomes, like residents and businesses, are integrated in the entire research process from problem framing and co-design to analysing problems and exploring impact (Pohl et al., 2017).

Depending on the discipline, risk can be analysed qualitatively or quantitatively (Doukas et al., 2019; Renn, 2008). All contributions to this special issue involve different levels of integration of qualitative and quantitative approaches (see Table 2 for details).

Quantitative research mostly explores close-ended research questions, with methods that include statistical and other types of modelling (Creswell, 2013). The quantitative approaches applied in the papers in this special issue includes: macroeconomic models (Antosiewicz et al., 2020; Bachner et al., 2020; Mayer et al., 2020; Nikas et al., 2020; Silaen et al., 2020; Spijker et al., 2020); energy models (Antosiewicz et al., 2020; Fell et al., 2020; Sharma et al., 2020; Schneider et al., 2020); agent-based models (Taylor et al., 2020; Nikas et al., 2020;); quantitative survey instruments (Arning et al., 2020; Bertheau et al., 2020); economic scenario analysis (Kitzing et al., 2020; Schneider et al., 2020; Wanitschke and Hoffmann, 2020); and fuzzy cognitive mapping, which is complemented by qualitative methods to include stakeholder preferences (see Nikas et al., 2020).

Generally, models are able to capture large or complex sets of data and provide insights on changes across multiple contextual factors including changes and impacts of technological innovations and policies on the economy (e.g. GDP), climate (e.g. carbon emissions) along temporal scales. However, there are many risks related to climate change and sustainability that cannot be easily quantified, usually bearing more subjective features (Wallquist et al., 2009; de Vente et al., 2016; Reed et al., 2018). These are most often located in the social, policy, and environmental dimensions mirroring changes in well-being, efficacy of policy measures and overall environmental integrity and are better assessed through qualitative approaches.

Qualitative research explores open-ended questions and research designs, with methods that include case studies, narrative research and participatory methods (Creswell, 2013). Fourteen out of 15 studies in this special issue integrated stakeholder engagement in their studies through interviews, focus groups, and/or workshops (Kitzing et al., 2020 took on a theoretical analysis of investors response as means to include stakeholder's perspective). Other qualitative methods applied in this special issue include: Q-method, a bottom-up approach to collect and interpret stakeholder viewpoints (Silaen et al., 2020); literature reviews (e.g. Skoczkowski et al., 2020; Wanitschke and Hoffmann, 2020); social discourse analysis (Silaen et al., 2020); and back casting exercises which complemented modelling work (Bachner et al., 2020; Sharma et al., 2020; Schneider et al., 2020).

4. Take home messages from the special issue

Transition pathways take place within different political, social, and economic contexts, and there is no universal approach for addressing risks associated with these pathways. However, based on the contributions in this special issue, we identify some overarching relevant trends and lessons on risks and risk management in low carbon transition pathways that are valid across different decision-making contexts.

Answering our first research question: "*what are the specific risks in low carbon transition pathways?"*, we find that the overall distinction between implementation and consequential risk is a first useful step to unravel the challenges decision makers face in designing and following low carbon transition pathways. Managing implementation risks requires detailed understanding not only of the barriers themselves, but also of the decision makers involved and stakeholders affected. Frequently, barriers result from consequential risks, which can fundamentally question aspects of or the entire pathway itself due to its potential negative impacts. This is for example the case for distributional injustices (Fell et al., 2020). Mitigating negative outcomes may include incremental or fundamental changes such as the abandoning a particular technology or policy that was initially intended to play a major role in the transition pathway (Silaen et al., 2020).

Risk can be more concretely explored when considering contextual factors relating to the *environment, society, economy, political, policy, and technology.* While the environmental context (i.e. climate change), may initially seem to be a driver for transition pathways at the global level, we have observed at the local level that economic, social, technological, political and factors are more important barriers or drivers of transitions. It is these factors that overlap, interact, and spill over.

For instance, several studies underline the shortfalls of globally-agreed climate strategies and the instability of a political, long-term and ambitious climate agenda, contributing to overarching implementation risks, especially hindering investment opportunities, a prerequisite for financing decarbonization pathways (Antosiewicz et al., 2020; Bachner et al., 2020; Bertheau et al., 2020; Kitzing et al., 2020; Silaen et al., 2020; Taylor et al., 2020).

Another example is carbon leakage, illustrating the inherent risks within changing global trade patters or shifts in the locations of industrial activities therefore causing socioeconomic risks such as loss of jobs in place of origin, and a shift in emissions from one country to another leading to political and environmental risks (Spijker et al., 2020).

Unjust outcomes are among the key consequential risks in low carbon transitions, and potentially very controversial. For example, regions that are economically and socially "locked in" to fossil fuel (Antosiewicz et al., 2020; Silaen et al., 2020; Skoczkowski et al., 2020) portray different risk perceptions among stakeholders faced with the transformational changes a low-carbon transition requires; particularly questions of justice require more profound risk analyses than a mere technocratic analysis and should consider the social dimension for a renewable transition agenda.

We discovered several key insights when addressing our second research question: "*What methods can be used to evaluate these risks across different contexts and disciplines?".* Because there are such diverse risks that are valued subjectively, single-discipline assessment of pathways runs the risk of introducing epistemic bias and highlighting very specific risks over others. The papers in this special issue suggest that quantitative (modelling) methods are often used to systematically assess consequential risks, and qualitative methods are often used to assess implementation risks (van Vliet et al., 2020). A mixed-method approach was applied as a starting point to provide a more comprehensive analysis of implementation and consequential risks. For example, stakeholders may contribute to quantitative methods through the co-creation of transition pathways narratives that form the basis for scenario model runs or by providing insights on technology preferences (Bachner et al., 2020; Nikas et al., 2020; Sharma et al., 2020; Taylor et al., 2020).

We have observed a disparity between different stakeholder groups that have been engaged within studies. Domain experts observe and analyse technologies or polices but do not directly have influence or implement actions (Antosiewicz et al., 2020; Nikas et al., 2020; Wanitschke and Hoffmann, 2020;). Influencers frequently interact with people on the ground, for example Non Governmental Organisations (NGOs) and lobbyists that engage closely with inhabitants of regions affected by a low carbon transition (Bertheau et al., 2020; Sharma et al., 2020; Silaen et al., 2020; Spijker et al., 2020). Another stakeholder group are decision makers such as end-users, banks/funding bodies, business, and policy makers (Nikas et al., 2020). Often the voices of powerful stakeholders tend to dominate the discussion on transition pathways (Lieu et al., 2020). Thus, bringing in voices of groups typically marginalised (Taylor et al., 2020; Fell et al., 2020; van Vliet et al., 2020) in peripheral settings (Bertheau et al., 2020) and in vulnerable communities (Fell et al., 2020) is important for an inclusive and representative policy agenda of risks in transition pathways.

Considering risks in the policy making process, we have overarching insights on reducing barriers and negative impacts in low carbon transition pathways. Risks are contextual and location specific, and mitigation efforts that may work in one region may not be applicable to another. Despite this, we encourage active policy learning to better understand risks observed in other sectors and countries. Analysing risks based on contextual factors and framing these as implementation and consequential risks may help with designing policies that minimise or avoid some of these known risks. Implementing a policy may be met with contestations, and this is an inherent risk if the policies are not co-created; an ex-ante participatory approach can therefore avoid repeated failure of policies that are designed top-down and undesirable by local stakeholders. Understanding stakeholders' response to (new) policies or technologies requires meaningful and inclusive stakeholder engagement across different governance levels. Integrating stakeholder's perceptions in the development of policies can improve societal acceptance and help link local priorities with wider national and global climate agenda and goals. Finally, taking on board cross-disciplinary and mixed methods with stakeholder to co-create actions may elucidate option not typically considered in policy making.

Overall, risks are pervasive in transitions pathways, at every level of detail, in every theme, and for every stakeholder. Systematically analysing specific risks while considering the needs and concerns of the people most impacted by a low carbon technology can potentially help mitigate the risks that could impact our ecosystems, communities, economy, and governance systems. Therefore, careful deliberation along with use of mixed methods may bring additional insight when looking into specific risks that emerge when studying multi-to-trans-disciplinary, complex issues in transition pathways. Addressing these risks can make it easier to gain societal and political buy-in to turn these pathways into real-world policies.

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