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Taming the Green Swan: a criteria-based analysis to improve the understanding of climate-related financial risk assessment tools

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ABSTRACT

Understanding climate-related risks has become a key priority in financial decision-making and for regulatory supervision in the financial sector since the Task-force on Climate-related Financial Disclosures (TCFD) launched its recommendations on climate risk disclosures in 2017. However, a systematic approach to identify scientifically sound and decision-useful climate risk indicators and the tools to derive such risk metrics is still missing. Focusing on climate-related financial transition risks, we propose a set of analysis criteria rooted in climate science, economics, finance, and risk management, to assess whether climate transition risk analysis tools provide high quality, comparable, and decision-relevant results. We find that for a sample of 16 climate transition risk tools, some tools perform high on all criteria, but that especially model transparency, scenario flexibility, output-related uncertainties, and assumptions communication require considerable improvements. Financial supervisors and regulators should define appropriate ways to obtain comparable climate risk metrics, to ensure their interpretability, and to ensure that climate risk metric disclosures reflect the underlying assumptions and uncertainties surrounding the analyses. Researchers and any user of climate risk metrics should carefully understand and report the analysis tools' setup, and interpret their findings in light of the analysis assumptions.

Key policy insights

- Providers of climate risk analysis tools should increase transparency on the tools' setup in standardized templates. Reporting templates should include information on whether the tool has been peer-reviewed, the depth of risk analysis, key modelling steps and underlying assumptions.
- Firms should report the tool setup and modelling assumptions in their voluntary climate-related disclosures. In addition, uncertainties surrounding the analysis should be reported, for example, via confidence intervals or probability distributions.
- Financial regulators and corporate reporting regulation should ensure that mandatory climate risk disclosures are understandable and comparable. Regulators should ask firms to disclose their risks based on harmonized climate risk metrics disclosure templates, to ensure that key assumptions, the model setup, limitations of the analyses and analysis uncertainties are reported alongside the metrics.

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1. Introduction

The transition to the low-carbon economy is associated with climate-related transition risks, i.e. changes in climate-related policies, technologies, and market demand and supply that will influence the performance of any investment. These types of risks were initially classified as financially relevant and potentially material in the context of the financial sector by the recommendations of the Task-force on Climate-related Financial Disclosures (TCFD, 2017). If the risks materialize simultaneously, or due to amplification across financial markets, they can lead to financial instability (Battiston et al., 2017; Roncoroni et al., 2019; Stolbova et al., 2018). So far, research finds that investors are not sufficiently aware of climate risks, and that financial markets currently do not adequately price-in climate-related financial risks (Campiglio et al., 2019; Faiella & Lavecchia, 2020; Ilhan et al., 2020; Karydas & Xepapadeas, 2019; Monnin, 2018b). In 2018, Benoit Couré, former member of the executive board of the European Central Bank and now at the Bank for International Settlements (BIS), highlighted prominently that climate risks might have financial stability implications, and that monetary policy needs to take them into consideration (Couré, 2018). The former governor of the Bank of England, Mark Carney warned of the potential for a transition-driven 'Minsky moment', whereby a disorderly transition leads to a sudden collapse in asset prices (Carney et al., 2019). A working group of the BIS characterized this situation with the presence of 'Green Swan' risks (Bolton et al., 2020). In a similar vein, the Financial Stability Board (FSB) prominently analysed how climate risks might impact or be amplified by the financial system (FSB, 2020). In addition, an increasing amount of academic literature assesses how and under which conditions central banks and financial supervisors could align their policies to these risks (D'Orazio, 2021; D'Orazio & Popoyan, 2019; Schoenmaker, 2021; Schoenmaker & Van Tilburg, 2016; Svartzman et al., 2021).

Due to the unprecedented nature of climate-related risks, backward-looking and status quo approaches might fail to properly assess the risks. This is why forward-looking analyses are key, as highlighted by researchers and practitioners (Campiglio et al., 2018; Carney, 2015; Monnin, 2018a). Climate risks are unprecedented, characterized by fat tails, deep uncertainties, non-linearity and path dependency, non-stationarity, and endogeneity (Battiston et al., 2019; Chenet et al., 2019; Karydas & Xepapadeas, 2019; Weitzman, 2011). This renders their analysis relatively difficult and requires novel approaches rather than standard backward-looking risk assessments. Such approaches usually apply scenario analysis and require multiple modelling steps to translate climate-related developments into financial risk indicators. A variety of off-the-shelf analyses is provided by various actors in the field, usually referred to as climate risk assessment tools. These tools are set up to calculate climate-related risk indicators, which are commonly referred to as climate risk metrics. However, a theoretical foundation and systematic approach towards meaningful climate risk indicators is still missing, and it has been recently criticized that most approaches are not well documented and hence black boxes (Fiedler et al., 2021; Raynaud et al., 2020a, 2020b; Semieniuk et al., 2020). Ilhan et al. (2020) find that most investors consider the climate risk metrics available to date not informative enough for decision-making, and they show considerable doubt about the precision of the climate risk estimates. The different coverage and focus of the tools (i.e. the risk sources and risk types, the assets covered, the climate scenarios used as input, and the climate-adjusted financial metrics produced as output) require different modelling steps, and could considerably impact the final risk estimate. If these approaches fail to produce transparent, high quality, comparable, and decision-relevant climate risk metrics, financial actors will likely fail to properly account for climate risks in their investment decisions. The importance of developing appropriate climate risk assessment approaches and tools is even greater to shape the post-pandemic economic recovery without aggravating climate risk exposure of the economic and financial systems (D'Orazio, 2021).

The aim of this research is to shed light on the current status quo of available climate risk tools, and to provide criteria for further improving the available approaches. In addition, our analysis provides the users of climate risk tools with a systematic approach to better understand the structure and the outputs produced, in order to enhance decision-making. This is equally important to investors, financial supervisors, and also academia, when selecting the appropriate climate risk metric for their analyses.

To this end, in a first step, we conduct semi-structured interviews with 12 experts in the field from academia, practice, policy making and governance, to derive a set of systematic criteria to identify important characteristics of the tools and analyse the quality, comparability, and decision-relevance of climate-adjusted financial risk metrics. In a second step, we then apply the criteria to analyse a sample of 16 climate transition risk tools, by aid of a structured questionnaire.

Our analysis is developed along two dimensions: First, a descriptive analysis focuses on the characteristics of the tools considered. Such descriptive climate risk tool analysis has previously been conducted in non-academic literature, for example by BCBS (2020), Eis et al. (2019) and Raynaud et al. (2020b) on alignment tools. Yet, these reports do not explicitly assess existing tools against distinct quality criteria, which is how our analysis can be differentiated from the previous literature. Second, a criteria-based analysis allows us to evaluate how the different tools perform against different dimensions, and thus enables a grounded cross-tool comparison.

Our results of the descriptive coverage analysis show that most important risk sources and types (i.e. orderly or disorderly risk developments) are relatively well covered across the tool sample, but few tools cover all analysed risk sources and the interaction among them. The tools' coverage of financial assets is best for publicly traded asset classes. The vast majority of tool providers relies on a limited number of climate scenarios, where most tools use scenarios from the International Energy Agency (IEA) or Integrated Assessment Models (IAMs), as published and recognized by the Intergovernmental Panel on Climate Change (IPCC).

In addition, in our criteria-based assessment of how tools are set up in terms of accountability, depth of risk analysis and usability, we find that some tools perform high on all criteria, but that especially model transparency, scenario flexibility, output-related uncertainties, and assumptions communication require considerable improvements to ensure climate risk tools are used widely to assess and manage climate-related financial risks. Moreover, there is a lack of peer-reviewed approaches. Considerable variation exists in terms of the depth of risk analysis of the different tools. Finally, communication of the tool outputs should be improved to ensure interpretability and usability of results.

Our research bears important implications for policy making, tool providers, and tool users. First, providers of climate risk analysis tools should increase transparency on the tools' setup. Standardized templates to report the key tool characteristics would be useful to enhance comparability around the tools' setups. This would significantly reduce search costs for potential users. Reporting templates should include information on whether the tool has been peer-reviewed, the depth of risk analysis, key modelling steps and underlying assumptions.

Second, if firms use those tools to disclose forward-looking climate-related information, for example, in the context of TCFD-related disclosures, the tool setup and modelling assumptions should be equally reported. Otherwise, the disclosed climate risk metrics might be hard to interpret. In addition, uncertainties surrounding the analysis should be reported, for example, via confidence intervals or probability distributions.

Third, we observe that an increasing amount of jurisdictions ask firms for mandatory climate risk disclosures. Financial regulators and corporate reporting regulation should ensure that such risk disclosures are understandable and comparable. Regulators should ask for disclosures based on harmonized climate risk metrics disclosure templates to ensure that key assumptions, the model setup, limitations of the analyses and analysis uncertainties are reported alongside the metrics.

Last, given the cost of acquiring information about each tools' structure, assumptions and characteristics, it would be highly useful for potential users of the tools and comparison analyses if policy makers set up a centralized online platform, where each tool provider would be asked to document the tool characteristics alongside pre-defined criteria. This platform could be regularly updated to provide information about the latest tool features in a streamlined fashion. In addition, if tools are used to fulfil regulatory requirements on climate risk disclosures, regulators might ask for tools to be listed in this platform in order to be eligible to be used for fulfilling mandatory disclosure requirements.

This paper is structured as follows: In Section 2, we describe the sample and the methodology adopted for our descriptive and criteria-based analyses. Section 3 shows our findings related to the assessment of the sample of tools along the different dimensions identified, and Section 4 concludes.

2. Methodology

To cover a representative sample of currently available climate risk tools in our analysis, 20 tool providers ranging from financial services providers to think tanks and academia were asked to participate in the study.

Table 1. Study sample.

Provider	Metric	Type	Sector
2 Degrees Investing Initiative	PACTA	alignment/risk	think tank
Battiston, Monasterolo and Mandel	CLIMAFIN	risk	academia
Cambridge Econometrics	E3ME-FTT-GENIE	risk	academia
Cambridge Institute for Sustainability Leadership	ClimateWise	risk	academia
Carbone 4	Carbon Impact Analytics	impact	think tank
ISS ESG	Portfolio Climate Impact Report and Raw Data	risk/impact	financial services
MSCI/Carbon Delta	Climate VaR	risk	financial services
Oliver Wyman	Climate Transition Risk Methodology	risk	financial services
Ortec Finance	ClimateMAPS	risk	financial services
PwC/The CO-Firm	Climate Excellence	risk	financial services
right. based on science	XDC Model	alignment/risk	think tank
Science-based Targets Initiative	SBT Tool and SDA Transport Tool	target	think tank
S&P Global Market Intelligence	Climate Linked Credit Analytics	risk	financial services
S&P Global Market Intelligence	Climate Linked Credit Risk Tool	risk	financial services
University of Augsburg	CARIMA	risk	academia
Vivid economics	Climate Risk Toolkit	risk	financial services

Their tools have been selected based on: (1) Focus on climate-related transition risks; (2) Potential applicability for financial decision-making; and (3) Distinctive interesting features to inform next steps and improve climate risk tools further (e.g. exceptional depth of analysis, especially sound scenario-analysis approach, considerably wide range of financial applicability). Of these 20 tool providers, 15 agreed to participate in the study. In sum, the 15 participants provided us with information for 16 tools, which they currently maintain for financial market actors and other users. The providers and their tools are reported in Table 1.

Three of the analysed tools were not distinct climate risk tools. They were designed to perform climate impact analysis, climate alignment assessment or to assist with climate target setting. Still, these tools are sometimes mentioned in the risk analysis context, and their output could be used to inform the first steps of climate risk assessments. We included them as examples, identifying them as separate types, to analyse how their approaches differ from dedicated risk assessment tools.

At the start of this exercise, most of the information required for this analysis was not in the public domain. To overcome this issue, we designed an extensive survey to get the information required to identify to what extent the currently available tools fulfil the criteria as identified before directly from the tool providers. For the survey, we followed key guidelines from existing literature on questionnaire design (Krosnick et al., 2015; Rossi et al., 2013; Sheatsley, 1983), and built on papers that apply surveys in related research fields (Ilhan et al., 2020). In order to avoid bias and incentives to overstate criteria fulfilment in the responses, the questionnaire did not reveal the specific criteria along which tools would be assessed.[1] Such an approach is recommended by Nederhof (1985) and Fisher (1993). In addition, we communicated clearly to all tool providers that we will not construct a final ranking of tools, since we were interested in a cross-tool criteria analysis to enhance the understanding of the overall landscape of climate risk tools available and to inform policy making, instead of a cross-criteria tool analysis which would rather inform tool providers on how to improve their tools individually.

In order to identify the analysis criteria, we conducted semi-structured interviews with 12 experts in the field, from academia (climate modelling and finance), practice (banking and investment), policy making analysis (think tanks and NGOs), and government policy makers (governmental agencies). The list of experts and the main elements of the interview protocol are documented in the supplementary material. The aim was to collect their perspective on most relevant criteria to analyse the quality, comparability, and decision-relevance of climate-adjusted financial risk metrics. We then grouped and merged the identified criteria, and allocated specific assessment elements for each criterion. The draft compiled list of criteria and the sub-elements for analysis were then again discussed with the experts, in order to ensure that all relevant criteria were covered, and that the sub-elements chosen for the analysis were meaningful according to the various perspectives. Eventually, we finalized a list of 11 criteria with 25 specific assessment sub-elements. We grouped the criteria along three broad dimensions: Accountability, Depth of risk analysis, and Usability.

2.1. Accountability

Accountability ensures that the data input, the tool setup and the tool output (i.e. the value of the specific climate-related metric) are verifiable and can be critically evaluated by users and experts in the field. Accountability has been identified as a crucial element in the context of using modelling approaches for decision-making in various fields of research (Bierens et al., 2020; Dalla Via et al., 2019; Eddy et al., 2012; Mulligan, 2005; Wheeler & Wheeler, 2006). Lately, Fiedler et al. (2021) specifically raised this issue as an important aspect to improve existing climate risk analysis tools.

For our analysis, accountability covers three criteria: (1) Public transparency[2], namely the public availability of the model description and ideally also the model code (Bierens et al., 2020; Eddy et al., 2012; Fiedler et al., 2021); (2) Emission data, namely whether data sources are reported, whether data are third party verified, and how the tool providers deal with missing data (Eddy et al., 2012; Fiedler et al., 2021); and (3) Scientific references, namely whether tools have an explicit scientific foundation, and whether the approach has been peer-reviewed (Fiedler et al., 2021; Mulligan, 2005; Wheeler & Wheeler, 2006).

2.2. Depth of risk analysis

An assessment of the depth of risk analysis is important for a correct interpretation of the tool output (i.e. the value of the specific climate risk metric), and to check whether the most important aspects of risk for a certain use-case have been covered. To operationalize the depth of risk analysis, we define and use the risk notion as commonly used in physical climate risk and adaptation analysis (Bresch et al., 2014; IPCC, 2014). We combine it with elements from microeconomic theory,[3] macroeconomic theory,[4] risk amplification mechanisms[5] and financial market amplification mechanisms.[6] This allows us to apply a more standard climate risk analysis concept, differentiating exposure, vulnerability/resilience, and adaptability, to firm-level financial climate transition risk analysis approaches.

We assess the depth of risk analysis by aid of the criteria 4-9. We first look at the criteria (4) Hazard, i.e. whether a 1.5°C or < 2°C scenario is employed[7] and whether the analysis is differentiated by country and sector; (5) Exposure, i.e. the amount of current and future projected greenhouse gas emissions (Battiston et al., 2017; Chenet et al., 2019); (6) Vulnerability and resilience, i.e. how well the unit of analysis could absorb the hazard via the amount of profits to cover costs, cost pass-through, the performance relative to peers and the degree of competition (Batten et al., 2020; de Bruyn et al., 2015; Fabra & Reguant, 2014; Hintermann, 2016; Lise et al., 2010; Sijm et al., 2012); and (7) Adaptability, i.e. the capability of the unit under analysis to adapt to transition developments over time, or to undertake measures, which reduce the impact of potential shocks via input substitution, its climate strategy, climate-aligned R&D or future CAPEX plans (Bresch et al., 2014; Thoma & Chenet, 2017). We then look at (8) Economic impact, i.e. transition-related economic losses, gains, and income statement effects via changes in the macroeconomic development (Bretschger & Karydas, 2019; Bretschger & Soretz, 2018; Gros et al., 2016; Liu et al., 2020; Semieniuk et al., 2020). Finally, we also assess (9) Risk amplification mechanisms, which could lead to mutual risk re-enforcements due to the dynamic interplay between economic policy, market and technological developments (Bretschger & Karydas, 2019), and financial market-related feedback effects due to network and second round effects, or sentiment and expectation revisions given herding behaviour (Battiston et al., 2017; Campiglio et al., 2019; Dunz et al., 2018; Roncoroni et al., 2019; Stolbova et al., 2018; Vermeulen et al., 2019).

2.3. Usability

We assess usability of the individual tools focusing on output interpretability and on how tools deal with uncertainty. This issue has been raised as important in practice, and has been prominently discussed by Fiedler et al. (2021).

We assess the usability by aid of criterion 10 and 11: (10) Interpretability, which assesses whether the model structure, key drivers, and assumptions are well reported by tool providers, and whether the tool output itself is communicated in direct relation to key assumptions and model limitations to the users

(Bierens et al., 2020). And (11) Dealing with uncertainty, which captures whether the tools are able to accommodate users' individual expectations and beliefs about baseline developments and future transition pathways, and how the uncertain nature of the transition pathway type (orderly or disorderly transition) is translated into financial risks (e.g. by providing probability distributions instead of point estimates as output) as discussed, for example, by Fiedler et al. (2021), Thoma and Chenet (2017) and Roncoroni et al. (2019).

In order to aggregate the individual tool assessments for the criteria-based analysis, we assign 1 point for each fulfilled element of each criterion, 0.5 points for partly fulfilled, and 0 points for not fulfilled or not applicable. The element assessment points are then summed up to obtain the overall score for a criterion. Based on the maximum obtainable points per criterion (which is Ni, with N the number of elements for criterion i), we define a criterion as fulfilled if more than 75% of the maximum points are achieved, as partially fulfilled if between 25% and 75% of the maximum score is achieved, and as not fulfilled for less than 25% of maximum obtainable criterion points. For the dimensions, we sum up the dimensions' criteria points, and assign the values 'High / Fulfilled' (more than 75% of maximum obtainable points), 'Medium low / Partially fulfilled' (25%–75% of maximum obtainable points) and 'Insufficient / Not fulfilled' (below 25% of maximum obtainable points).

3. Results and discussion

3.1. Descriptive analysis

Regarding tool coverage, we found that the most important risk sources and transition pathway types (orderly or disorderly transition) are relatively well covered across the tool sample, as can be seen in Table 2. However, few tools cover all analysed risk sources and the interaction among them – despite the fact that the risk sources could mutually reinforce each other (Brausmann et al., 2020).

The vast majority of tool providers use climate scenarios from the IEA, or scenarios as derived from IAMs. This is because these scenarios present desirable characteristics for the analysis of transition risk. However, both types of scenarios also exhibit significant shortcomings. The IEA scenarios, for example, systematically underestimated the growth of renewable energies, with the risk of introducing a bias in the analysis (Creutzig et al., 2017; Mohn, 2020). IAMs have been criticized for their complexity, limited granularity, and the reliance on generalized assumptions about socio-economic processes (Pindyck, 2013, 2017). Own scenarios are used or can be used in customized settings in 6 out of the 16 tools. The advantage of own scenarios is that users have more flexibility to adapt the scenarios to their own beliefs and expectations. However, this comes at a major disadvantage: The scenarios lack transparency, are usually not peer-reviewed or critically discussed in the scientific community, and render the comparison of results across different tool users much more difficult. They might be useful in terms of decision-relevance; however, scientific quality and comparability of the tool output might be negatively affected.

This shows that scenario-neutral tools have major advantages. They would allow the users to run the analysis with multiple scenarios from various climate model developers. This enables users to better capture the deep uncertainty surrounding future transition developments. Furthermore, such tools allow users to use the latest state-of-the art scenarios in most cases.

Regarding the coverage of financial assets, it is the highest for publicly traded asset classes. This is due to better data availability for listed companies (see the supplementary material for a detailed overview table). Mortgages and real assets are, instead, not sufficiently covered, yet. The same holds for project loans. When it comes to the tool outputs, most of the tools in the analysis sample focus on climate-adjusted financial asset metrics (Value-at-Risk and expected returns) and credit risk metrics (probability of default and credit rating).

Overall, given the variety in tool coverage of risk sources, risk types (orderly or disorderly transition), output types and scenarios, more stringent and streamlined information for potential tool users and supervisory authorities about tools' specific setup would be beneficial to ensure a correct interpretation of the tools' output.

Table 2. Tool coverage: risk sources and transition pathway types.

Risk source	Tool 1	Tool 2	Tool 3	Tool 4	Tool 5	Tool 6	Tool 7	Tool 8	Tool 9	Tool 10	Tool 11	Tool 12	Tool 13	Tool 14	Tool 15	Tool 16
Policy																
Smooth	x	-	x	x	(x)	x	x	x	x	x	x	n/a	x	x	(x)	x
Shock	x	x	x	-	x	x	-	x	x	(c)	(c)	n/a	x	x	(x)	x
Market upstream (supply chain)																
Smooth	(c)	-	x	x	x	x	-	x	x	x	(c)	n/a	(c)	-	(x)	x
Shock	(c)	x	x	-	x	x	-	x	x	(c)	(c)	n/a	(c)	-	(x)	x
Market downstream (demand)																
Smooth	(c)	-	x	x	x	x	-	x	x	x	(c)	n/a	(c)	-	(x)	x
Shock	(c)	x	x	-	x	x	-	x	x	(c)	(c)	n/a	(c)	-	(x)	x
Technology																
Smooth	(c)	-	x	x	-	x	x	x	x	x	(c)	n/a	-	x	(x)	x
Shock	(c)	x	x	-	-	x	-	x	x	(c)	(c)	n/a	-	(c)	(x)	x
Other																
									Financial disruption						divestment	

x: covered; (x): indirectly covered (e.g. via market expectations); (c): only in customized approach; -: not covered; n/a: not applicable; .: information not available or confidential dvp: under development.

Sources: Study questionnaire, tool documentation.

Figure 1. Results of the analysis of the assessment of the 16 tools against the 11 criteria. The figure shows the number of tools fully (green), partially (yellow) or not (red) fulfilling the three dimensions (capitalized), the dimensions' underlying 11 criteria (numbered) and the sub-elements to assess each criterion (letters).

3.2. Criteria-based analysis

Overall, we find that only three tools display high total criteria fulfilment when combining the scores of all the criteria assessed, whereas the rest of our sample (13 tools) performs medium. No assessed tool performs low in terms of total criteria fulfilment (Figure 1).

On the individual criteria dimensions, accountability is medium for 12 tools, and only four tools perform high on this dimension. The depth of risk analysis is high for seven tools and medium for nine tools. On the usability,

Table 3. Tool input: climate scenarios.

Tool input: climate scenarios Scenario	Tool 1	Tool 2	Tool 3	Tool 4	Tool 5	Tool 6	Tool 7	Tool 8	Tool 9	Tool 10	Tool 11	Tool 12	Tool 13	Tool 14	Tool 15	Tool 16
						IEA										
IEA ETP scenarios*	x	(c)	(c)	x	x	x	-	-	-	x	x	-	(c)	-	-	(c)
IEA WEO/WEM scenarios**	x	(c)	(c)	x	-	x	-	-	-	x	x	-	(c)	-	-	(c)
IAMs																
REMIND (PIK) – MAgPIE (IIASA) scenarios***	-	-	(c)	-	-	-	x	x	-	dvp	-	-	x	-	-	(c)
MESSAGEix-GLOBIOM scenarios	-	-	(c)	-	-	-	-	x	-	-	x	-	(c)	-	-	(c)
Other																
Greenpeace Energy [R]evolution	x	(c)	(c)	-	-	-	-	-	-	(c)	-	-	(c)	-	-	(c)
PRI IPR: Forecast Policy Scenario	-	(c)	(c)			- - - - -			-		- - -		-		- - x	
Own scenario	-	-	x			- - - - x			x		- - x		(c)		- - x	

x: covered (c): customized / scenarios adaptable; -: not covered; n/a: not applicable; .: information not available or confidential dvp: under development.
* e.g. RTS and B2DS/2DS/4DS/6DS.
** e.g. CPS and STEPS/SDS.
*** e.g. NGFS reference scenarios.
Sources: Study questionnaire, tool documentation.

Table 4. Criteria-based analysis results by tool.

Criterion	Tool 1	Tool 2	Tool 3	Tool 4	Tool 5	Tool 6	Tool 7	Tool 8	Tool 9	Tool 10	Tool 11	Tool 12	Tool 13	Tool 14	Tool 15	Tool 16
I. ACCOUNTABILITY																
1. Public transparency																
a) Model modules, code public	x	(x)	(x)	-	-	-	-	-	-	-	(x)	(x)	-	-	x	-
b) Study questionnaire completed*	x	(x)	x	x	(x)	x	(x)	x	x	x	x	x	x	x	x	x
2. Emission data strategy																
a) Data sources reported	x	x	x	(x)	x	x	x	x	(x)	x	x	x	x	x	x	x
b) Third party verified	(x)	(x)	-	(x)	(x)	(x)	(x)	(x)	(x)	(x)	x	-	-	(x)	x	(x)
c) Missing data strategy explained	x	(x)	(x)	(x)	x	x	x	x	(x)	(x)	(x)	x	x	x	x	x
3. Science-based approach																
a) Scientific references	x	x	x	x	(x)	(x)	x	(x)	x	x	x	(x)	(x)	-	x	x
b) Peer-reviewed	x	x	x	(x)	-	(x)	(x)	-	(x)	x	x	x	-	x	x	(x)
II. DEPTH OF RISK ANALYSIS																
4. Hazard (shock / smooth transition)																
a) 1.5/<2°C scenario	x	x	x	-	-	x	x	x	x	x	x	x	(c)	(c)	-	x
b) Country-differentiated	(c)	x	x	x	(x)	(c)	x	x	x	(x)	x	-	x	x	-	x
c) Sector-differentiated	x	x	x	x	x	x	x	x	x	x	x	x	x	x	-	x
5. Exposure																
a) Current GHG emissions	(x)	x	x	(x)	x	x	(x)	x	(x)	(x)	x	x	(x)	x	(x)	(x)
b) Expected GHG emissions	x	-	x	-	n/a	(c)	-	x	-	x	x	n/a	x	x	(x)	x
6. Vulnerability & Resilience																
a) Profits to cover costs	n/a	(x)	(x)	-	n/a	(c)	(x)	x	-	x	(x)	n/a	x	(x)	(x)	x
b) Peers performance, competition	n/a	x	-	-	n/a	x	(x)	x	-	x	-	n/a	x	x	(x)	x
c) Cost pass-through	n/a	x	x	-	n/a	(c)	x	x	x	x	x	n/a	x	x	(x)	x
7. Adaptability																
a) Input substitution	n/a	x	x	-	n/a	x	-	x	x	x	x	n/a	-	-	(x)	x
b) Climate strategy, climate-aligned R&D or future CAPEX plans	x	-	-	-	x	x	x	x	-	x	x	=tool out- put	-	x	(x)	(x)
8. Economic impact																
a) Economic losses and gains	n/a	x	x	x	n/a	(x)	x	x	x	x	x	n/a	x	x	(x)	x
b) Macroeconomic development	n/a	x	x	(x)	n/a	x	x	x	x	x	x	n/a	x	(x)	(x)	x
9. Risk amplification																
a) Mutual risk amplification	n/a	(c)	x	-	n/a	(c)	-	x	x	-	x	n/a	(x)	-	(x)	-
b) Financial market amplification	n/a	x	dvp	-	n/a	(c)	-	x	x	-	-	n/a	-	-	x	-
III. USABILITY																
10. Output interpretability																
a) Model structure, scenarios and assumptions reported	x	x	x	x	(x)	(x)	(x)	(x)	x	x	x	x	(x)	x	x	x
b) Assumptions-based output communication	(x)	-	(x)	-	-	-	.	-	-	(x)	(x)	-	(x)	(x)	-	x
11. Uncertainty																
a) Baseline adaptable x		x	x	(x)	-	(x)	x	(x)	(x)	(x)	-	-	(c)	(c)	-	x
b) Scenario-neutral)	x	x	x	(x)	-	(x)	x	(x)	(x)	(x)	x	(x)	(x)	(x)	-	x
c) Probability distribution input (timing)	dvp	x	(x)	(x)	n/a	(c)	(c)	(c)	(c)	-	(x)	n/a	(x)	(x)	-	(x)
d) Probability distribution output (values)	(c)	(c)	(c)	(c)	n/a	(c)	(c)	(x)	(x)	(c)	(c), dvp	(x)	(c)	(c)	-	(c)

x: fulfilled; (x): partially fulfilled; (c): only in customized approach; -: not fulfilled; n/a: not applicable; .: information not available or confidential dvp: under development.
Sources: Study questionnaire, tool documentation.
* Documented in the results, but does not count into the meta analysis.

we find low performance for two tools, medium performance for 12 tools, and high usability for only two tools. In terms of tool inputs, the majority of tools also provides the option for customized scenario inputs. The individual results of each assessment criterion for each tool show that most providers enable features on customized basis, or fulfil the criteria partially (Tables 3 and 4).

3.2.1. Accountability

Overall, only four out of the 16 analysed tools score high across the set of accountability criteria. These tools produce output, which is verifiable by users and external experts in the field, whilst undertaking specific measures to ensure data accuracy. For the majority of tools (12), accountability could be improved.

Performance on the transparency criterion is generally weak. Ten out of 16 tools' model code and model setup are not publicly available. The majority of tools (nine out of 16) performs relatively well on the emission data strategy: Data sources are well reported by the vast majority of tools (14 out of 16), and a majority of 10 tool providers explicitly explains the missing data strategy. Yet, only three providers use third party verified data, while 11 providers rely on their own strategies to verify the emission data. Furthermore, 11 of the 16 tools follow a science-based approach: ten tools build on academic publications and use scientifically developed scenarios. Yet, we also see that six tools perform medium or even low in terms of being anchored in scientific literature and references. Half of the tools surveyed here are not peer-reviewed. However, of these, five tools are documented in working papers. For three of the tools, a scientific review is generally not possible because their approach is not in the public domain at all.

3.2.2. Depth of risk analysis

Overall, tool providers face a significant trade-off between the depth of risk analysis, and modelling complexity and coverage of risk sources. The depth of risk analysis varies considerably amongst the tools in our sample.

The hazard criterion is generally well covered in 12 of the 16 tools. 11 tools provide analysis including a 1.5°C/<2°C scenario. When using a tool, which does not cover a 1.5°C/<2°C scenario, it might not capture the relevant potential transition-related firm-level hazards (Rogelj et al., 2018). When modelling hazards, most tools differentiate between countries (ten out of 16) and sectors (15 out of 16).

All tools of the present study model exposure by aid of greenhouse gas emissions, although for tools focusing on technological developments, these are only a minor risk factor. Only eight of the 16 tools take all three emission scopes (scope 1, 2, and 3) into account, cover greenhouse gas emissions other than CO2, and/or perform a proper materiality assessment to make sure that the most important greenhouse gases and scopes are considered in the analysis. Eight of the 16 tools do not sufficiently make use of forward-looking data, i.e. expected emissions (in addition to status quo data).

Vulnerability and resilience are covered by six of the 16 tools. Another six tools model vulnerability and resilience only partially or on a customized basis. Most tools use cost pass-through to model vulnerability and resilience (ten of 16 tools provide it in the standard setting). Peer performance and competition aspects are not considered by seven of the 16 tools. Firms current or expected profits as a buffer to cover additional transition-induced costs or lower revenues are only analysed by four tools.

Adaptability is fully covered by only five of the 16 tools. However, nine tools cover it partially or on a customized basis. Input substitution and climate strategies, research and development (R&D) expenditures and future capital expenditure (CAPEX) plans are considered by eight and nine tools, respectively. However, of the nine tools which cover climate strategies, four tools are not risk tools, but alignment, target setting, or impact tools.

The economic impact is explicitly analysed by the large majority of tools. Only three of the 16 tools do not capture this aspect, all of which are not risk tools but focus on alignment, target setting, or impact. Balance sheet or income statement losses and gains, and macroeconomic developments, are fully or partially covered by 13 tools.

Risk amplification mechanisms are not sufficiently covered, yet. Only four tools cover mutual amplifications of various risk sources, four cover it partially or customized, and eight tools do not consider this aspect. 11 of the 16 tools do not model additional financial market amplification mechanisms at all.

3.2.3. Usability

Only two tools perform generally high across the set of usability criteria. The vast majority, 12 of the 16 tools, perform medium, and two tools have low usability for financial climate transition risk analysis.

The criterion output interpretability is only medium for 11 out of the 16 tools. All tools report their model structure, scenarios, and assumptions at least to their clients. However, of these, only a minority of six tools publicly disclose this information. In consequence, third party users of reported risk data, like financial supervisory authorities and investors, might struggle to correctly interpret the risk as reported by the tool user. This limits, for example, the usability of TCFD disclosures. In addition, it would be useful if the output was communicated in direct relation to the assumptions, for example, by aid of a standardized sentence that lists the most important assumptions before stating the output value. We find that none of the tools communicate the output in such an interpretable manner – which significantly reduces the possibility that TCFD-disclosing firms do so in their climate reporting. Seven tools communicate key assumptions and modelling choices in the output report, which is an important first step. However, nine out of the 16 tools do not fulfil this criterion at all. This is a serious issue that needs to be addressed to enhance interpretability of climate-related disclosures for the tool users directly, and for potential third party users of the climate risk information as disclosed by the firm in their TCFD reporting.

Only four tools are able to explicitly deal with uncertainties. Two tools are, in general, not able to capture uncertainty, and ten tools perform medium with regards to this criterion. Eight tool providers allow users to assess various transition trajectories, which are to be chosen from a pre-defined set of scenarios. Only six tools are fully scenario-neutral. Scenario-neutral tools have a major advantage over tools with a pre-defined set of scenario choices: They could flexibly accommodate the dynamic developments in scenario modelling, and use the most up-to-date scenarios as soon as they become available (e.g. more granular scenarios). The majority of tools allow to select between different pre-defined baseline specifications or to adapt the baseline flexibly. Similarly, the majority of tools allow users to flexibly adapt the timing of the risk realization (for example, in which year a certain policy is modelled to be introduced, or a certain technology might reach cost-parity with another existing technology, etc.). A major caveat is that, so far, none of the tools provide output values by default as a probability distribution or as an estimate with associated confidence intervals. This issue needs to be overcome if tools are to provide information for improved climate risk strategy planning by the firms.

4. Conclusion

Climate-related financial risk assessments are a dynamically evolving field. With our analysis, we provide a snapshot of the status quo and contribute to improve the tools available. This study had two aims.

First, we conducted a descriptive analysis that can be used as a starting point for practitioners, academics and supervisory or regulatory authorities to understand the general setup, coverage and modules of individual climate risk assessment tools currently available. We found that it would be beneficial to extend the coverage of risk sources in order to cover policy, market upstream, market downstream and technology developments, and to capture what risk sources could reinforce each other. Also, the unlisted financial assets need to be included in the analysis coverage.

The second main contribution of this analysis was to identify criteria to assess climate risk assessment tools for financial decision-making. These criteria were designed to guide academics and practitioners to select and correctly interpret climate transition risk metrics. Based on these criteria, we analysed 16 state-of-the-art climate risk tools alongside the three dimensions: ‘Accountability’, ‘Depth of risk analysis’, and ‘Usability’. We found that some tools perform high on all criteria, but that considerable improvements are required. The main issue for accountability is the current low transparency of the tools’ specific setup, combined with a lack of peer-reviews of the individual tools. We also found that the depth of risk analysis varies considerably amongst tools. Depending on the use case, tool users need to be aware that the output might only capture some risk aspects, like exposure, and not the full scope of climate-related financial risk, including vulnerability, resilience, adaptability and risk amplification mechanisms. In terms of usability, we found that that tools do not sufficiently account for uncertainty in the output (i.e. by providing probability distributions and confidence intervals instead of point estimates). In addition, to enhance interpretability, tool providers could significantly improve how they communicate the final output in relation to the core model assumptions. Finally, scenario-neutrality (or at least a certain extent of scenario flexibility) would also increase usability of the tools.

The findings of our research have important implications for policy making, tool providers, and tool users. First, providers of climate risk analysis tools should increase transparency on the tools' setup, for example, by aid of standardized templates to report the key tool characteristics, assumptions and modelling steps. Second, to improve the interpretability of climate risk metrics in climate disclosures by firms, the tool setup and modelling assumptions should be reported alongside the metrics. In addition, uncertainties surrounding the analysis should be reported, for example, via confidence intervals or probability distributions. Third, financial regulators and corporate reporting regulation should introduce harmonized climate risk metrics disclosure templates when developing mandatory climate risk disclosure requirements, to ensure interpretability and comparability of disclosures. Last, policy makers could set up a centralized online platform, where each tool provider would be asked to document the tool characteristics alongside pre-defined criteria. This platform could be regularly updated to provide information about the latest tool features in a streamlined fashion. In addition, regulators might ask for tools to be listed in this platform in order to be eligible to be used for fulfilling mandatory disclosure requirements.

Notes

1. For instance, instead of directly asking whether providers would label their tool as transparent, we asked for the availability of information of various aspects of the methodology, that could eventually be subsumed under the transparency dimension.
2. Clearly, at least for for-profit tools, lack of transparency is by construction, to a given extent by construction. However, we follow the literature that this criterion remains an important part of tool assessments. In addition, among for-profit tools, too, different levels of transparency can be observed.
3. As outlined in Lise et al. (2010); Sijm et al. (2012); Fabra and Reguant (2014); de Bruyn et al. (2015); Hintermann (2016); and Batten et al. (2020).
4. As outlined in Gros et al. (2016); Bretschger and Soretz (2018); Bretschger and Karydas (2019); Semieniuk et al. (2020); and Liu et al. (2020).
5. As considered in Bretschger and Karydas (2019) and; Brausmann et al. (2020).
6. As analysed in Battiston et al. (2017); Dunz et al. (2018); Stolbova et al. (2018); Vermeulen et al. (2019); Roncoroni et al. (2019); and Campiglio et al. (2019).
7. There are significant differences on the scale and speed of emission reduction requirements between 2°C and 1.5°C/<2°C, which have an impact on the probability and intensity of potential hazards (i.e. transition-related developments or shocks). For example, emissions from fossil fuels and industry need to be close to zero by 2050 for most 1.5°C pathways, 20 years earlier than projected in many 2°C pathways (Rogelj et al., 2018).

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