Climate Change: EU taxonomy and forward looking analysis in the context of emerging climate related and environmental risks

Giuliana Birindelli (G. d'Annunzio University of Chieti-Pescara), Vera Palea (University of Turin), Luca Trussoni (LTlogics), Fabio Verachi (Intesa Sanpaolo)

Article submitted to double-blind peer review, received on 14th September 2020 and accepted on 24th November 2020

Abstract

Climate change is causing substantial structural adjustments to the global economy. Several sectors, such as coal and steel, are undergoing severe problems related to the inevitable transition to a low-carbon economy, while others such as renewables and new environmental adaptation technologies are benefiting substantially. In this context, regulators are beginning to intervene on the legislation, while investors, customers and civil society are looking for alternatives to mitigate, adapt and make these issues more transparent. This article aims to analyze the impact that these changes will inevitably have on banks' balance sheets, introducing new risks but also opportunities. The final purpose is to help banks integrate climate risks into their organizational framework and to provide guidance on the implementation of the recommendations published by the Task Force on Climate-related Financial Disclosures (TCFD) within the broader Financial Stability Board (FSB) objectives and the UN Environment Finance Initiative (UNEP FI). Starting from a long-term perspective, the work suggests considering climate risk as a financial risk, overcoming traditional approaches that focus on reputational risk. This change implies the integration of climate change risk into the logic of Risk Management (Credit, Market and Operational risks) and a consequent sharing of responsibilities with the structures of Corporate Social Responsibility (CSR). The TCFD recommendations urge banks to use forward looking scenario analyzes, including stress tests, to evaluate and disseminate the "actual and potential impacts" of climate-related risks and opportunities, suggesting in particular to consider the consequences in terms of two categories of risk: physical and transition risk.

Keywords: "climate change", "transition risk", "physical risk", "EU taxonomy", "IPCC scenarios", "RCP-SSP-SPA pathways", "forward looking analysis", "climate stress test", "PD assessment"

1. Introduction to climate change risk

Climate change implies significant economic costs. The most common are damage caused by extreme weather events such as storms or floods. Further examples are disruptions in supply chains, higher prices as a result of shortages due to drought or lower labor productivity in case of severe heat waves. These events, better known as **physical risks**, are already affecting our economies and scientists agree that they will increase over time.

On the other hand, the transition to a low-carbon economy, necessary to mitigate these costs, has economic and social consequences: investments in low-carbon technologies and higher carbon prices combined with a possible carbon tax will reduce margins with the consequence that some polluting activities will have to be dismissed. It is likely that these phenomena, known as **transition risk**, will be substantial and must be managed with an unprecedent attention.

Physical and transition risks, in addition to their direct impact in terms of reducing the value of tangible and intangible assets (market risk, technological risk and reputational risk), will ultimately result in higher expenses and lower revenues, or will reduce cash flows of the Corporate, SME and Retail segments. Lower cash flows and lower asset values, as well as their volatility, are key determinants in assessing financial robustness and therefore the ability to repay debts, with obvious implications in the creditworthiness. As a consequence, physical and transition risk are a source of credit risk, namely the climate change credit risk.

Capasso et al. (2020) [7] indeed show that the exposure to climate change decreases firms' distance to default. This implies an increase in banks' asset value at risk. Battiston et al. (2017) [6] indicate that, in the Euro Area, the bank exposures to climate-policy relevant sectors are large, heterogeneous, and possibly amplified by indirect exposures via financial counterparties. Thus, the exposure to climate risk could potentially pose systemic threats to global financial stability. Demtz et al. (2016) [14] estimate that, in a business as usual scenario, the climate value at risk would be around 2.5 trillion dollars.

This work aims to be a reference tool for risk managers of the financial industry that need to deepen the methodologies for managing climate change risk: it focuses on the relevant aspects from a financial point of view, providing an overview of the literature and illustrating some quantitative tools useful for the risk assessment. The data and estimates presented are purely illustrative and informative: they are largely taken from scientific works and public databases that do not take into account, as they were previously produced, the economic impact and consequences on the markets generated by the Covid-19 pandemic.

However, before introducing the analysis of the methods for assessing climate risks, it is useful to provide some indications on the action plan adopted in this context by the European Commission and, in particular, on the methods of identifying sustainable activities (so-called taxonomy).

The structure of the paper is as follows. Section 2 deals with the taxonomy mentioned above, Section 3 focuses on issues related to climate risk assessment, Sections 4 and 5 explore the issue of climate scenarios, Section 6 focuses on transition risk approaches, Section 7 on the implications of transition risk on creditworthiness measurement, Section 8 on the impact of physical risk on creditworthiness. Finally, Section 9 concludes.

2. EU taxonomy of "sustainable" financial products

The European Commission, as part of the action plan for sustainable finance, has promoted a series of activities including the mandate to the Technical Expert Group on Sustainable Finance (TEG) to develop a unique classification within the EU, the so-called taxonomy of economic activities that can be considered sustainable. The development of this classification, based on technical-scientific definitions, aims to guarantee the reliability and comparability of information on sustainable investments, promote transparency and long-term vision and discourage the phenomenon of greenwashing through the adoption of a common language.

The taxonomy does not constitute a list of activities to invest in, nor a classification system for the quality of businesses or a list of activities that must excluded. Instead, it represents a list of economic activities to which performance criteria are associated to evaluate the contribution with respect to the environmental objectives identified by the European community:

1. climate change mitigation;
2. climate change adaptation;
3. sustainable use and protection of water and marine resources;
4. transition to a circular economy, waste prevention and recycling;
5. prevention and control of pollution;
6. protection and safety of ecosystems.

To be included in the taxonomy, an economic activity must: (i) contribute significantly to at least one of the environmental objectives (respecting specific technical criteria, metrics and thresholds); (ii) not significantly harm the other objectives (Do No Significant Harm - DNSH); (iii) comply with the "minimum social standards". The technical evaluation criteria can include qualitative or quantitative thresholds (often expressed in terms of CO_2 emissions), representative of the environmental performance objectives expected from the economic activities under exam.

In line with the mandate of the European Commission, the work of the TEG on taxonomy initially focused on climate change objectives. The reports on the new EU taxonomy published by the European Commission in March 2020 [32] therefore focus on the first two environmental objectives and on the activities that can provide a substantial contribution to climate change mitigation and adaptation.

In particular, the new EU taxonomy analyzes the activities relating to seven macro-sectors selected on the basis of CO_2 emissions and potential savings also in terms of "enabling technologies"[1]:

- agriculture, forestry and fishing;
- manufacturing;
- electricity, gas, steam and air conditioning;
- water, sewage, waste and remediation activities;
- transportation and storage;
- ICT (Information, Communication and Technology);
- construction and real estate activities.

With reference to the mitigation and transition objective towards a zero-emission economy, the activities included in the taxonomy can be classified into three macro-categories:

- "low carbon" economic activities characterized by zero / near-zero or negative emissions and therefore already compatible with the objectives of zero net emissions by 2050 (e.g. transport activities with electric vehicles and the production of energy from renewables);
- economic activities that contribute to the transition process which, although not close to the zero emissions target, are characterized by performances above the sector average. For these activities, the compliance with specific technical criteria and emission thresholds subject to regular revisions is required (e.g. the generation of electricity with emissions lower than 100g CO_2/KWh);
- other activities ("enabling activities") that allow and support the transition towards a zero-emission economy (e.g. the construction of solar panels for electricity generation and turbines for wind farms or interventions to improve the energy efficiency of buildings).

Regarding the issues of "climate adaptation", the analysis must be carried out on the basis of an assessment related to the specific context and geographical location, following three guiding principles:

1. economic activity adopts all possible measures to reduce the relevant physical risks deriving from the variability of meteorological phenomena and climate change;
2. the economic activity does not negatively impact other activities;
3. the contribution to adaptation can be identified by means of appropriate indicators.

Furthermore, in line with the EU strategy for increasing resilience to climate change, the TEG has developed a specific classification of climate risks. With reference to the importance and frequency of these events, "chronic" or "acute" effects are distinguished.

With respect to the area of relevance, the effects produced by climate change may affect: climate, temperature, winds, water and soil (see table below).

---

[1] Failure to include some activities does not automatically imply that these are harmful to the environment. In fact, some of the activities not included may have a positive marginal contribution or be neutral.

Table 1 – Classification of climate change related risks and events in terms of frequency/severity

	Temperature / climate	Winds	Water	Soil
Chronic effects	Increase in average temperatures (air, water)	Change of direction and intensity of winds	Changes in intensity, frequency and duration of precipitation	Coastal erosion phenomena
	Temperature variability		Changes in hydrogeological system	Desertification
	Ice melting / permafrost		Marine system modifications (acidification, salinity, etc.)	
			Rise in level of seas and rivers	
Acute effects	Intense heat waves	Hurricanes, cyclones, typhoons, windstorms and tornadoes	Drought	Landslides and avalanches
	Intense cold waves		Extraordinary precipitation (rain, snow, hail, etc.)	
	Fires		Floods (fluvial, pluvial, marine)	
			Melting glaciers	

Concerning the scope of application, the taxonomy includes:

- companies and other subjects that are included within the scope of application of the Non Financial Reporting Directive (Directive 2014/95) for the related disclosure and reporting obligations;
- financial institutions[2] for identifying, evaluating and classifying sustainable financial products;
- European Community countries to define measures and requirements related to sustainable financial products.

It is therefore reasonable to expect that the availability of a reference taxonomy promoted at EU level will have a significant effect in terms of standardization and convergence of the methodologies adopted by other agents, including non-EU ones. In operational terms, the application by investors must be divided into the following steps:

- identify the financed activities carried out by a company (or a project) to assess their consistency with the taxonomy;
- for each activity, check whether the criteria, metrics and thresholds indicated by the taxonomy are met (i.e. compliance with the CO2 emission thresholds);
- verify, through a due diligence process, compliance with the Do Not Significant Harm (DHSH) criteria;
- verify compliance with the "minimum social standards"[3];
- prepare, after verifying the alignment of the investment with the taxonomy, the correct information at the product level.

Finally, it should be noted that the taxonomy will be implemented in the EU through delegated acts by December 2020, with entry into force expected in December 2021.

3. How to assess climate risks? From building climate scenarios to measuring financial impacts

The tools for assessing climate risks from a financial perspective are in an experimental phase and only a few studies provide an integrated and comprehensive overview[4]. This work proposes a framework based on forward looking stress tests for the analysis of physical and transition risk related to different climate scenarios. The authors tried to align with the stress test best practices (Basel Committee on Banking Supervision, 2018). This implies that these methodologies can, in principle, be applied by banks both in the bottom-up stress tests and in the top-down exercises proposed by the supervisors (e.g. EU-wide stress test proposed by EBA).

To assess the impact of climate change risks, a building block approach is therefore proposed with methodologies that can be mainly divided into three phases:

1. definition of climate scenarios: the estimate of the climate change impact is primarily based on the definition of forward looking scenarios. These scenarios define how climate change will impact the variables relevant for the economic activities, how a transition will mitigate those impacts, and what measures could be taken to steer the transition;

2. estimation of the economic and financial impacts: once the impact of climate change has been estimated, its consequences must be translated into financial terms through macro and microeconomic simulations. This step essentially evaluates the direct and indirect effects of climate change, the transition modalities and identifies which actors are affected and to what extent;

[2] Including, for example: asset managers and investment fund management companies (with underlying equities, ETF bonds), real estate funds, private equity and venture capital funds, alternative investment funds, infrastructure funds, funds of funds, etc.

[3] Alignment with the Minimum Social Safeguard allows to grasp the social and governance aspects by verifying, on the basis of a due diligence, compliance with international legislation on human, job and anti-corruption rights (e.g. OECD Guidelines on Multinational Enterprises and for Responsible Business Conduct [26], UN Guiding Principles on Business and Human Rights, International Labor Organizations [37]).

[4] Fundamental works on the subject, just to name a few, are Monnin (2018) [25], UNEP FI – OW/Acclimatise (2018) [29], Jansen (2019) [23] and DNB (2019) [40].

3. transformation of financial impacts into risk measures: based on the assessment of the impacts, the next step is to calculate how changes in cash flows and balance sheets will affect the various risk measures (e.g. market values of assets, creditworthiness in terms of rating and probability of default).

4. Climate change scenarios

The first tool for modeling climate change (and therefore also the related risks) is the development of specific scenarios. Since 1992, the Intergovermental Panel on Climate Change (**IPCC**) built a first set of scenarios, then revised in 2000 when the IPCC released the Special Report on Emissions Scenarios (**SRES**), proposing a set of 40 scenarios organized into 4 families (see for example [20], the following description is taken from [17]):
A1: this family of scenarios describes a future with very rapid economic growth, the global population will have a maximum until 2050 and then decrease, and a rapid introduction of new and more efficient technologies. This family is developed into three groups that describe alternative directions in the technological changes of the energy system: A1Fl future with fossil fuels, A1T non-fossil resources, A1B equilibrium between fossil fuels and other sources;
A2: this scenario describes a very heterogeneous world. There will be a continuous demographic increase with a per capita economic growth. Technological changes will be very fragmented and slow;
B1: this scenario as well foresees that the population growth will reach its peak in the middle of the century and then decline, but a rapid evolution towards an information and services economy, with a reduction of materials and the introduction of new technologies, will be capable of generating efficient and clean resources;
B2: the population is growing continuously, but at a lower rate than the A2 family. The economic development will reach intermediate levels with slow and differentiated technological changes, but always oriented towards sustainable development.

Subsequently, starting from 2007, in response to the need of improving the SRES, the IPCC approach has changed and turned towards the development, not anymore of a complete set of scenarios, but rather to the "Representative Concentration Pathways" (**RCP**) defined in the Assessment Report 5 (**AR5**): RCPs are quantitative forecasts of the trend of greenhouse gases and atmospheric pollutants derived from human activities (and therefore also imply specific forecasts on the trend of global warming and land use). More specifically the RCPs (Van Vuuren et al. (2011) [38]):

1. are based on the scenarios outlined in the literature. Individually, each RCP represent a coherent description of the future;
2. describe the chemistry of the atmosphere and pollutants with a geographical and temporal basis;
3. are supported by common assumptions on a year by year time horizon;
4. contain forecasts up to 2100.

The AR5 proposes, with the aim to arrive at an integrated description such as that proposed by the previous SRES scenarios, a matrix approach that can be combined with the RCP:

a. the **Shared Socio-economic Pathways** (**SSP**), which represent 5 possible future evolutions of the socioeconomic variables associated with the scenarios (they describe quantitative projections of gross domestic product, population, urbanization and education indexes);
b. the **Shared climate Policy Assumptions** (**SPA**), which represent the mitigation actions implemented in response to climate change, possibly defined locally.

A scenario is then fully described by the association of RCP, SSP and SPA. Comparing the literature describing the interaction between RCP and SSP (O'Neil et al. (2014) [27], O'Neil et al. (2016) [28], Rihai et al. (2017) [24]), for the purposes of this study it was decided to associate RCP and SSP on the basis of the possible overlap in the different path narratives, highlighted by the bold cells in the following table.

Table 2 – Association and choice of RCP and SSP scenarios

	SSP1	***SSP2***	***SSP3***	***SSP4***	***SSP5***
RCP2.6	**Mitigation**	Mitigation	Mitigation	N/A	N/A
RCP4.5	Mitigation	**Mitigation**	Mitigation	Mitigation	Mitigation
RCP6.0	Baseline	Mitigation	**Mitigation**	Mitigation	Mitigation
RCP8.5	N/A	N/A	N/A	N/A	**Baseline**

5. Enrichment of climate scenarios with macroeconomic variables

The previous section introduced the process of constructing future scenarios of climate change, starting from the most commonly adopted hypotheses in the literature and based on Representative Concentration Pathways (RCP) appropriately "enriched" with Shared Socioeconomic Pathways (SSP) and Shared Policy Assumptions (SPA).
Among the various possible combinations, this work has chosen to propose scenarios for the evolution of the financial system according to the classification generally adopted by the TCFD recommendations: Rapid Transition (+ 1.5°, global warming above pre-industrial levels), Two Degree (+2°, slight increase), Business as Intended (+ 3°, increase) and Business as Usual (+ 4°, strong overheating).
The main parameters of the scenarios involved, with a particular focus on GDP by area (OECD the highest level of detail available), are summarized in the following tables. The authors consider appropriate to recall, once again, that the data presented

does not incorporate the effects of the Covid-19 pandemic. However, it should be noted that the adoption of different scenarios leads to very different estimates of the main macroeconomic variables.

Table 3 – Scenario 1 RCP2.6, SSP1, SPA1 (Rapid Transition +1,5°)

Region	Model	Variable	Unit	2020	2030	2040	2050	2100
World	IMAGE - SSP1-26	Temperature	°C	1.22	1.48	1.66	1.76	1.76
OECD	IMAGE - SSP1-26	Population	Million	1,180	1,232	1,276	1,312	1,262
OECD	IMAGE - SSP1-26	CO2 emissions	Mt CO2/yr	10,653	8,834	6,837	4,783	-4,888
		OECD GDP	**% yr/yr**	**2.22%**	**2.45%**	**2.21%**	**1.73%**	**0.74%**

Table 4 – Scenario 2 RCP4.5, SSP2, SPA2 (Two Degree +2°)

Region	Model	Variable	Unit	2020	2030	2040	2050	2100
World	MESSAGE-GLOB SSP2-45	Temperature	°C	1.24	1.49	1.74	1.97	2.63
OECD	MESSAGE-GLOB SSP2-45	Population	Million	1,168	1,215	1,251	1,279	1,272
OECD	MESSAGE-GLOB SSP2-45	CO2 emissions	Mt CO2/yr	10,932	10,739	10,882	11,104	3,189
		OECD GDP	**% yr/yr**	**2.38%**	**2.03%**	**1.64%**	**1.41%**	**0.88%**

Table 5 – Scenario 3 RCP6.0, SSP3, SPA3 (Business as Intended +3°)

Region	Model	Variable	Unit	2020	2030	2040	2050	2100
World	AIM/CGE SSP3-60	Temperature	°C	1.23	1.52	1.85	2.10	3.18
OECD	AIM/CGE SSP3-60	Population	Million	1,153	1,159	1,146	1,116	865
OECD	AIM/CGE SSP3-60 (Baseline)	CO2 emissions	Mt CO2/yr	14,519	14,140	13,481	12,875	5,907
		OECD GDP	**% yr/yr**	**2.18%**	**1.40%**	**0.81%**	**0.46%**	**-0.23%**

Table 6 – Scenario 4 RCP8.5, SSP5 baseline (Business as Usual +4°)

Region	Model	Variable	Unit	2020	2030	2040	2050	2100
World	IMAGE SSP5 (Baseline)	Temperature	°C	1.25	1.59	1.96	2.38	4.86
OECD	REMIND-MAGPIE SSP5-85 (Baseline)	Population	Million	1,296	1,386	1,477	1,574	1,916
OECD	REMIND-MAGPIE SSP5-85 (Baseline)	CO2 emissions	Mt CO2/yr	11,872	14,399	17,508	21,155	33,246
		OECD GDP	**% yr/yr**	**2.62%**	**3.15%**	**3.78%**	**2.95%**	**2.10%**

However, these scenarios must be translated into quantitative measures with reference to the geopolitical area of Italy. First of all, we could estimate the relationship between the OECD GDP evolution, contained in the IPCC scenarios, and the possible dynamics of Italy's GDP.

As example, if we want to use the data relating to the period 2010-2020, with the aim to consider the most recent Italian macroeconomic context, and by adopting a linear regression, we would arrive at the estimate of the coefficients shown below:

$$Y_i = \beta_0 + \beta_1 X_i + \varepsilon_i$$
$$Y_i = \text{Italy GDP}_i$$
$$\beta_0 = -1.953$$
$$\beta_1 = 1.171$$
$$X_i = \text{OECD GDP}_i$$
$$\varepsilon_i = \text{statistical error}_i$$
$$\theta_\varepsilon = 1.461$$

Starting from these long-term estimates, it is possible to hypothesize 5-year projections (2020-2025) which could be taken as a reference for the first exercises in a ***forward looking*** perspective using the stress test framework. In the case in question, it was decided to incorporate the previous estimation error mentioned θ_ε, considering a confidence level of 96% that is consistent with the stress test used in the banking sector (so-called stress 1/25, i.e. occurring once every 25 years and with probability 1/25=4%=100%-96%). The table below illustrates the Italy GDP trend by incorporating the stress assumptions adopted.

Table 7 – Stress projections (2020-2025) of Italy GDP

Scenario	Variable	Unit	2021	2022	2023	2024	2025
Scenario 1 RCP2.6, SSP1, SPA1 (Rapid Transition +1,5°)	**Italy GDP**	**%/yr**	**-1.89%**	**-1.35%**	**-0.81%**	**-0.27%**	**0.27%**
Scenario 2 RCP4.5, SSP2, SPA2 (Two Degree +2°)	**Italy GDP**	**%/yr**	**-1.77%**	**-1.29%**	**-0.82%**	**-0.35%**	**0.12%**
Scenario 3 RCP6.0, SSP3, SPA3 (Business as Intended +3°)	**Italy GDP**	**%/yr**	**-2.05%**	**-1.63%**	**-1.21%**	**-0.79%**	**-0.37%**
Scenario 4 RCP8.5, SSP5 (Business as Usual +4°)	**Italy GDP**	**%/yr**	**-1.38%**	**-0.81%**	**-0.24%**	**0.34%**	**0.91%**

The last step concerns the complete construction of the scenarios with the extension of the projections, in addition to the GDP of each geographical area, to the other macroeconomic variables useful for the completion of the stress exercises. In the following sections, we will show the underlying assumptions and the multi-country GVAR model, which represents one of the examples we could refer for the development of different climate scenarios, will be introduced.

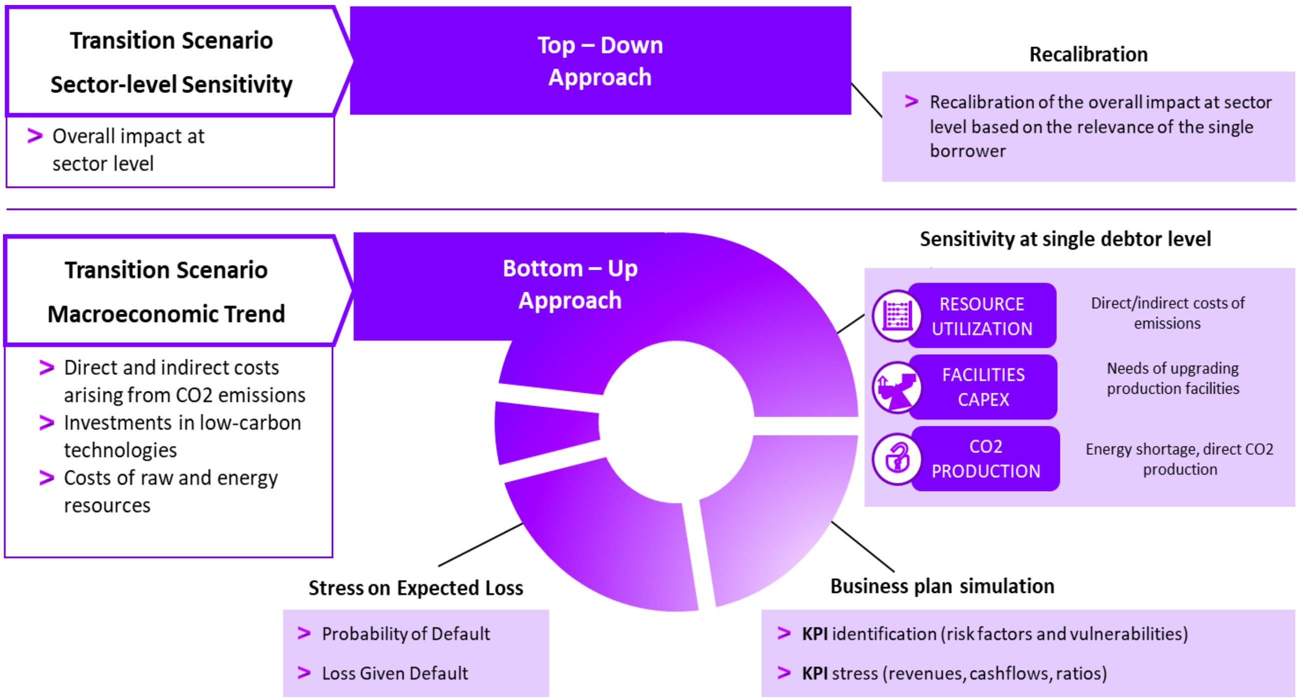
6. Overview of transition risk approaches: macroeconomic models, Top-Down and Bottom-Up methodologies

As widely discussed, scenario analyzes require all the macroeconomic variables that represent the input of any macro and microprudential stress test exercise.
Therefore, the declination of the 4 scenarios mentioned above requires a complete narrative which, according to the indications of the literature, can be based on various hypotheses around the two risk factors that emerge as the main drivers of transition risk: the so-called climate policies adopted by regulators and any technological developments.
The last scenario is an exception (so-called Business as Usual), in which the energy transition is postponed, and technological discoveries are limited or absent: in this case, the hypotheses only take into consideration a strong decline in consumption and investor confidence.
Another aspect already mentioned concerns the time horizon of the analyzes. The scenarios must be defined in such a way that they materialize within five years, thus ensuring that the results of the climate stress tests are relevant to both financial institutions, regulators and other stakeholders. It should be emphasized that physical risks could also insist on the same scenarios, but phenomena such as floods, tornadoes or earthquakes will have to be treated separately[5].
With this in mind, to translate each scenario into a series of macroeconomic impacts, we can make reference to macroeconometric models, such as those known as multi-country Global Vector AutoRegressive (GVAR)[6]. The use of this type of macroeconometric models provides several advantages.
Firstly, they allow a simulation of a series of mutually correlated macroeconomic impacts that can serve as inputs to top-down stress test models. Secondly, given the strong correlations in the markets, it is possible to measure the *spillover effects* between various countries and between various sectors.
On the other hand, there are also strong limitations. These models, based on long-term historical data, are not designed to simulate structural economic breaks that can be triggered by entirely new phenomena, such as the transition to a low-carbon economy.
Once the impacts on the main macroeconomic variables have been estimated, it remains to understand how to transform them into changes in risk measures of the economic activities.
As shown in the figure, there are different methodological approaches on the topic and, obviously, each method offers a compromise between feasibility and analytical rigor. The methodologies can be basically summarized in 2 macro categories:

- **top-down approaches**: the risk deriving from the variations in country-level macroeconomic variables is first calculated at sectoral level and then disaggregated referring to specific indicators (e.g. CO2 emissions);
- **bottom-up approaches**: the analysis takes place directly at the individual borrower level, based on the financial figures that affect the counterparty creditworthiness.

[5] The impact of these scenarios on physical risks could be very significant for financial institutions. Some papers from the Bank of Italy have estimated, for example, that the flooding risk could result in substantial losses for the Italian financial system (Faiella, Natoli, 2019 [18]).
[6] For analytical details on the GVAR methodology, refer to Pesaran, Schuermann & Weiner (2004) [31], Mauro & Pesaran (2013) [15] and Barbanti Brodano, Cocco & Moramarco (2014) [5].

Figure 1 – Transition risk: general overview and main approaches



6.1 Drill-down of the 4 transition risk scenarios: adaptation of the DNB approach

Climate scenarios can generate projections in line with stress exercises by leveraging two key factors generally accepted in the literature: climate policies on CO2 emissions and technological developments in the energy sector, in particular on the renewable side (see for example CISL (2015) [9] and CERS/ESRB (2016) [8]).
Very interesting on the subject is the working paper proposed by the central bank of the Netherlands (DNB, 2019 [40]) which proposes 4 transition scenarios that leverage exogenous shocks deriving from the implementation of a *carbon tax* at global level and from the introduction of new technologies or a combination of both shocks.
Instead, the approach presented in this work, illustrated in the table below, starts from the IPCC scenarios, proposing their enrichment also with the help of the transmission models used by banks (e.g. the aforementioned GVAR).

Table 8 – Estimation of stressed macro variables based on IPCC and GVAR projections (example)

	2021	2022	2023	2024	2025	Totale
Rapid Transition (Scenario 1 RCP2.6, SSP1, SPA1)						
Italy GDP	-1.89%	-1.35%	-0.81%	-0.27%	0.27%	-4.00%
Euribor 3M	-0.35%	-0.25%	-0.15%	0.00%	0.10%	-0.13%
Equity ITA (FTSEMIB)	-9.36%	-6.48%	-1.12%	0.96%	2.36%	-13.38%
Btp / Bund 10Y (Spread)	1.60%	1.50%	1.40%	1.30%	1.30%	1.42%
Two Degree (Scenario 2 RCP4.5, SSP2, SPA2)						
Italy GDP	-1.77%	-1.29%	-0.82%	-0.35%	0.12%	-4.05%
Euribor 3M	-0.40%	-0.30%	-0.20%	-0.05%	0.05%	-0.18%
Equity ITA (FTSEMIB)	-8.36%	-4.05%	-0.60%	0.56%	1.68%	-10.63%
Btp / Bund 10Y (Spread)	1.70%	1.60%	1.50%	1.30%	1.40%	1.50%
Business as Intended (Scenario 3 RCP6.0, SSP3, SPA3)						
Italy GDP	-2.05%	-1.63%	-1.21%	-0.79%	-0.37%	-5.91%
Euribor 3M	-0.40%	-0.30%	-0.30%	-0.20%	0.00%	-0.24%
Equity ITA (FTSEMIB)	-12.60%	-9.08%	-3.96%	2.16%	3.36%	-19.41%
Btp / Bund 10Y (Spread)	1.90%	2.10%	1.80%	1.50%	1.50%	1.76%

Business as Usual (Scenario 4 RCP8.5, SSP5)						
Italy GDP	-1.38%	-0.81%	-0.24%	0.34%	0.91%	-1.19%
Euribor 3M	-0.30%	-0.20%	-0.10%	0.05%	0.15%	-0.08%
Equity ITA (FTSEMIB)	-6.56%	-4.44%	-0.96%	1.53%	3.08%	-7.45%
Btp / Bund 10Y (Spread)	1.50%	1.40%	1.50%	1.50%	1.60%	1.50%

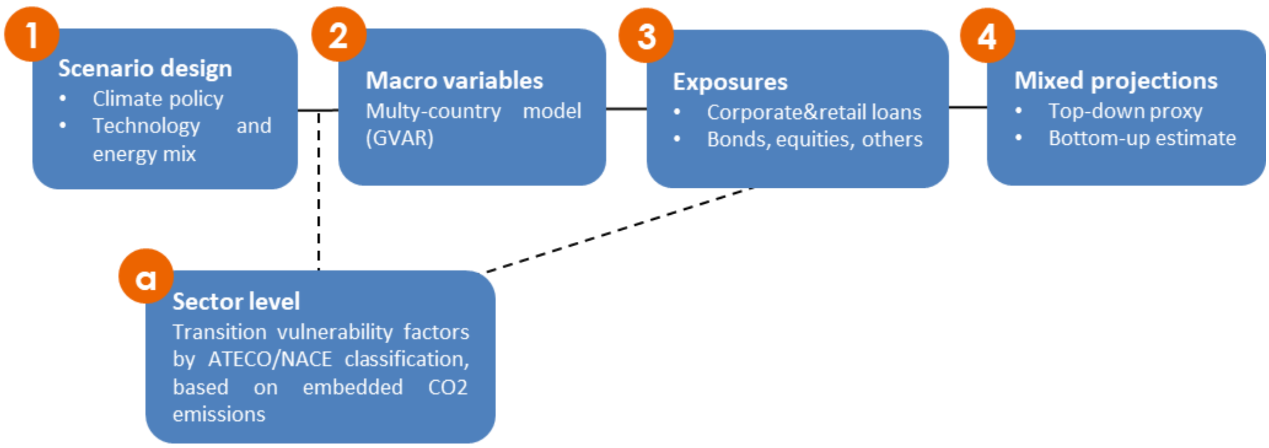
Given the lack of historical data, it is not immediately obvious how to choose the shocks necessary to complete the 4 transition scenarios. The underlying hypothesis concerns the impact that climate policies can have on oil price trends and consequently, through the implicit correlations in GVAR models, on other variables such as interest rates, equities and credit spreads between different countries. For calibration, the hypothetical introduction of a carbon tax of $100 per ton of CO2 was converted into the amount of CO2 emitted per oil barrel[7]. In particular, given that a gallon of crude oil emits 10.3 kg of CO2, it follows that burning a barrel of oil, which contains 42 gallons, will emit 432 kg of CO2 in the event of a carbon tax $100 per ton ($100*0.432=$43.20).
The scenarios that incorporate a technological shock, mainly the first and second, but to a lesser extent also Scenario 3 RCP6.0, SSP3, SPA3 (Business as Intended), instead focus on a progressive technological substitution. More specifically, it is assumed that the percentage of non-renewables over the total energy produced will be lower, over a 5-year time horizon, respectively by 25%, 15% and 5% in the Rapid Transition, Two Degree and Business as Intended scenarios. These shocks are substantial, even though several studies predict that renewables will play an important role in energy production by 2030[8].

The last relevant hypothesis is present only in the last scenario, namely Scenario 4 RCP8.5, SSP5 (Business as Usual), and concerns a possible confidence shock. In the case of GVAR, it is possible to implement shocks on consumption and investments through exogenous shocks on the GDP trend of all countries considered.

6.2 Top-Down approach: general framework for the implementation of the stress test analysis

It remains to discuss how to transform scenario narratives into impacts on the financial system. With this aim, it is necessary to apply a mix of different methodological approaches which, as we have already seen, can be classified into two macro-categories: top-down and bottom-up approaches.
As for the top-down approaches, firstly we need to calculate the impacts on the various sectors derived from the narratives described above and, subsequently, disaggregate these impacts referring to specific drivers, for example the CO2 emissions of each individual borrower. The figure below describes this process which, also in this case, adapts the DNB proposal to the Italian context.

Figure 2 – Transition risk measurement: top-down approach



This figure is an elaboration from DNB 2018 [39]

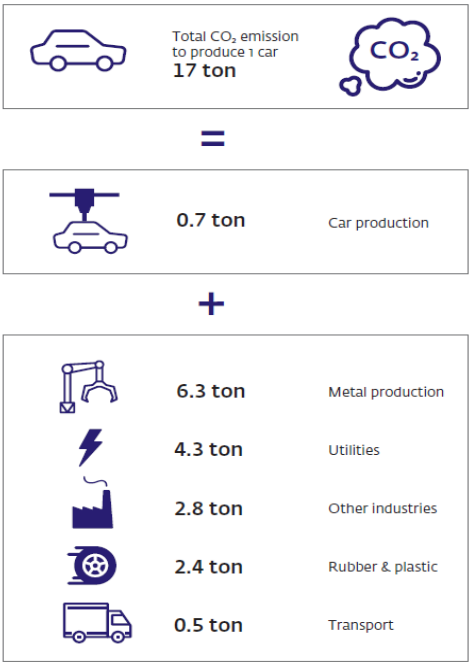
We have already mentioned the points sub 1), sub 2) and sub 3), regarding how to generate reliable paths of the macroeconomic variables taking as a reference an econometric model. The next part of this type of approach, described below, involves the construction of specific factors to reallocate transition risk both across the different sectors and within them by using sectoral classifications available (ATECO/NACE).

[7] It is not difficult to find estimates even in the order of several hundred dollars per ton that will materialize within the next decade. For in-depth discussions, see IPCC (2014) [22], Poelhekke (2017) [30] and Tol (2018) [33].
[8] See for example Creutzig et al. (2017) [12] or IEA (2017) [21].

6.3 Further hypotheses for the Top-Down approach: construction of the transition vulnerability factors and mapping by sectors

Given that the transition to a low-carbon economy will affect companies that emit greater quantity of CO2 more than those that emit less, it is necessary to capture this heterogeneity both between sectors and, possibly, at the individual counterparty level. To obtain this result, it is possible to refer to the theory of the so-called transition vulnerability factors. These "drivers" vary according to the scenario in order to reflect the different types of risk present in the evolution path, thus making it possible to translate the general macroeconomic conditions into specific sector/segment losses.
With the aim to estimate the transition vulnerability factors of each sector/segment, the authors refer to the approach used in Hebbink et al. (2018). The input-output table of this study provides detailed information on suppliers and customers of each economic activity and the total CO2 of the production process. For implied emissions, it is instead possible to use information provided by different providers, generally available at the ATECO/NACE classification level.
In this way, the transition vulnerability factors can reflect the CO2 emissions implied in the value chain of the entire production process, with the consequence that a sector/segment containing twice CO2 emitted than the average will have to be affected two times higher. To give an example, in the automotive sector (sector NACE C29), the perspective of the value chain would lead to consider not only the obvious CO2 emissions of the car assembly, but also those related to the production of individual components, such as rubber to produce its tires (NACE sector C22). The following figure shows the drill-down of this example at the level of a single car produced.

Figure 3 – Example of CO2 emissions per single car produced



This figure is an elaboration from DNB 2018 [39]

6.4 Bottom-Up approach: single name analysis and extension of the impacts at sectoral and portfolio level

The bottom-up approach has a different logic than the previous one, as it analyzes the change in creditworthiness at the single borrower level and then extends the calibration to the portfolio, basing on a selection of names that represent the estimation sample. The bottom-up approach to transition risk (as described in UNEP FI / OW, 2018) can be divided into three phases:

- **transition scenarios**: description of economic developments by sectors and by geographical areas. The scenarios must provide a detailed narrative to define the exposure at the sector level;
- **calibration at single name level**: punctual assessment that tries to solve the lack of data using industry experts to estimate the impact of transition scenarios on individual borrowers;
- **impact assessment on the portfolio**: use of a systematic and repeatable approach to extend the risk to the rest of the portfolio (discussed in the next section).

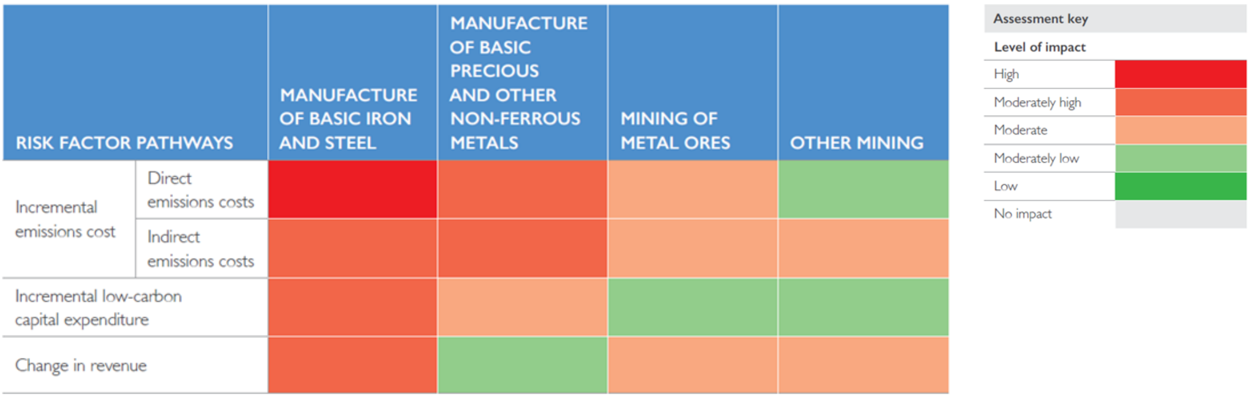
As we have seen, in order to translate the scenario dynamics into impacts on the financial figures of the companies, the results must be summarized in a set of risk factors that insist on the main financial statement variables. Each sector/geographical area should therefore contain the main financial risk factors with respect to a baseline or a reference scenario, for example:

1. **cost of direct emissions or increased costs of CO2 emissions**: in transition scenarios, the increase in costs is determined by the amount of emissions. In the real world, these costs could be translated into a carbon tax on greenhouse gas emitters;
2. **cost of indirect emissions or increased costs of inputs**: given that carbon-intensive inputs will be impacted on prices, sectors that use them most will be heavily penalized. Some costs may be passed on to customers through the product prices, indirectly balancing the cost increases;

3. **capital expenditure or increase in costs associated with investments to move to a low carbon economy**: capital expenditure increases to meet the assumptions of an increase in energy demand and technology efficiency that are implicit in the scenarios;
4. **changes in price and/or consumer demand**: it is foreseeable that an increasing percentage of costs will be passed on to consumers. Consumers, in turn, will respond to rising prices by reducing the demand for certain goods and/or by increasing the demand for other products.

The joint assessment of these factors provides a significant overall picture for assessing the probability of default of the companies involved. At present, the scenario models only provide results at the sector level. Analysts could define specific *sensitivities* with the aim of specifying the impact of transition risk factors on a specific segment compared to the others. The following figure provides an exemplary and synthetic representation of the mapping process aimed at building sensitivities for the mining and metallurgical sector.

Figure 4 – Mapping for the *sensitivity* estimation of the mining and metallurgical sector



However, these sensitivities do not quantify the specific risk impact at the individual customer level. The calibration should be identified through an analysis at the level of the individual borrower. For the energy sector, for example, coal-fired power plants will have a greater sensitivity with a high negative impact to reduce the costs associated with emissions than a company already focused on nuclear or renewables. Another case could be the occurrence of increased sales for electric vehicle manufacturers even though car manufacturers as a whole could experience a sharp decline in demand.
The calibration at the single debtor level must therefore be based on the variables provided by the scenarios and then fill any information gaps using the judgment of internal analysts. *Expert judgment* could interpret each scenario and specify the potential impact on the creditworthiness of some particularly significant borrowers. Each of these "calibration points" will provide the information basis for extrapolating the impact to the rest of the portfolio.
Note that a bottom-up approach also allows for a bank-by-bank personalization. Through internal calibration, analysts have the opportunity to use the most appropriate tools for assessing the impact of the scenario, while ensuring that these decisions are consistent with their own risk appetite framework.
Lastly, calibration allows experts to reflect on how each individual company reacts to a transition scenario, basing on its operational characteristics. For example, an electric car manufacturer could be influenced differently than a traditional car manufacturer even in the presence of strong adaptability to market changes and competition. It goes without saying that such an in-depth analysis can only be limited to Most Significant Transactions (MST) and/or the most critical exposures.

7. Transition risk: from projections to creditworthiness measurement

Once the climatic costs have been estimated - ideally at the single counterparty level - the final step is to translate them into risk measures that can be introduced into the risk management systems. The risk measures traditionally used by financial intermediaries are the Probability of Default (PD), the Exposure at Default (EAD) and the Loss Given Default (LGD) and, as easily deductible from these measures, the credit rating process summarized by the concept of Expected Loss (EL). In summary:

$$EL = PD \times EAD \times LGD$$

7.1 The impact on the Probability of Default (PD) of the Top-Down approach

Since the introduction of the Basel 2 framework, banks have developed a significant amount of internal methodologies to assess the exposure of their portfolios to credit risk. The existing framework can be exploited, with the appropriate modifications, to evaluate the changes induced by the transition risk in the PDs.
In particular, we can refer to theories similar to those implicit in the Merton model to justify the impact on PDs of this new type of risk. As known, the model relates the PD with the probability that the future values of a company's assets may decrease below of its liabilities. Assuming that the other idiosyncratic and systemic risks remain unchanged, the change in PD could be measured by a shift from its initial value. This movement could be determined by the different risk factor paths of the scenarios, or by the top-down impacts on the various sectors calculated by using the aforementioned transition vulnerability factors. With regard to the top-down approach, the authors propose to use the equation set out below:

$$PD_i|s^* = \Phi\left(\Phi^{-1}(PD_{i,TTC}) - \frac{1}{\Gamma_k}\tau^r_{j,k}\left(\Phi^{-1}(PD^s_{0,TTC}) - \Phi^{-1}(PD^s_{t,TTC})\right)\right)$$

$PD_i|s^* =$ scenario-adjusted PD of borrower i given sector/segment s
$PD_{i,TTC} =$ through-the-cycle PD of borrower i
$\tau_{j,k}^r =$ transition vulnerability factor of shock r in segment j of sector k
$\Gamma_k =$ total sum of transition vulnerability factor within the sector k

$PD_{0,TTC}^s =$ initial through-the-cycle PD of sector s
$PD_{t,TTC}^s =$ through-the-cycle PD resulting from *top-down* stress for sector s

$\Phi =$ standard normal cumulative distribution function

Essentially, this equation increases the initial PD based on a top-down estimated risk value through the scenarios' paths enriched with the GVAR model previously described. This movement is nothing more than the product between the outputs of the stress scenarios calculated at sector level and the sensitivity of the sector/segment, in this case represented by the transition vulnerability factor.
It also should be noted that the term Γ_k is strictly necessary, since it allows to obtain that the sum of the weights concerning the implied CO2 per sector is always equal to 1.
This methodology refers to the commonly used stress analyzes, adding new internally estimated parameters that take into account CO2 emissions. The framework can therefore be applied to all sectors and can take into consideration both the composition of each segment, the different transition vulnerability factors and, eventually, a judgmental override provided by credit analysts.

7.2 The calibration of the PDs in the Bottom-Up approach

As in the top-down approach, also for the bottom-up approach it is useful to refer to the theories implicit in the Merton model to calculate the impact of transition risk. For the bottom-up approach, the starting point in this case will not be the variation of the PDs expressed at sector level, but the calibration will start from the variation of the probability of default calculated for a specifically selected sample of borrowers.
The equation that was used is very similar to the one above and can be summarized as follows:

$$PD_i|c^* = \Phi\left(\Phi^{-1}\left(PD_{i,TTC}\right) - \frac{1}{\alpha_k}\sum_j \left(s_{j,k}^r f_k^r\right)\right)$$

$PD_i|c^* =$ scenario-adjusted PD of borrower i
$PD_{i,TTC} =$ through-the-cycle PD of borrower i
$s_{j,k}^r =$ sensitivity of risk factor r for segment/geographic area j of sector k
$f_k^r =$ evolutionary path for risk factor r of sector k
$\alpha_k =$ calibration factor of sector k
$\frac{1}{\alpha_k}\sum_j (s_{j,k}^r f_k^r) =$ Climate Credit Quality Index (CCQI) for segment/geographic area j

This equation shifts the PD from its normal time path, based on a value that is defined as the "climate credit quality index" (UNEP FI / OW, 2018 [34]). This index is nothing more than the sum of the products between the outputs of the stress scenarios, the so-called risk factors, and the sensitivity of the sector (high/medium/low), multiplied by a specific calibration factor α_k of the reference sector. From a theoretical perspective, CCQI identifies the size of the sectoral impact of the scenario, normalizing the variation of risk factors so that they can be interpreted with a unitary distribution, as required by the Merton framework.
It should be noted that this type of methodology interprets the qualitative levels of sensitivity provided by credit analysts (*expert judgment*) as optimization constraints. These constraints ensure that the sensitivity values, resulting from the calibration, are consistent with the expert-based assessments (e.g. "high" sensitivities, associated with a target beta of 1.2, will have a more negative impact than those marked as "low", corresponding to a target beta of 0.8).
Once all parameters of the above equations have been calibrated, it is possible to estimate the PD implied in the different stress scenarios for all debtors of a given segment. It should be remembered that also in this case the methodology refers to the most commonly used stress techniques, but consistently with internally estimated parameters and allowing for any customization. The framework can therefore be applied to all sectors and can take into account both the composition of each segment, the series of sensitivities $s_{j,k}^r$ and a different judgmental calibration provided by internal analysts.

7.3 The effects on Loss Given Default (LGD) of the transition risk

The estimation of LGD variations, the second element of the expected loss, should be largely guided by the type and value of collaterals provided at the individual transaction level. Banks should identify cases where an industry-specific LGD assessment is sufficient and where customized valuations should be developed. Alternatively, simplified approaches could be used, for example by assuming that the impact on LGD is based on its relationship to PD. More in depth:

- directly evaluation of LGD based on stressed PD using the Frye-Jacobs formula, which provides a single generic relationship parameter between PD and LGD;

$$LGD_{Transition} = \frac{\Phi(\Phi^{-1}(PD_{Transition}) - [\Phi^{-1}(PD_{TTC}) - \Phi^{-1}(PD_{TTC}LGD)])}{PD_{Transition}}$$

$$LGD_{Transition} = \text{scenario-adjusted LGD}$$
$$PD_{Transition} = \text{scenario-adjusted PD}$$
$$PD_{TTC} = \text{initial PD, portfolio specific}$$
$$LGD = \text{implied starting LGD}$$

- use of LGD forecasts based on an internally estimated correlation between PD and LGD.

Given the lack of data and a shared approach, it is preferable to adopt the Frye-Jacobs relationship as a reasonable approximation. Obviously, all the methodologies described in the previous sections represent a first starting point for any future insights into the transition risk.

8. Physical risk: the assessment of impacts on creditworthiness

In this section, we propose a framework for assessing the impact of physical risk on creditworthiness. The methodology addresses, both in top-down and bottom-up modalities, the estimate of the reduced ability of a borrower to meet payment commitments following the occurrence of an event linked to climate change. The assessment of the change in credit risk takes the form of a revision of both the estimate of the probability of default and the LGD (due to the direct impact of physical events on the value of the borrower's assets) with different levels of granularity in the bottom-up and top-down:

Table 9 – Physical risk: *top-down* and *bottom-up* approaches

	PD	LGD
TOP DOWN	**Penalties rating/sector**	**Systematic review of LGD**
BOTTOM UP	**Review of Credit Risk Score/PD**	**Haircut on collaterals**

The ability of a single institution to apply the framework depends on the robustness of the database linked to the borrowers' assessment: therefore, particular attention must be paid to the structure of the information to be used for a complete evaluation of the risk deriving from the climate change.

8.1 The frameworks of the Bank of England and ClimateWise

For the estimation of the impact of physical risk, the literature essentially provides two overall frameworks, mainly related to the anglo-saxon and reinsurance markets. The main proposals are those of the **Bank** of England 2018 [3] and 2019 [4] [9] [10] and ClimateWise [11][11], the latter resulting from an insurance association whose secretariat is held by the University of Cambridge. Both frameworks are mainly oriented to the insurance sector.

The approach proposed by the Bank of England is essentially divided into **six phases**:

Figure 5 – Bank of England framework for the physical risk

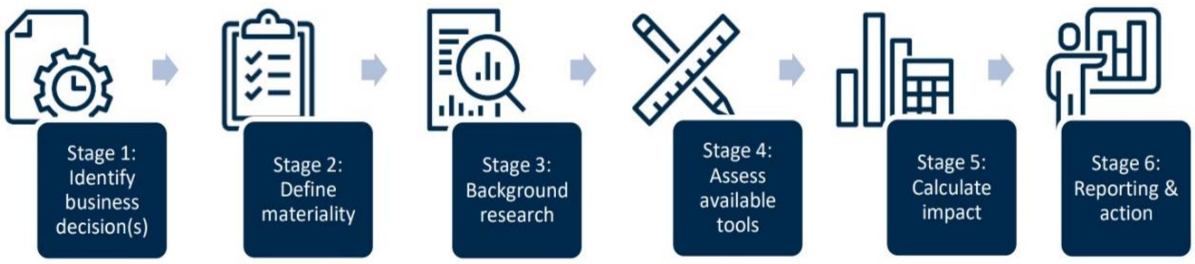


Figure taken from Bank of England, 2019 [4]

[9] Bank of England. (2018). Transition in thinking: The impact of climatechange on the UK banking sector.
[10] Bank of England (2019). A framework for assessing financial impacts of physical climate change. A practitioner's aide for the general insurance sector.
[11] www.climatewise.org.

In describing its specific implementation, the Bank of England makes particularly interesting considerations regarding to:

- the assessment of the materiality of the physical risk, suggesting that the estimations should be based on the scientific evidence that links climate change to the modification of a specific phenomenon. In particular, if the impact is immaterial, a threshold should be defined beyond which the risk can become significant;
- the choice of scenarios makes explicit reference to the RCP previously described;
- the pros and cons of the different tools available (expert judgment, hazard maps, footprints and catastrophe models), suggesting to adapt the tools to the needs of the assessment (for example, the use of event footprints and catastrophe models is recommended for portfolio analysis, as well as hazard maps at the level of individual exposures and, in general, an accurate recalibration of tools based on observations and future scenarios is recommended);
- the accurate representation of the uncertainty of the estimates (based on sensitivities and qualitative assumptions).

The Bank of England approach is essentially based on the same considerations that insurance companies normally include in the ORSA reports: in particular, the choices for the development of new products or business lines in relation to their internal risk appetites.

Instead, the ClimateWise proposal is articulated in a four steps approach (ClimateWise [10]);

1. collection of data on exposures: in particular the geographical location is essential since most climate risk models require data with a high spatial resolution;
2. selection of the model for natural disasters: the approach lists several modeling options. The OASIS project deserves particular mention[12], given that is an open source model;
3. selection of the climate change scenario: the definition of the scenario normally requires managing the discrepancy between the geographical resolution of the catastrophe models and the scenarios, usually defined with a lower precision;
4. execution of the catastrophe model: although catastrophe models are very different, they provide some standard outputs:
    - the AAL, (Average Annual Loss), loss in the value of portfolio assets;
    - annual probability of occurrence;
    - return time;
    - Annual Exedance Curve: probability of exceeding certain loss levels.

The fundamental requirements of the ClimateWise approach are the classifications of exposures, which should be geolocated and equipped with attributes that describe the exposure to risk factors, the use of catastrophe models for the deduction of statistics and the use of models for the reactivity of the prices.

8.2 Relationship between physical risk and creditworthiness

The proposed approach to estimate the exposure to physical risk related to credit exposures will be divided into both for the *top-down* and *bottom-up* approach in the following steps:

- define a series of climate change scenarios (see for example AIFIRM, [1]);
- explain, using an econometric model, the effects of physical risk on certain business sectors and geographical areas over a given time horizon (by using sensitivities and shock factors);
- apply, for each of these scenarios, the results of the previous point, evaluating the changes in PD and LGD of credit positions;
- organize, based on the results of the previous point, a specific reporting that highlights the changes in economic capital and average defaults.

This articulation is in particular consistent with the Bank of England approach described above, which aims to define:

- the scope of application of physical risk, which in the case of this study is limited to the assessment of credit risk;
- the materiality aspects, to be considered on the basis of existing portfolios;
- the need to consider the “background research”, which led to the decision to adhere to the research available at the drafting date of this study;
- the choice of tools: mainly the available *risk maps* will be used. The in-depth analysis of catastrophe models goes beyond the scope of this analysis;
- calculation of impacts, based on sensitivity techniques, as clarified in the following paragraphs;
- reporting, which in the case of this study will essentially focus on the estimate of the worsening of creditworthiness and the consequent increased need for economic capital.

[12] https://climateoasis.com.

In the Italian banking sector, the use of "reduced form" models or credit risk scores is widespread, especially for the evaluation of credit lines. A credit risk score is typically the result of a linear discriminant analysis, which assigns weights to a certain group of observed variables (for example in the case of the Z-score, Altman [2], a series of financial ratios).

The weighted sum of the variables determines the score: a discriminating threshold is then defined in relation to which an exposure is classified as a probable default.

In practice it is not only necessary to link the credit risk score to an insolvency forecast, but also to an assessment of the probability of default: this happens empirically (observing the default rates) or analytically (with a transfer function that links the score to the PD, typically a logistics):

$$PD = f(Z) = \frac{1}{1 + \exp[a + bZ]}$$

8.3 Proposals for implementing the Top-Down approach

In a top-down approach, the assessment of physical risk can be defined in a similar way to what has already been seen for transition risk, bearing in mind that, if the transition risk by its nature allows a sectoral declination, the physical risk, depending on from micro-local exposure profiles (e.g. geographical or idiosyncratic such as the layout of production facilities), is better described with a bottom-up approach[13]. As with transition risk, physical risk assessment can also be carried out by introducing corrections to the probability of default on a geo-sectorial basis. In particular, having defined π_{0P} and π_{0Q} the neutral and current probability of default observed without taking into account the risk of climate change, we can introduce the following corrective (which can be interpreted as a credit quality factor for physical risk):

$$q_{j,k} = \frac{1}{\alpha_j} \sum_r s_j^r \times f_k^r$$

where index k represents the climate change scenario considered, index j the geo-sectorial declination and index k the declination by vulnerability factor, while the letter α indicates a calibration factor, the letter s a factor of sensitivity and the letter f the shock of the factor r determining the PD (the factor f is valued by developing the quantitative description of the scenarios). With respect to the transition risk approach (in which CO2 emissions are used as the main driver), in this case the sensitivity factors will have to take into account the direct effects on the borrower production capacity and on the costs that it should bear both to cope with changes in the production chain and with any extreme events (and can be calculated simulating the effects of incremental physical risk on average balance sheet setup for a particular class of borrowers). Therefore, the calibration of the various scenarios should take into account both the forecast assessments and the historical response to extreme events in the variation of the probability of default (extreme events can be taken into account through the calibration factor).
The (current) default probability π_{kQ} in the climate change scenario k is obtained as:

$$\pi_{kQ} = \Phi\left(\Phi^{-1}(\pi_{0Q}) - q_{j,k}\right) = \Phi\left(\Phi^{-1}(\pi_{0P}) + \frac{\mu - r}{\sigma}\sqrt{\tau} - q_{j,k}\right)$$

where the term $\frac{\mu-r}{\sigma}\sqrt{\tau}$ represents the market price of risk (see for example Crouhy et al. 2000 [13]).
The corrective introduced to take into account the physical risk can be seen as a change in the market price of risk declined according to the geo-sectorial key adopted for the definition of the sensitivity: the underlying hypothesis, assuming risk parity, is a reduction in the value of the return on equity, due to the manifestation of physical risk in an idiosyncratic form. It should be noted that this correction only impacts the current probability, since by construction the risk-neutral probability already contains all the market evaluations also with respect to physical risk factors[14].
From the point of view of the change in LGD in a top-down approach, the value of the collateral is not explicitly taken into account, but it is possible to proceed, as already seen, to increase the LGD starting from the PD (following the approach proposed by J. Frye, M. Jacobs Jr., 2012, [19], the expected variation of LGD can be regarded as a function of the variation of PD).

8.4 Bottom-Up approach: first developments

The bottom-up framework focuses on the assessment of the physical risk for each borrower, taking into account the geo-sectorial and idiosyncratic characteristics. Also in this case, the creditworthiness of the various exposures will be linked to the changes in the fundamental quantities present in the expected loss: probability of default and LGD.

Relating to the probability of default, the PD will be assumed dependent from a linear credit risk score Z as defined below:

$$PD = f(Z); Z = \sum_{j=1 \dots N_j} \beta_j w_j$$

where the weights w_j are considered assigned, while the variables β_j vary according to the borrower.

13 Regard this aspects, it is useful to recall the comparison with the Solvency II insurance legislation (Commission delegated regulation 35/2015, articles 120-126), which in fact suggests a bottom-up approach.

14 This statement does not take into account the fact that the risk neutral probability is related to the weighted realization with the neutral probability of the different scenarios intended not only as RCP, but also as SSP/SPA. Therefore, the risk neutral changes in probability, dependant on the realization of a single scenario, should also be considered.

Concerning the LGD, the impact is evaluated in both simplified and advanced approaches considering collateralisation: the physical risk related to this element is relevant, since on the one hand it must be considered that a physical climatic event damages significantly the physical assets placed as collateral for a loan and, on the other hand, the demand for conservativeness in estimating LGDs in advanced approaches requires that extreme events also be taken into account. The relationship could be:

$$LGD_i = LGD_{uncoll} \times \frac{E_i - Coll}{E_i}$$

The effect of physical risk has basically two types of effects on the borrower creditworthiness: an **incremental effect**, due to the progressive change of the environment in which the borrower conducts its activities, and a **catastrophic effect**, due to the occurrence of an extreme event which directly affects the productive assets of the borrower or its supply and sale chains.

To assess the impact of climate change risk, physical risk side, the authors propose an approach consistent with the indications of Acclimatise (UNEP FI [36]):

- description of the borrower operating environment (regional, national, global operations, etc.) and selection of k climate change scenarios defined on a geographic basis;
- for each scenario k, identification of the economic aggregates P_i^k relating to the borrower (affecting the variables used in the Z score, or the evaluation of collateral) that could undergo variations as a result of physical risk (for example, variation in the plants' capacity, variation in sales prices, variation in purchase prices, etc.);
- estimate of the variations $\Delta_{incr} P_i^k = (P_i^k - P_i^0)/P_i^0$ that would occur in the various scenarios due to the changed operating conditions of the borrower;
- for each type of extreme event q, calculation of the increase in probability $\Delta\psi_q^k$ that affects the borrower in scenario k. The increase is calculated as the difference between the probability of the event and the probability found in the current observations $\Delta\psi_q^k = \psi_q^k - \psi_q^0$. The shocks that the occurrence of a single event would happen are then assessed $\Delta_{cat} P_i^q = (P_i^q - P_i^0)/P_i^0$;
- determination of which aggregate β_j, used by the credit risk score, is influenced by assigning specific coefficients $\delta_j^i = \frac{\partial \beta_j}{\partial P_i}$;
- evaluation of the Z-score variation by combining the incremental and catastrophic effects:

$$\Delta Z^k = \sum_j \alpha_j \Delta\beta_j = \sum_j \alpha_j \left(\sum_i \delta_j^i \left(\Delta_{incr} P_i^k + \sum_q \Delta\psi_q^k \Delta_{cat} P_i^q \right) P_i^0 \right)$$

- final estimate of the PD variation by deriving the transfer function from Z-Score to PD:

$$\Delta PD^k = f'(Z)\Delta Z^k$$

With regard to collateral, identified with A the assets placed as collateral, the changes in the value of the assets are directly estimated according to a similar scheme ($\Delta_{incr} A_i^k$ and $\Delta_{cat} A_i^q$), and the consequent variation $\Delta Coll^k$ is thus determined:

$$\Delta LGD^k = -LGD_{uncoll} \times \left(\frac{\Delta Coll^k}{E_i} \right)$$

Alternatively, where there is no precise information on collaterals (and on the effect of climate change on them), the same approach of the previous paragraphs can be used (i.e. applying the Frye Jacobs formula).

Clearly, for the application of the framework several factors are fundamental:

- an accurate database that allows the identification of the individual production units of the borrower, with reference to both their geographical location, their physical characteristics (type of buildings, security systems, etc.) and the production processes (type of supply chain, etc.);
- a clear definition of the climatic scenarios that allows, from a qualitative point of view, to carry out an accurate inventory of both the incremental effects and the possible catastrophic events;
- the quantitative specification of the factors $\Delta_{incr} P_i^k, \Delta_{cat} P_i^q, \Delta_{incr} A_i^k, \Delta_{cat} A_i^q$, for which it is possible to use both sources available in the literature, econometric evaluations (e.g. global econometric models [15]) and expert judgment, applying methods consistent with the aforementioned framework of the Bank of England;
- the quantitative specification of the factors $\Delta\psi_q^k$, for which we can refer both to officially recognized sources, for example the UNEP Global Risk Data Platform which has risk maps available at national level (e.g. the maps drawn up by the various regional environmental agencies pursuant to Directive 2007/ 60/EC for the risk of floods).

9. Conclusions and final remarks

This paper is inspired by the strong acceleration given to the financial industry by the TEG work on the EU taxonomy, without mentioning the recent ECB Guide on climate and environmental risks (ECB, 2020), and aims to be a useful tool for a possible

15 Global and National Macroeconometric Modelling: A Long Run Structural Approach, by Tony Garrett, Kevin Lee, Hashem Pesaran and Yongcheol Shin, Oxford University Press, 2006. ISBN 0-19-929685-5.

implementation of these issues in internal processes of the financial intermediaries. Without claiming to be exhaustive, the authors provided an overview of the available literature on physical and transition risk, focusing on forward looking scenario analysis, and in-depth examinations of quantitative and qualitative tools commonly considered fundamental in the assessment of this type of risk.
However, several issues remain open and have been addressed in the discussion in a qualitative way and within the limits of reasonableness: 1) address the lack of historical data, 2) choice of the correct time horizon for the risk models used, 3) find the right level of data granularity , 4) identification of relevant KPIs and KRIs to be used for climate risk exposures and 5) translation of economic impact into financial risk metrics.
The proposed methodologies should therefore be seen as a first attempt to assess the potential impact of climate change scenarios on the capital and liquidity of banks, to be refined with the development of new approaches and enrichment of data that in the natural evolutionary path will gradually become available.

Giuliana Birindelli, Vera Palea, Luca Trussoni, Fabio Verachi

Bibliography

[1] AIFIRM, Climate Change: assess and advance awareness of a new Financial Risk, Position Paper n. 20, April 2020

[2] Altman, E. I. "A fifty-year retrospective on credit risk models, the Altman Z-score family of models and their applications to financial markets and managerial strategies." Journal of Credit Risk 14 (2018): 1-34

[3] Bank of England, Transition in thinking: The impact of climatechange on the UK banking sector, September 2018

[4] Bank of England, A framework for assessing financial impacts of physical climate change. A practitioner's aide for the general insurance sector, May 2019

[5] M. Barbanti Brodano, F. Cocco, G. Moramarco, Global Economy, Sovereign Spreads and Public Debt in the Euro Area: a GVAR Approach, Prometeia Technical Report, 2014

[6] S. Battiston, A. Mandel,F. Schuetze,G. Visentin (2017). A Climate Stress-Test of the Financial System. Nature Climate Change. 7. 10.2139/ssrn.2726076

[7] Giusy Capasso, Gianfranco Gianfrate, Marco Spinelli, Climate change and credit risk, Journal of Cleaner Production, Volume 266, 2020, 121634, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2020.121634

[8] CERS/ESRB, European Systemic Risk Board (2016). Too late, too sudden: Transition to a low-carbon economy and systemic risk, Reports of the Advisory Scientific Committee. No 6 / February 2016

[9] Cambridge Institute for Sustainability Leadership (CISL), (2015, November). Unhedgeable risk: How climate change sentiment impacts investment. Cambridge, UK: Cambridge Institute for Sustainability Leadership

[10] Cambridge Institute for Sustainability Leadership (CISL), (2019, February). Physical risk framework: Understanding the impacts of climate change on real estate lending and investment portfolios. Cambridge, UK: Cambridge Institute for Sustainability Leadership

[11] www.climatewise.org

[12] Creutzig, F., Agoston, P., Goldschmidt, J. et al. The underestimated potential of solar energy to mitigate climate change. Nat Energy 2, 17140 (2017). https://doi.org/10.1038/nenergy.2017.140

[13] M. Crouhy, D. Galai, R. Mark, Risk Management, New York, McGraw Hill 2000

[14] Dietz, Simon & Bowen, Alex & Dixon, Charlie & Gradwell, Philip. (2016). 'Climate value at risk' of global financial assets. Nature Climate Change. 6. 10.1038/nclimate2972

[15] F. di Mauro, H. Pesaran, The GVAR Handbook: Structure and Applications of a Macro Model of the Global Economy for Policy Analysis, Oxford University Press, 2013

[16] ECB, Guide on climate-related and environmental risks - Supervisory expectations relating to risk management and disclosure, May 2020

[17] ENI scuola energia e ambiente, Scenari futuri secondo l'IPCC, http://www.eniscuola.net/argomento/cambiamenti-climatici/scenari-futuri/scenari-futuri-secondo-lipcc/

[18] I. Faiella, F. Natoli, Climate change and bank lending: the case of flood risk in Italy, Conference on Climate Change and its Impact in the Financial System Mexico City, 5-6 December 2019

[19] J. Frye, M. Jacobs Jr., Credit loss and systematic loss given default, The Journal of Credit Risk Vol 8, 1-32, Spring 2012

[20] IPCC, Special Reports on Emission Scenarios, Cambridge University Press 2000

[21] IEA, World Energy Report 2017, a world in trasformation, Flagship report - November 2017

[22] IPCC (2014) Climate Change 2014 Mitigation of Climate Change. Working Group 3 Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Technical Summary and Chapter 6 (Assessing Transformation Pathways)

[23] Jansen D.J. (2019), A Framework for Measuring Financial Stress under Disruptive Energy Transition Scenarios, EBA/EBF Workshop on Sustainable Finance, 4 April

[24] K. Riahi, D. P. van Vuuren, E. Kriegler, J. Edmonds, B. C. O'Neill, S. Fujimori, N. Bauer, K. Calvin, R. Dellink, O. Fricko, W. Lutz, A. Popp, J. Crespo Cuaresma, Samir KC, M. Leimbach, L. Jiang, T. Kram, S. Rao, J. Emmerling, K. Ebi, T. Hasegawa, P. Havlik, F. Humpenöder, L. Aleluia Da Silva, S. Smith, E. Stehfest, V. Bosetti, J. Eom, D. Gernaat, T. Masui, J. Rogelj, J. Strefler, L. Drouet, V. Krey, G. Luderer, M. Harmsen, K. Takahashi, L. Baumstark, J. C. Doelman, M. Kainuma, Z. Klimont, G. Marangoni, H. Lotze-Campen, M. Obersteiner, A. Tabeau, M. Tavoni, The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview, Global Environmental Change, Volume 42, 2017, Pages 153-168, ISSN 0959-3780, https://doi.org/10.1016/j.gloenvcha.2016.05.009

[25] Monnin, P. (2018). Integrating Climate Risks into Credit Risk Assessment-Current Methodologies and the Case of Central Banks Corporate Bond Purchases. Council on Economic Policies, Discussion Note, 4

[26] OECD Guidelines on Multinational Enterprises and for Responsible Business Conduct, https://www.oecd.org/corporate/mne/responsible-business-conduct-matters.htm

[27] O'Neill, B.C., Kriegler, E., Riahi, K., et al., 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Clim. Chang. 122, 387–400

[28] Brian C. O'Neill, Elmar Kriegler, Kristie L. Ebi, Eric Kemp-Benedict, Keywan Riahi, Dale S. Rothman, Bas J. van Ruijven, Detlef P. van Vuuren, Joern Birkmann, Kasper Kok, Marc Levy, William Solecki, The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century, Global Environmental Change, Volume 42, 2017, Pages 169-180, ISSN 0959-3780, https://doi.org/10.1016/j.gloenvcha.2015.01.004

[29] See [34] and [35]

[30] Steven Poelhekke, How expensive should CO2 be? Fuel for the debate on optimal climate policy, DNB Working Paper n. 579 (2017)

[31] Pesaran M.H., T. Schuermann, and S.M. Weiner, Modelling Regional Interdependencies using a Global Error Correcting Macroeconometric Model, Journal of Business and Economic Statistics, 2004, 22, 129-162

[32] Technical Expert Group on sustainable finance (TEG), TEG Final Report on the EU taxonomy, European Commission, March 2020. The report published in March 2020 revise and update, also in light of the evidence gathered in the public consultation phase, the first version of the documents published in June 2019

[33] Richard S J Tol, The Economic Impacts of Climate Change, Review of Environmental Economics and Policy, Volume 12, Issue 1, Winter 2018, Pages 4–25, https://doi.org/10.1093/reep/rex027

[34] UNEP FI, Extending Our Horizons: Assessing Credit Risk and Opportunity in a Changing Climate - PART1: Transition-related risks & opportunities, April 2018

[35] UNEP FI, Navigating a New Climate: Assessing Credit Risk and Opportunity in a Changing Climate - PART2: Physical-related risks and opportunities, July 2018

[36] UNEP FI, Piloting the TCFD recommendation for Banks, July-August 2019

[37] UN Guiding Principles on Business and Human Rights, International Labor Organizations, https://www.ungpreporting.org/resources/the-ungps/

[38] van Vuuren, D.P., Edmonds, J., Kainuma, M. et al. The representative concentration pathways: an overview. Climatic Change 109, 5 (2011). https://doi.org/10.1007/s10584-011-0148-z

[39] R. Vermeulen, E. Schets, M. Lohuis, B. Kölbl, D.J. Jansen, W. Heeringa, An energy transition risk stress test for the financial system of the Netherlands, DNB Occasional study n. 7, 2018

[40] R. Vermeulen, E. Schets, M. Lohuis, B. Kölbl, D.J. Jansen, W. Heeringa, The Heat is on: a framework for measuring financial stress under disruptive energy transition scenarios, DNB Working Papers 625, Netherlands Central Bank, Research Department, 2019