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Scenario-based climate stress testing: From risk analysis to modeling

Working document

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Finance ClimAct contributes to the implementation of France's National Low-Carbon Strategy and the European Union's Sustainable Finance Action Plan. It aims to develop tools, methods and new knowledge that will enable (1) savers to integrate environmental objectives into their investment choices, (2) financial institutions and their supervisors to integrate climate issues into their decision-making processes and to align financial flows with energy and climate objectives, and (3) industrial companies to promote investment in energy efficiency and the low-carbon economy.

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SUMMARY

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This working paper presents a review of the state of the art on the conduct of climate stress tests by central banks, supervisors and international institutions and on the macroeconomic modeling of climate scenarios that they require. These risk management tools, commonly used by financial institutions to measure their resilience to the materialization of short-term economic and financial risks, require to extend structural adaptations to climate risks, whether physical, transition or liability risks. Specific issues must be considered: potentially very long time horizons, fine granularity of scenarios to take into account the numerous international and sectoral specificities, radical uncertainty and extreme amplitude of risks, interdependence of physical and transition risks.

The construction of climate scenarios by supervisors is based on a large number of choices and assumptions: narrative methods chosen (historical, hypothetical, enumerative or prospective), transition levers (environmental policy instruments, technological changes, markets) and socio-economic and climate trajectories (IPCC SSP and RCP scenarios, for example). Faced with this wide range of choices, the risk incurred will be conditioned by the choice of scenarios and the horizon of the exercise. Moreover, in the absence of historical reference on the effect of these risks on the economy, the choice of a model also has a significant influence on the results, in particular according to its category (IAM, CGE, macro-econometric models), its properties (Keynesian or Walrasian), its representation of the economy (sectoral disaggregation, energy needs) and the choice of redistribution of carbon tax revenues. Finally, the representation of the effects of the transition at granular level brings out opportunities and winning investment strategies, which is also a new element for a stress test.

In view of the long road ahead for climate stress tests and the multiplicity of hypotheses and methodological choices, ADEME aims at making proposals and recommendations based on the agency's macroeconomic, prospective and sectoral expertise. This note, which presents our vision of the state of the art and of the issues at stake in climate stress testing, is the first step in this process.

1. Introduction and background

The materialization of climate risks on financial portfolios is becoming more sensitive and is the subject of diligent attention by financial supervisors and regulators. The "tragedy of the horizons"[1], theorized in 2015 by Bank of England Governor Mark Carney (Carney, 2015) describes the materialization of climate change-related risks[2] to financial portfolios. Supervisors and central banks are now developing new models based on this assumption. These models allow them to carry out scenarios integrating the effects of climate change and enabling them to carry out their statutory missions in light of this new variable.

What is at stake here is the question of knowing how to integrate these new models into stress-testing exercises, which are periodic exercises aimed at ensuring the individual resilience of institutions and preventing systemic risks. Public authorities are defining the first outlines of a future financial regulation, thus paving the way to the integration of climate risks in the exercises conducted by European authorities (EBA, ECB). :

- European Systemic Risk Board recommendation to include a transition scenario in stress testing exercises in 2016 (ESRB, 2016);
- Creation of the TCFD (Task Force on Climate-Related Financial Disclosures) in 2015 and recommendation to expand climate stress testing (TCFD, 2017) ;
- Creation of the NGFS (Network for Greening the Financial System) in 2017, a network bringing together central banks from five continents and organizing a working group on the analysis of the macroeconomic and financial stability impacts of climate change, followed by the publication of a first methodological guide and a set of exploratory scenarios for use by supervisors (NGFS, 2020).

Finally, several national central banks are conducting exploratory macroeconomic and financial scenario exercises incorporating climate change risks: Netherlands Bank (Vermeulen, et al., 2018), Californian Department of Insurance in 2019 (2DII, 2019), Bank of England (Bank of England, 2019), Bank of Canada (Ens & Johnston, 2020) and Banque de France (Allen, et al., 2020). These exercises, which do not impose any capital requirements or specific internal models on institutions, aim to measure the exposure and resilience of institutions to climate risks and thus lay the groundwork for a common methodology and tools for the future implementation of "climate stress tests. However, their definition is still subject to discussion and their articulation with the usual stress-testing exercises is not obvious, given the specificities of climate risks and in particular their uncertainty and their materialization in distant time horizons.

First of all, the very definition of a climate stress test remains vague from a methodological point of view: stress tests do not belong to any kind of regulation and very few actors claim that they have achieved such exercises. While the regulations governing traditional stress tests can serve as a basis for an initial benchmark, they still seem limited to assess the climate risks identified by supervisors on the basis of specific portfolio exposures.

In order to share experiences and to define a common frame of reference between all stakeholders involved (supervisors, central banks, environmental agencies, financial institutions, academia), the aim of this report is to propose a minimum set of standards. This set of standards can be applied according to the present regulations for usual exercises, according to the methodological framework for scenario-based analysis as defined by the NGFS and to the first climate exercises conducted by some institutions. It also takes into account the academic publications and the expectations of different stakeholders of what a climate stress test could be and should be. This document focuses on the formalization of climate stress test scenarios organized in three main axes

[1] According to this theory, actors would have no incentive to act against climate change, given the short-term constraints of the business cycle, the political cycle and the action horizons of public authorities.
[2] Physical risks, transition risks, liability risks.

(i) The analysis of climate-related financial risks and the definition of several relevant normative and statistical indicators, prior to the implementation of a stress test to ensure its relevance and the consideration of all identified vulnerabilities;

(ii) The use and limitations of climate scenario analysis through several possible narratives, relying where appropriate on academic long-term projections;

(iii) The contribution of macroeconomic modelling, in particular to fine-tune transition scenarios to the granular levels relevant to their use by financial institutions and to observe the winners and losers of the transition.

2. Identification of climate risks and vulnerabilities in portfolios

2.1. A reading of climate risks among financial risks

In order to arrive at standards and good practices for "climate stress tests" (which are not defined by any text to date), it may be appropriate to refer to the existing regulations and standards around classic stress tests. *Stress tests,* which appeared in the late 1990s, are a set of management tools used by supervisors and financial institutions to assess the resilience of an institution to a shock[3] and the adequacy of its balance sheet to prudential requirements (see **Box 1**). They should cover a set of "severe but plausible" scenarios, and ensure that this severity reflects the specific risks of the institution (EBA, 2018).

The financial world proposes a usual typology of financial risks, which should be clarified with respect to the definition of climate risks proposed by Mark Carney (2015). To fully understand this risk framework, we can define three successive levels of risk materialization and transmission:

- 1st level: the risk trigger; climate risk as defined by Mark Carney, can be read as an additional (or formally identified) source of financial loss because it specifies a cause *upstream of* the financial impacts and is therefore defined in terms of the *stress* trigger, which makes both appear:
    - Physical risks, which include chronic and extreme weather events;
    - Transition risks, which are related to the adjustment process towards a low-carbon economy;
    - Litigation risks, which include the financial risks associated with potential compensation claims by parties who have suffered from climate change to parties they hold responsible.

- 2nd level: its transmission in economic effects, essentially linked to shocks on macroeconomic parameters for classical stress tests, they include transmission channels at more granular levels (for example: increase in input costs, technological disruption, damage to physical capital...).

- 3rd level: its impact on financial risks, through the current typology used by financial institutions (credit, market, operational and liquidity risks).

According to the European Central Bank (ECB), climate risks are potential financial risk factors at all levels usually considered by institutions (see **Table 1**). One should note that institutions are already supposed to protect themselves from all forms of material risks, notably within the framework of "Pillar 2" (see **Box 1**), which in fact and in theory include climate risks. The European Central Bank (2020) stresses that banks are already required to assess the effect of climate risks on their regulatory capital ratios over a horizon of one to three years, and are "encouraged to adopt a broader time horizon for (these) risks given the likelihood that they will materialize mainly in the medium to long term" and to incorporate them "into stress tests from an economic perspective". The European Banking Authority (EBA) regulatory framework already refers to the supervisor's mandate to assess "potential systemic environmental risk"; this framework has since been strengthened by CRD 5[4] and the mandate to conduct stress tests and scenario analyses to assess the impact of ESG risks under scenarios of varying severity.

When asked, French banking groups believe they cover climate risks using traditional approaches (ACPR, 2019). However, their approaches focus on short-term horizons, and their internal tools are not geared towards the materialization of climate risk, whether in stress-testing exercises or quantitative risk measurement exercises. In particular, the latter methods (including the VaR[5]), based on empirical loss

[3] This can be of several kinds, essentially macroeconomic (an economic slowdown) or financial (bankruptcy of a counterparty).

[4] *Capital Requirements Directive.*

[5] The *Value at Risk* (VaR) method, for example, makes it possible to establish a theoretical distribution of the value of a portfolio and to establish a minimum value of expected losses at a given confidence level.

distributions and confidence intervals, seem less adapted to the evaluation of climate risk, which materializes through extreme events and discontinuities, that remain inexistent at this stage.

Class	Financial risk	Link to physical risk	Link to transition risk
Credit/counterparty risk	Risk that a borrower will not repay all or part of his or her loan on time	Valuation of collateral in real estate and infrastructure portfolios	Increased costs and reduced profitability in certain businesses due to price signals
Market risk (interest rates, exchange rates, equities, commodities)	Risk of loss that may result from fluctuations in the prices of the financial instruments that make up a portfolio	Changing expectations Volatility and losses due to asset revaluation	Rapid revaluation of company shares and debts based on anticipated future cash flows (losses, stranded assets)
Operational risk	Risk of direct or indirect losses due to inadequate or failed institutional procedures	Disruption related to damage to property, plant and equipment	Degradation of reputation Legal actions
Liquidity risk	Risk that a bank will not have sufficient liquidity to meet its short-term commitments	Withdrawal of liquidity to repair physical damage	Revaluation of liquid assets, affecting liquidity cushions

Table 1: Major financial risk categories, assets and links to climate risk

Source: from European Central Bank (2020), Guide on climate-related and environmental risks.

The financial risks of climate change have now become a reality, as the IMF has noted (Adrian, Morsink, & Schumacher, 2020) through two examples:

- on the physical risk side, a sharp increase in insurance losses: from $10 billion in the 1980s, they rose to nearly $138 billion in 2017[6].
- on the transition risk side, major U.S. coal producers saw their stock values fall by nearly 95% between 2010 and 2017.

According to the standards of the Bank for International Settlements, a stress test must be carried to identify the risks of financial institutions and their vulnerabilities, both with regard to on-balance sheet activities and off-balance sheet activities, as well as any form of material risk identified. This identification is the basis for the calibration of the stress test and the principle of proportionality: the analysis and the parameters of the stress test must highlight the nature, scale, size and complexity of the institution concerned, as well as the characteristics of its portfolio and its business model. In order to estimate its vulnerabilities, scenario analysis is one method of capturing risk by providing a reduced set of relevant key variables.

[6] Nearly 80% of insurance losses caused by catastrophes are now said to be climate-related (Despres & Hiebert, 2020).

Box 1: Stress tests as a tool for managing financial risks

Many stress tests were developed because of the 2008 crisis. Since then, they have become common risk management tools, used in parallel or in combination with quantitative methods. Their evolution follows the framework of prudential regulations initiated by the Bank for International Settlements (BIS) and the "Basel Accords" (banks) and "Solvency Standards" (insurances). These recommendations have been transcribed into European directives and then into national law (see **Figure 1**).

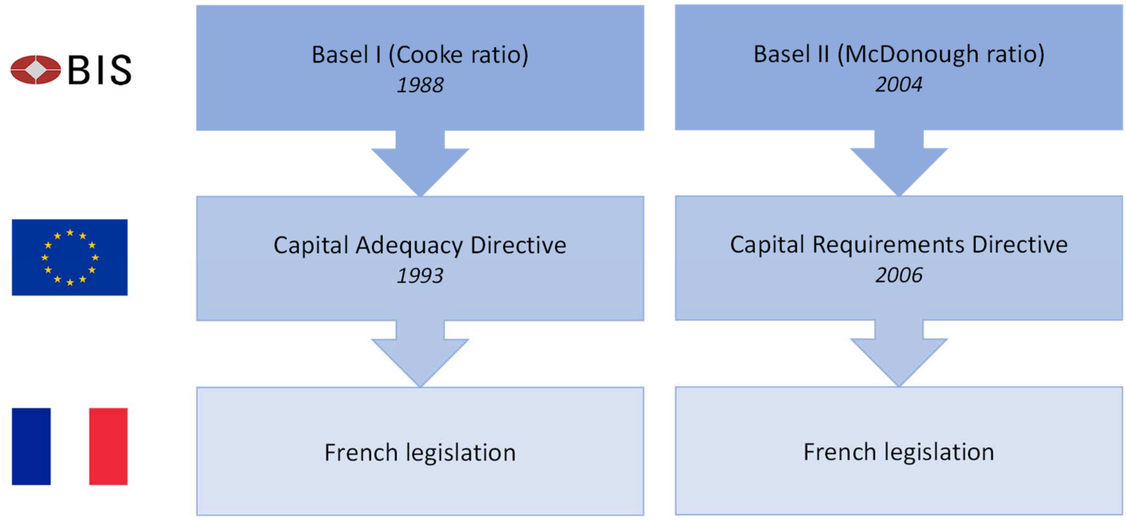

Figure 1: Prudential regulation breakdown - examples of Basel I and Basel II

Basel I introduced the regulatory principles of the solvency ratio (originally the "Cooke" ratio). Banks are subject to a minimum capital requirement of 8% of total loans, weighted according to the type of counterparty. In 2004, Basel II explicitly defines three regulatory pillars[7], intended to correct the weaknesses of Basel I and to refine banking risk management. Pillar I sets a new minimum capital requirement ("McDonough" ratio), more in line with all financial risks and weights the calculations by the risk of default of counterparties. It opens the way for banks to use internal models ("IRB[8] approach").

Finally, Pillar 2 organizes the prudential supervision procedure, through the bank's analysis of all its risks (including those already covered by Pillar 1), the calculation of its capital requirements in terms of economic capital and the comparison by the banking supervisor of its own analysis of the bank's risk profile with that conducted by the bank itself. To this end, the supervisor establishes recommendations with a view to adapting its prudential action, whether by means of capital above the minimum requirements or any other appropriate technique.

Since 2008, a complementary approach to stress-testing, known as "macroprudential" and encouraged by Basel 3, has developed in order to prevent instability in the financial system as a whole. Stress tests contribute to defining an optimal macroprudential policy through specific steering tools (such as the counter-cyclical capital buffer).

Under European law, the ECB must conduct annual stress tests on a list of banks subject to prudential supervision. These complement the EU-wide stress test conducted by the EBA, as well as ad hoc assessment programs. The IMF also conducts stress tests under the Financial Sector Assessment Program (FSAP) to assess the vulnerability of national economies to systemic risk. In all of these exercises, the scenarios and assumptions are left to the discretion of supervisors, based on a review of the vulnerabilities of institutions or the financial system.

[7] These three pillars are: the capital requirement, the procedure for monitoring capital management, and market discipline.
[8] Internal ratings-based approach.

At first glance, most actors consider that climate risks are already taken into account in the class-based approach used by supervisors. Climate risks are assumed to materialize through credit risk and market risk (these cover on average nearly 9/10ths of risk-weighted assets in the EBA exercises). In particular, credit risk represents the main amount of exposures and appears to be the main channel for the materialization of climate risk. Market risks, which are generally minor in banks' RWAs[9], are also subject to hedging strategies, for example against variations in the price of carbon on the EU-ETS markets (BNP Paribas, 2016).

Liquidity risks are subject to specific stress tests and are still outside the framework of the climate scenario analysis[10]. Operational risk (considered "idiosyncratic"[11]) is supposed to materialize through the channel of damage to physical assets, defined by the Basel Committee as all losses resulting from the deterioration or destruction of the bank's physical assets linked to natural disasters or other events; but also through the channel of liability risks, and the risks of legal action to which they are exposed as a result of their inaction or their unsustainable strategy (financing of high emitting companies for example).

		Transition risks	Physical hazards	Liability risks
Banks	Loans	Credit risk	Credit risk Market risk	
	Titles	Credit risk Market risk	Credit risk Market risk	
	Current management		Operational risk	Operational risk
Insurance	Securities (assets)	Credit risk Market risk	Credit risk Market risk	
	Commitments (liabilities)		Insurance risk	Operational risk

Table 2: Risks by financial institutions and instruments

Source: author.

2.2. What are transition risks?

Transition risks

"Financial risks associated with the process of adjustment to a low-carbon economy. Changes in policies, technologies, and physical risks can lead to a revaluation of the value of a wide range of assets as costs and opportunities become apparent. »

(Carney, 2015)

According to the original definition of the Governor of the Bank of England, transition risks arise from all the processes leading to a decrease in the net emissions of an economy (or at least a decline in the observed trend). However, contrary to usual stress-testing exercises, sensitivity analyses and the sectoral heterogeneity of portfolios tend to reveal both "losing" institutions and potentially "winning" institutions in several scenarios. In this respect, a climate stress test can highlight the opportunities of certain investment strategies directed towards green assets; these would then, on the contrary, be exposed to scenarios of no transition or incomplete transition. Mark Carney's definition therefore excludes, a priori,

[9] *Risk-Weighted* Assets are a method of calculating a financial institution's assets or exposures (each asset being weighted according to its risk) to determine its capital requirement.
[10] Liquidity risk is not covered by capital requirements but is regulated by ratios.
[11] That is, it is inherent to the activity of the financial institution: procedures, human factors, internal systems...

transition risks modelled as inaction scenarios.

Through this definition, ADEME distinguishes two main categories of transition risks:

- The transition risks linked to the implementation of public actions following the occurrence of triggering events (reaction to the concrete materialization of the effects of climate change, better perception of its consequences, collective actions or complaints against the States, etc.); they are more or less coercive and meet various objectives (informing, inciting, offering or eliminating alternatives); they rely on economic mechanisms (price signal and rationality of the agents, constraints on supply to make demand evolve), but also on sociological and psychological mechanisms (ADEME - S. Martin, A. Gaspard, 2016).
- Transition risks linked to spontaneous changes in the economy, in response to technological shocks or changes in the preferences of agents[12] (households, companies).

Classification	Transition levers
Environmental policy actions	Environmental policy instruments
Technological changes	Costs of low-carbon technologies
	Substitution of products with low carbon options
	Effects of unsuccessful investments
	Carbon capture and sequestration technologies
Market developments	Changes in consumer behavior
	Increase in the cost of raw materials
Reputation	Stigmatization of a company or sector

Table 3: Classification of transition risks

Source: author.

(i) Environmental policy tools, their temporality and the coordination of actors

Environmental policy instruments, listed in **Table 4** below, include all institutional measures (local, national, EU) aimed at discouraging or prohibiting emitting economic behavior, as well as practical examples of implementation in France. Among them, economic instruments aim to modify the economic environment through price signals to encourage economic agents to adopt less emitting behaviors. The expected effect depends on the integration by these agents of these new parameters and is therefore non-coercive. However, their application can be based on a constraint (e.g. carbon tax). Economic instruments are distinct from regulatory instruments that constrain the behavior of agents under the threat of economic, administrative or judicial sanctions. These instruments are more difficult to integrate into climate scenarios through modeling. For example, ADEME uses the so-called "shadow price signal" method, a technique that can "allow for a rigorous mimicry of regulatory public policy measures... to reproduce the expected emissions and investment reduction trajectories"; it is "an acceptable approximation when the effects of the modeled measure are well defined". (ADEME - G. Callonnec, H. Gouëdard, P. Jolivet, 2020). However, this technique requires that the measure be subject to microeconomic studies beforehand.

[12] One should note that such developments can also be stimulated by the exact same public actions. For example, according to endogenous growth theories, higher energy prices can encourage innovation and R&D in this sector.

Class	Instrument	Example
Economic instruments	Carbon tax	Carbon component
	Energy taxation	TICPE
	Grants	Car bonus-malus
	Pollution rights market	EU-ETS market
	Steering the energy mix[13]	Multiannual Energy Programming
Legal instruments	Emission standards / Technical standards	European standards for CO2 emissions from cars & light commercial vehicles
	Product standards	Obligation of catalytic converter for cars
	Marketing procedures	Automobile emission standards according to the WLTP procedure
	Prohibitions	Announced ban on the sale of thermal vehicles by 2040
Information tools	Ecolabels, eco-audits	Climate label for EPD diagnosis
Planning and infrastructure instruments	Network improvement, land use planning	Improvements to public transport networks
	R&D and training policies	National strategy for the development of decarbonised and renewable hydrogen in France
Voluntary and negotiated agreements	Agreements on the reduction of CO2 emissions	Voluntary agreements of European car manufacturers (1998)

Table 4: Environmental policy instruments

Source: author, based on a study by ADEME (2016).

The NGFS (2020) also introduces several metrics related to the implementation of these tools:

- the notion of temporality: whether the action is implemented smoothly or not;
- anticipation of the action;
- international coordination: whether the action is implemented simultaneously around the world or not.

(ii) The evolution of the business model

The evolution of the business model can be endogenous or linked to the implemented environmental actions listed above (signals encouraging behavioral changes) or exogenous and spontaneous evolutions of the economy. I4CE (2017) distinguishes between market, technology, and reputational transition risks. The tenfold reduction in the cost of large-scale solar power generation between 2009 and 2020 (see **Figure 2**) is a good example of a materialization of technology transition risk.

[13] This category includes both public steering (when the energy mix is a public good), but also feed-in-tariffs and renewables portfolio standards.

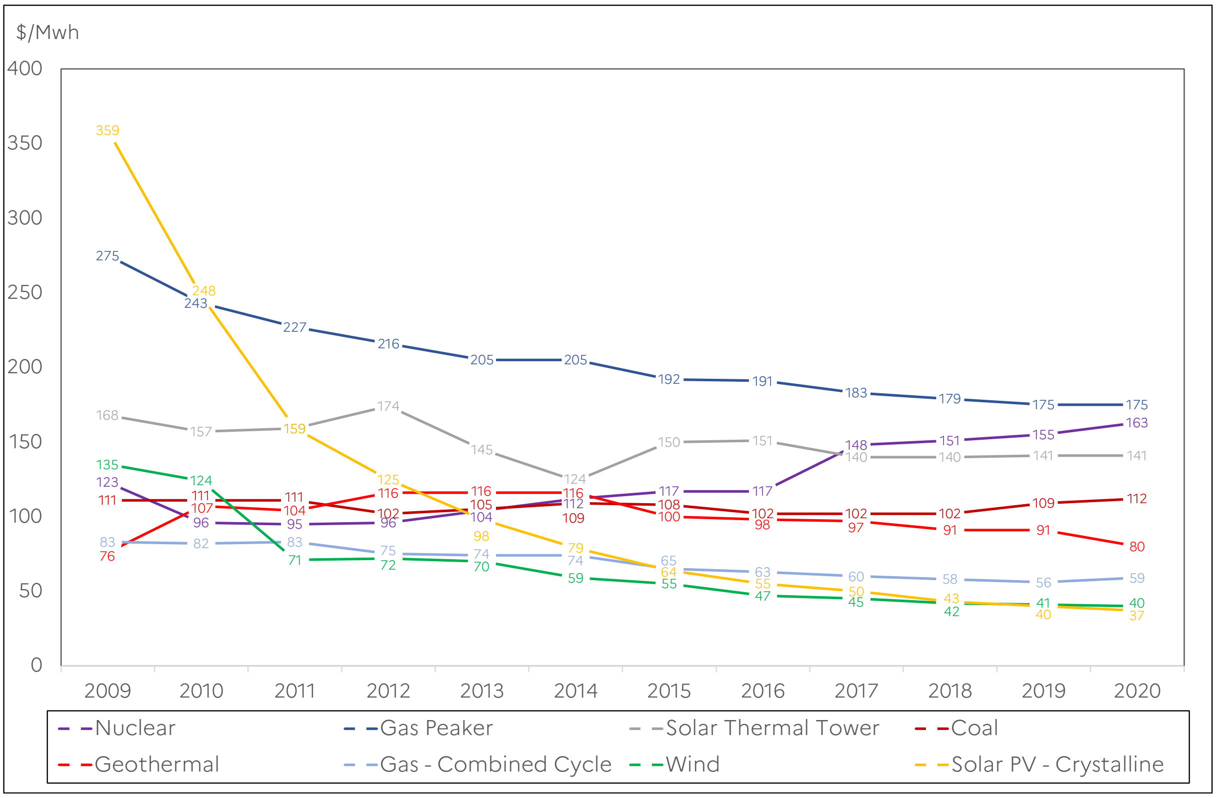

Figure 2: Example of a transition risk - evolution of levelized cost of energy without subsidy

Source: Lazard (2020), Lazard's Levelized Cost of Energy Analysis - Version 14.0.

2.3. What are physical risks?

Physical hazards
"Impacts today on insurance liabilities and financial asset values resulting from weather and climate events, such as floods and storms that damage property or disrupt commerce. »
(Carney, 2015)

The physical risks referred to include all the physical damage linked to climate change that is estimated to have a direct impact on the functioning of the economy. These consequences are multiple, include a large number of sectors and regions and are difficult to quantify, as they may be linked to one another and generate additional effects (positive or negative feedback loops), as well as lead to irreversible and as yet unpredictable consequences (tipping points). As an example, ECB (2020) lists the following events:

- acute risks, when they materialize in the form of extreme events that cannot be predicted: droughts, floods, storms;
- chronic risks, when they materialize through progressive evolutions of already existing periodic events: temperature variation, sea level rise, water shortage, diversity losses, resource scarcity.

	Temperature	Wind	Water	Solid mass
Chronicles	Temperature evolution (air, sea water, river water) Thermal stress Melting of permafrost Temperature variability	Changes in wind regimes	Changes in precipitation patterns (rain, hail, snow/ice) Precipitation or hydrological variability Sea level rise Saline intrusion Ocean acidification Water stress	Coastal erosion Soil degradation Soil erosion Solifluction
Highs	Heat wave Cold/Frost Wave Fires	Cyclones, hurricanes, typhoons Thunderstorms (blizzards, dust and sandstorms) Tornadoes	Drought Heavy precipitation (rain, hail, snow/ice) Flooding (coastal, fluvial, pluvial, underground) Abrupt emptying of a glacial lake	Avalanche Landslide Subsidence

Table 5: Classification of physical risks

Source: Taxonomy Delegated Acts (2020).

However, an initial review of the literature can help us identify different levels of impact:

- At a macroeconomic level, the French Treasury identifies, for example, three main transmission channels for physical risks that disrupt the functioning of the economy as a whole, via effects on health, labor productivity and international trade;
- a sectoral level, highlighting four particularly exposed sectors: the agricultural sector, the energy sector, the infrastructure sector and tourism.

In order to assess the costs of climate change, ADEME has carried out an exhaustive survey of all the economic consequences of climate change observed in France to date. It has focused individually on each impact channel, detailing the methods and models used to obtain the reference results, and proposing a calibration of these impacts at the national level (see **Table 6** and **Annex 4**)

Environmental phenomenon	Economic action channel
Sea level rise	Capital loss (infrastructure)
Increase in temperature and modification of the pH of the sea	Fish yields
Increase in air temperature and change in precipitation regime	Silvicultural yields Agricultural yields Tourism revenues Labor productivity Energy demand Energy yields
Extreme weather events (tornadoes, floods, heat waves, fires...)	Labor productivity Capital loss (infrastructure)
Loss of biodiversity	Ecosystem services provided by biodiversity Decrease in pollinators
Diseases	Labor productivity

Table 6: Summary of the economic impacts of climate change in France

Source: ADEME.

2.4. Assessing the climate risks of financial institutions' counterparties

A consensus is emerging among all actors: exposure to climate risks must be reflected both in macroeconomic and financial scenarios. These scenario need to be numerous to capture all the uncertainties and varieties of futures, but also present a breakdown of specific impacts at a sectoral and regional granular level. The central bank of the Netherlands was the first institution to assess the effect of an energy transition scenario (2018). It acknowledged that the exposures of Dutch banks were both domestic and international[14] and highly heterogeneous across sectors. The ACPR argues that considering climate risks requires "substantial adaptations, in particular when it comes to the horizon exercise, the international dimension of exposures and the segmentation of portfolios according to activities" (2020).

(i) Transition risk exposures

The transition to a low-carbon economy will lead all economic actors to significantly reduce both their direct emissions and their carbon footprint. These emissions are linked to the production and consumption of energy, to the carbon intensity of the energy consumed (because of the energy mix chosen upstream) but also to direct non-energy emissions, particularly in the heavy industry sector. In particular, nine industrial manufacturing sectors have been identified by ADEME and are the subject of Sectoral Transition Plans: paper and cardboard, chemical industry (ethylene, ammonia, chlorine), metallurgy (steel, aluminium), food industry (sugar) and mineral industry (cement, glass).

At the European level, official statistics show that carbon emissions from the non-financial sector are very heterogeneous, both at the sectoral or regional level, which tends to encourage more granular approaches than for usual risk analyses. Such an approach can be based on a new indicator proposed by DNB (Vermeulen, et al., 2018), the Transition Vulnerability Factor (TVF), which is gradually being adopted by supervisors and academic research. By definition, this indicator is based on the total of CO2 emissions[15] released to produce the final goods and services of a company or a sector (embodied emissions), for one unit of value added, and in relation to the economy's average. In particular, this indicator may include, depending on data availability, both direct emissions and indirect emissions linked to the value chain of the sectors; in the case of the Dutch exercise, it includes the direct emissions of each industry and those of its suppliers, but does not include the entire scope of emissions, in particular all those of Scope 3 as defined by ADEME, including the entire life cycle of products (see **Table 7**), as these data are not widely available at aggregate levels.

Levels	Emission perimeters	Examples
Scope 1	Direct emissions (from sources owned or controlled by the organization)	Combustion of fixed and mobile sources, industrial processes outside combustion, ruminants
Scope 2	Indirect energy emissions	Consumption of electricity, steam, heat or cold
Scope 3	Other indirect emissions (not accounted for in scope 2 but linked to the complete value chain)	Purchase of raw materials, employee travel, upstream and downstream transportation of goods, waste management, end-of-life products

Table 7: Emission categories and operational scope of the GHG assessment

Source: ADEME.

[14] 50% of Dutch banks and insurance companies are exposed to foreign counterparties. This share rises to 86% for pension funds.
[15] It could also include all GHG emissions, with respect to the instruments implemented to combat emissions in the transition scenarios.

At the European level, such a calculation remains complicated, particularly with regards to the total carbon footprint of an activity. However, intermediate indicators allow us to observe a high degree of heterogeneity in exposure between sectors and between countries. In France, the energy sector alone stands out because of its highly decarbonized mix. Such an indicator makes it possible to measure the relative exposure of each sector to a transition scenario, but is subject to several limitations:

- The extractive industry seems to have a low exposure to both Scope 1 (direct emissions) and Scope 2 (indirect energy emissions), but is the upstream source of a majority of the economy's emissions and should appear to be one of the most vulnerable sectors to transition risks.
- The relative inaccuracy of certain data; as the European Systemic Risk Board notes, financial markets still adopt very different strategies with regards to climate risks and do not allocate capital efficiently, both because externalities are not sufficiently taken into account and because of a certain lack of information. To date, this information remains "insufficient (companies report unevenly), incomplete (they only report production-related emissions and omit product life cycle emissions) and inconsistent (subject to greenwashing)". (Despres & Hiebert, 2020).
- Inadequate nomenclatures for risk assessment; as noted by Battiston et al. (2016), standard classifications of economic activities, such as NACE[16] or NAICS[17] , may be inadequate for the financial sector's exposure to transition risks. For example, NACE Section B (mining and quarrying) includes activities unrelated to fossil fuel extraction, while such activities may be associated with other sectors (manufacturing or transportation).
- The failure to take into account the capacity of sectors to adapt to the transition (share of intermediate consumption that emits, substitution possibilities, market power, degree of openness to international competition, etc.); as explained in section 4, such approaches can, however, be used in macroeconomic models;
- The heterogeneity of the emission levels within the same sector, some firms conducting their activities in a more sober and efficient way than others (Despres & Hiebert, 2020). However, the availability of this level of information remains incomplete to date, and observation at a sectoral level (which is that of macroeconomic modeling) necessarily leads to a methodological bias.
- The evolution of this factor in the different transition scenarios considered; a transition to a more renewable energy mix could, for example, increase the relative exposure of the fossil fuel sector (Vermeulen, et al., 2018).

[16] NACE (Nomenclature des Activités économiques dans la Communauté Européenne) is the classification of economic activities in the European Union (EU). The third revision of NACE, NACE Rev. 2, adopted at the end of 2006, has been implemented since 2007.
[17] NAICS (North American Industry Classification System) is a statistical classification of economic activities for North America.

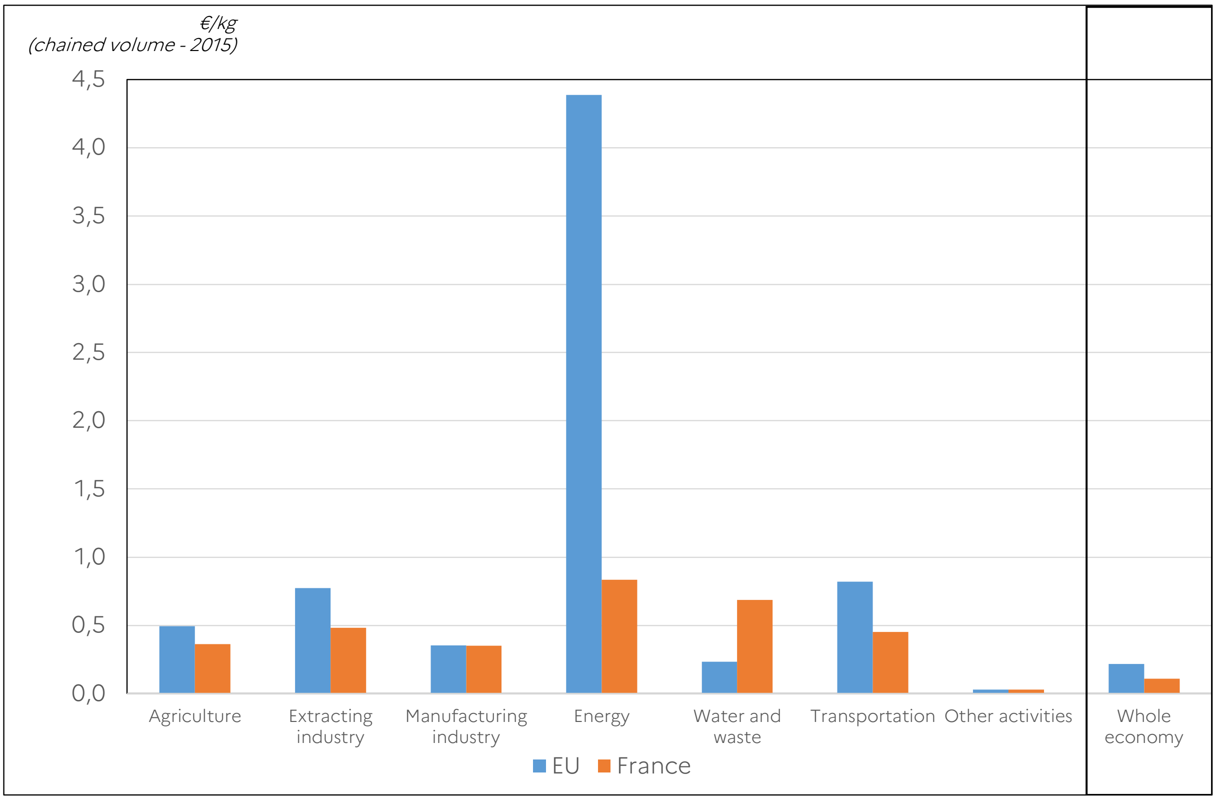

Figure 3: CO2 air emission intensity[18] by Economic Activity

Source: Eurostat, author's calculations.

Note: Sectoral CO2 emissions are derived from air emissions accounts. They include emissions produced by the economic activities of resident units, regardless of whether they occur on national soil or not ("residence principle"). They do not include emissions caused by private consumption of households (use of private vehicles and home heating in particular).

Other academic works choose to further explore sectoral exposures to transition risk. In particular, Battiston and Monasterolo (Monasterolo, 2019) identify five sectors that are particularly exposed to transition risk, known as "climate policies relevant sectors" (CPRS): fossil fuels, energy production and distribution, energy-intensive sectors, transportation and housing. This classification is based on three distinct criteria:

- direct and indirect greenhouse gas emissions (Scopes 1, 2 and 3); the authors also note the difficulty of assessing this field exhaustively, as only Scope 1 is readily available to actors (see **Figure 3**); for example, the extractive industries are responsible for few direct emissions and indirect energy emissions, but contribute massively to the emissions of the rest of the economy;
- the place in the energy supply chain: in particular, sectors are distinguished according to whether they are suppliers of fossil fuels, suppliers of electricity or users of fossil fuels or electricity;
- the relevance for public policies of transition, linked for example to the risk of carbon leakage or to the historical presence of the State in certain sectors (e.g. energy, transport).

As discussed below, approaches that are even more refined are emerging, particularly in macroeconomic models dedicated to the energy transition, which refine, for example, the sectoral disaggregation with the exposure of each sector to international competition.

- Households

Households appear to be primarily exposed to transition risk related to the economic tools and price signals sent by fiscal policy (see Part 3.). According to ADEME, the carbon component of €44.6/tCO2 would have contributed €5.2 billion in tax revenues in 2018, or nearly 0.4% of the gross disposable income

[18] This indicator reports the level of direct emissions from each sector per unit of value added.

of French households (ADEME, 2019), divided between 0.23% for fuel consumption and 0.15% for heating buildings.

In this respect, an increase in taxation towards the targets defined by the scientific community to achieve carbon neutrality (~650€/tCO2 in 2050) poses a high risk to household solvency. In particular, energy taxation is regressive and its impact appears to be very heterogeneous among the different deciles of French households: it would weigh on average almost five times more as a proportion of income for the 10% of the poorest households than for the most affluent, while the level of emissions associated with the use of personal vehicles and housing would be three times higher for the latter. The place of residence appears to be a determining factor, as the supply of alternative transport to the car is less concentrated in the smallest urban areas (< 20 000 inhabitants).

In addition, households could be subject to a high risk of property revaluation when their properties are located in areas deemed to be at risk (e.g., the coastline): in addition to weighing on their assets and their financial solvency, these risks add a new credit risk on banks, when the properties are used as collateral for property loans.

- Sovereigns

Generally considered risk-free assets in financial portfolios, government bonds are also receiving increased attention in the face of climate risks. Some risk models explicitly consider them as exposed to default risk (Battiston & Monasterolo, 2019). The risk factors include the fundamentals usually considered in financial models, which would be affected in adverse scenarios: economic growth, inflation rate, interest rate, debt/GDP ratio, primary public balance, composition of the budget, evolution of the financial markets... They are also exposed to market risk, the price depending on the way actors choose to price future climate risks, on a day-to-day basis, with respect to future ambitions and announced climate policies. Some authors point out that, to date, bond prices do not reflect all the climate information available to investors.

(ii) Exposures to physical risks

Physical risks also point to heterogeneity at both the sectoral and geographic levels. The Intergovernmental Panel on Climate Change (IPCC) notes that warming trajectories exceeding 2°C by the end of the century would cause higher physical damages and that these would be highly heterogeneous across geographic areas and their ecosystems. The set of climate projections (RCP 2.6 to 8.5) highlights a heterogeneous materialization of risks through three main climatic and physical indicators: mean surface temperature, mean annual precipitation and sea level (see **Table 8**). Other initiatives exist, such as the University of Notre Dame Adaptation Index (ND-GAIN), which measures country-specific vulnerability as the "propensity or predisposition of human societies to be negatively impacted by climatic events" through specific exposure to climate change (Chen, et al., 2015) and through the specific exposure to 6 sectors: food, water, health, ecosystem services, housing and infrastructure. These indicators are then broken down into three components: the sector's level of exposure (direct damage from climate change), its sensitivity (indirect effects linked to damage suffered by other agents on which they depend) and its capacity to adapt (see **Figure 4**).

In addition to socio-economic impacts, which could affect economies at the aggregate level (health, labor productivity, international trade), the survey conducted by the French Treasury (2020) highlights four non-financial sectors that are dependent on climate and weather conditions: the agricultural sector, the energy sector, the infrastructure sector and tourism. The survey conducted by ADEME also highlights a variety of sectoral impacts for the French case alone (see **Table 6**and **Annex 4)**. Few indicators are yet available to assess, either qualitatively or quantitatively, exposure to physical risks, but the European Systemic Risk Board (2020) notes that the geographical location of activities could provide an initial overview of resilience. To date, these approaches are not easily replicable and remain at the initiative of individual sectors and actors[19].

[19] For example, the Carbon Disclosure Project (CDP) mainly analyzes physical risks in relation to water availability for the steel sector. For transition-related risks, it analyzes the alignment of carbon intensity trajectories in scope 1 and 2 as well as the transparency of climate data.

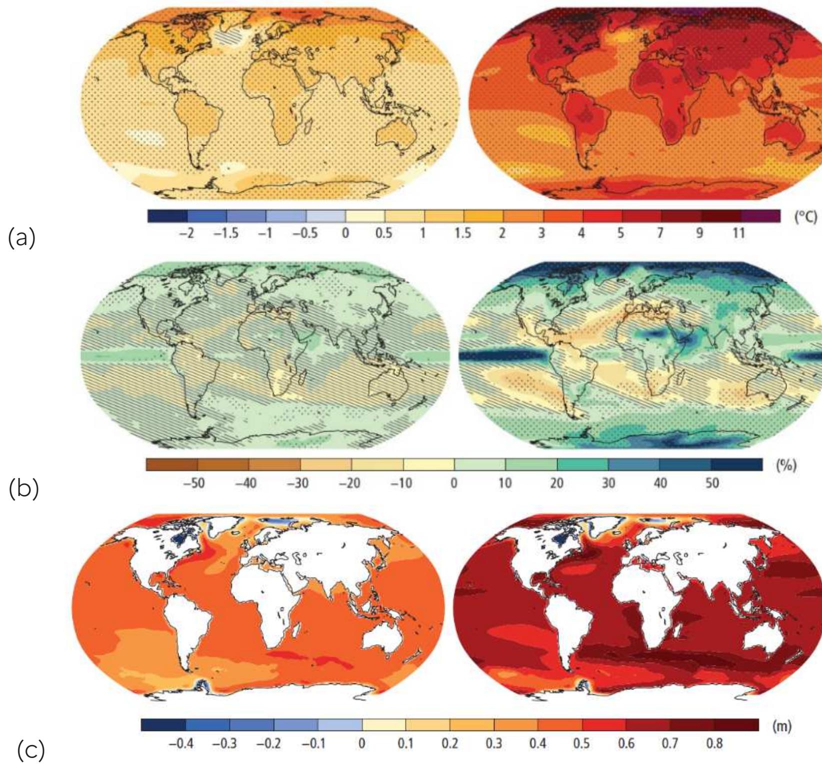

Table 8: Changes in mean surface temperature (a), mean annual precipitation (b) and mean sea level (c), RCP 2.6 (left) and RCP 8.5 (right) profiles

Source: IPCC (2014), Climate Change 2014: Synthesis Report.

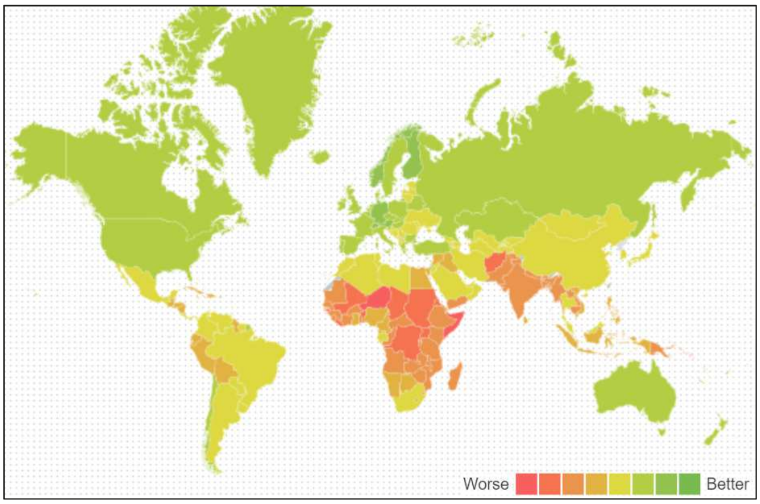

Figure 4: ND-GAIN Climate Change Vulnerability Index

Source: Notre Dame-Global Adaptation Index (ND-GAIN) Country Index.

2.5. Confronting climate risks with financial institutions' sectoral and geographic exposures

The sectoral composition of financial institutions' portfolios remains difficult to access and available only to supervisors and central banks, even though it was not originally collected with a climate perspective (e.g., the European Banking Authority's transparency exercise publishes a breakdown of credit risk by counterparty sector). To date, there is a lack of granular data and information on sectoral breakdown, which often requires preliminary statistical and accounting estimation. At the level of lending activities, the breakdown estimated by the ECB suggests a low exposure of financial institutions to the extractive (0.5%) and energy (5.1%) sectors, which are the largest contributors to direct emissions (see **Table 9** and **Figure 5)** but this could be largely impacted by supply chains and the indirect exposure of energy-intensive sectors.

The forthcoming implementation of a European taxonomy would help facilitate access to this information, notably by communicating the proportion of underlying investments that are aligned with its principles, expressed as a percentage of the investment, fund or portfolio[20]. The granularity could then be refined according to the actual activities financed by the instruments. Financial institutions note, however, that disclosure at such a level remains unfeasible and that the taxonomy principle is not applicable and scalable to all lending activities.

NACE Code	Economic activities	Total % (Q2 2020)
A	Agriculture, forestry and fishing	4,1
B	Mining and quarrying	0,5
C	Manufacturing	14,4
D-E	Electricity, gas, steam and air conditioning supply; water supply, sewerage, waste management and remediation activities	5,1
F	Construction	7,1
G	Wholesale and retail trade; repair of motor vehicles and motorcycles	12,6
H-J	Transportation and storage; information and communication	8,5
I	Accommodation and food service activities	3,6
L-M-N	Real estate activities; professional, scientific and technical activities; administrative and support service activities	37,7
P-Q-R-S-T-U	Other activities	6,5

Table 9: Sectoral breakdown of outstanding loans of monetary financial institutions (MFIs) to non-financial corporations, by economic activity

Source: European Central Bank.

At the European level, although the direct exposures of financial institutions to the fossil fuel sector are estimated to be quite limited (from 3 to 12% depending on the institution), the inclusion of all sectors dependent on the fossil fuel supply chain would reveal an exposure that is "very broad, heterogeneous, and potentially amplified by indirect exposures through financial counterparties." (Battiston, Mandel, Monasterolo, Schütze, & Visentin, 2016). The EBA estimates, based on a sample of exposures, that nearly 55% of banking exposures would be related to sectors exposed to transition risk (EBA, 2020).

Analysis of the credit risk data of the European banks monitored by the EBA reveals very heterogeneous exposures between players, in particular in certain sectors that are extremely exposed, such as manufacturing and construction (see **Table 10**). This observation seems to apply to the main French banks,

[20] The disclosure requirement applies only to certain products. For the others, the publication of this information is recommended ("*comply or explain*" principle).

where service activities are more exposed (see **Table 11**) and by opposition with sectors directly at risk, such as the extractive industries and the energy sector. Over a longer period, the ECB observes that banks' exposure to emissions has changed little, despite a trend showing industrial decarbonization, which suggests that the orientation of investments has not benefited green players (Despres & Hiebert, 2020).

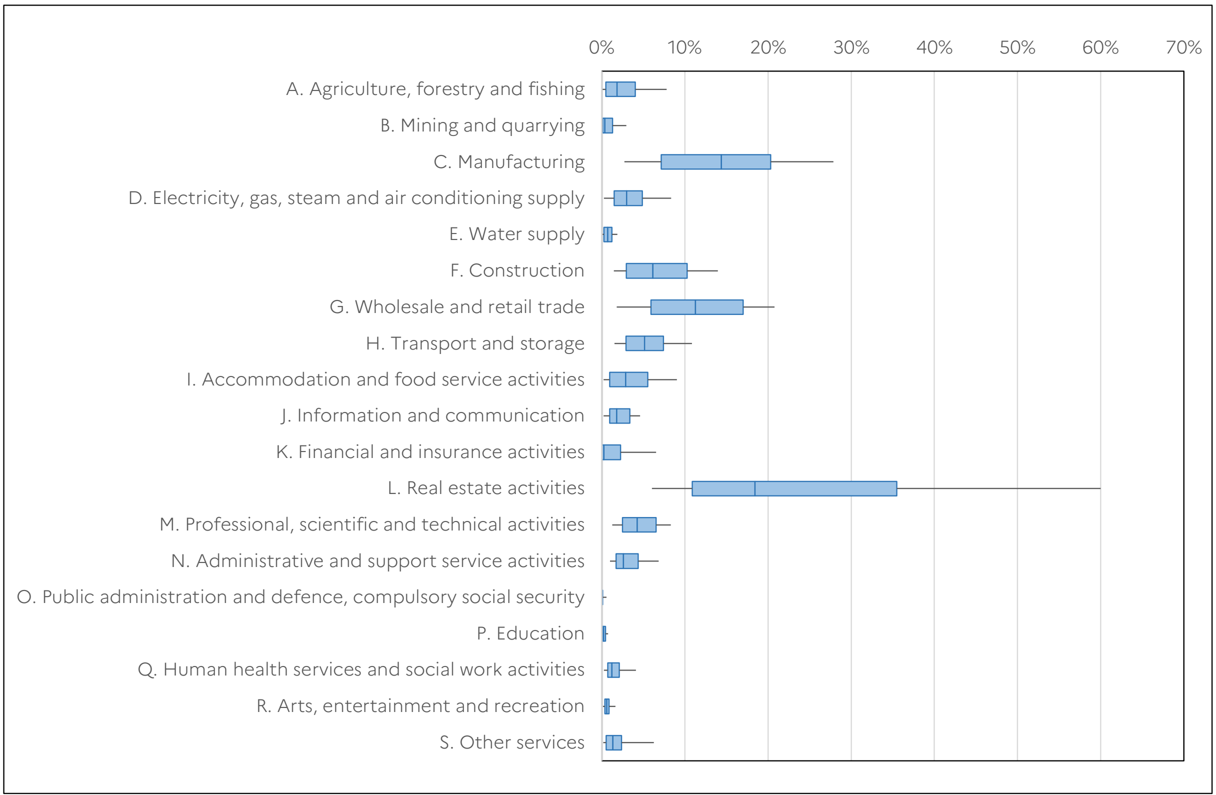

Table 10: Distribution of counterparty sectors for European banks' loans and advances to the non-financial sector (June 30, 2020)

Source: EBA EU-wide transparency exercise (autumn 2020), author's calculation.

Note: The three ends of the two rectangles represent, from left to right, the 1st quartile, the median and the 3rd quartile. The segments at the ends lead, on the left to the 1st decile, on the right to the 9th decile (extreme values are excluded).
The data represent 129 banks across 26 countries at the most aggregated level of consolidation in the EU (27) and the European Economic Area (EEA), as well as six institutions in the United Kingdom. Gross amounts are considered, excluding cumulative impairments and downward revaluations of non-performing loans at fair value.

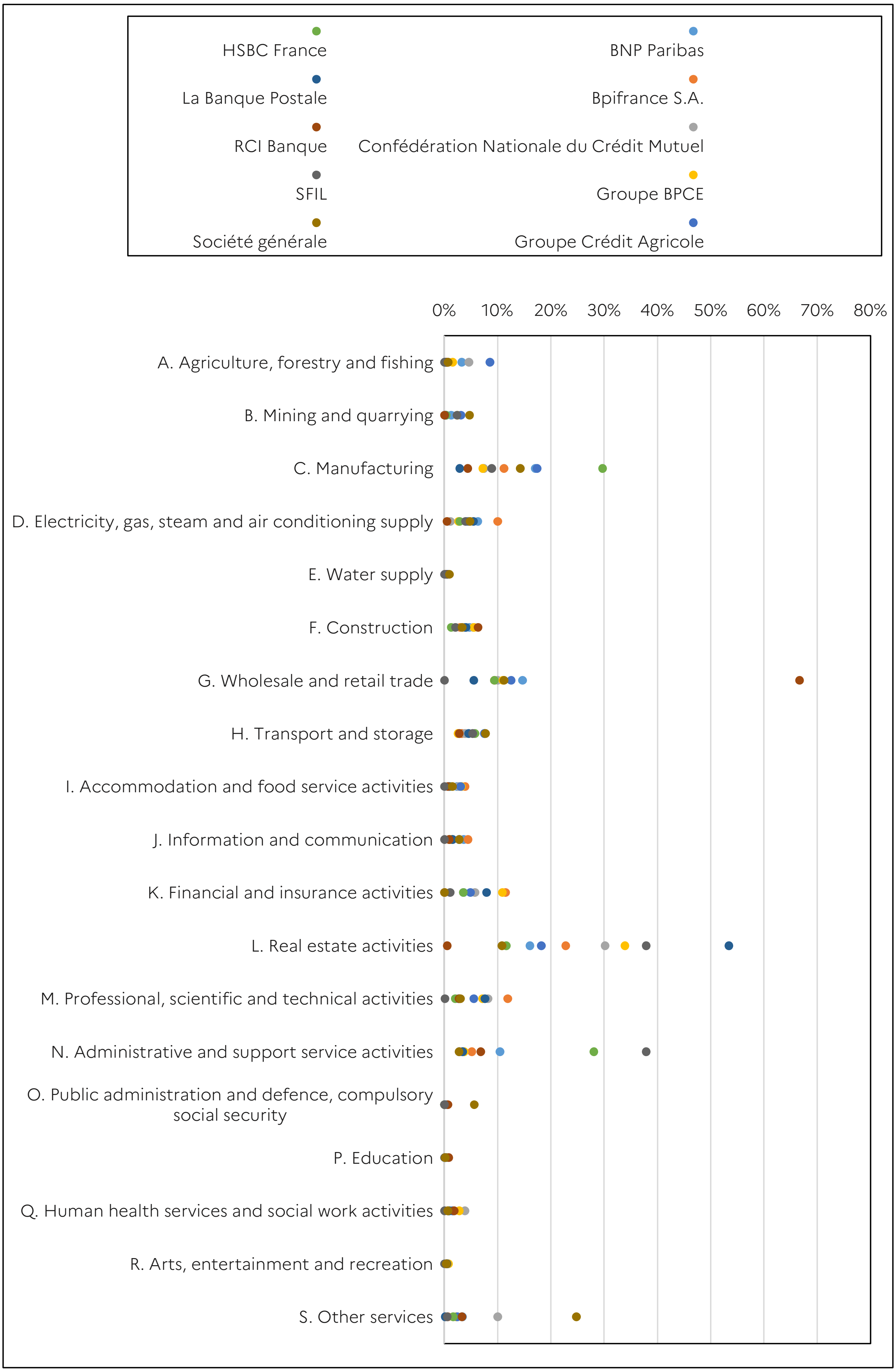

Table 11: Counterparty sectors of loans and advances of the main French banks to the non-financial sector, as of June 30, 2020

Source: EBA EU-wide transparency exercise (autumn 2020), author's calculation.

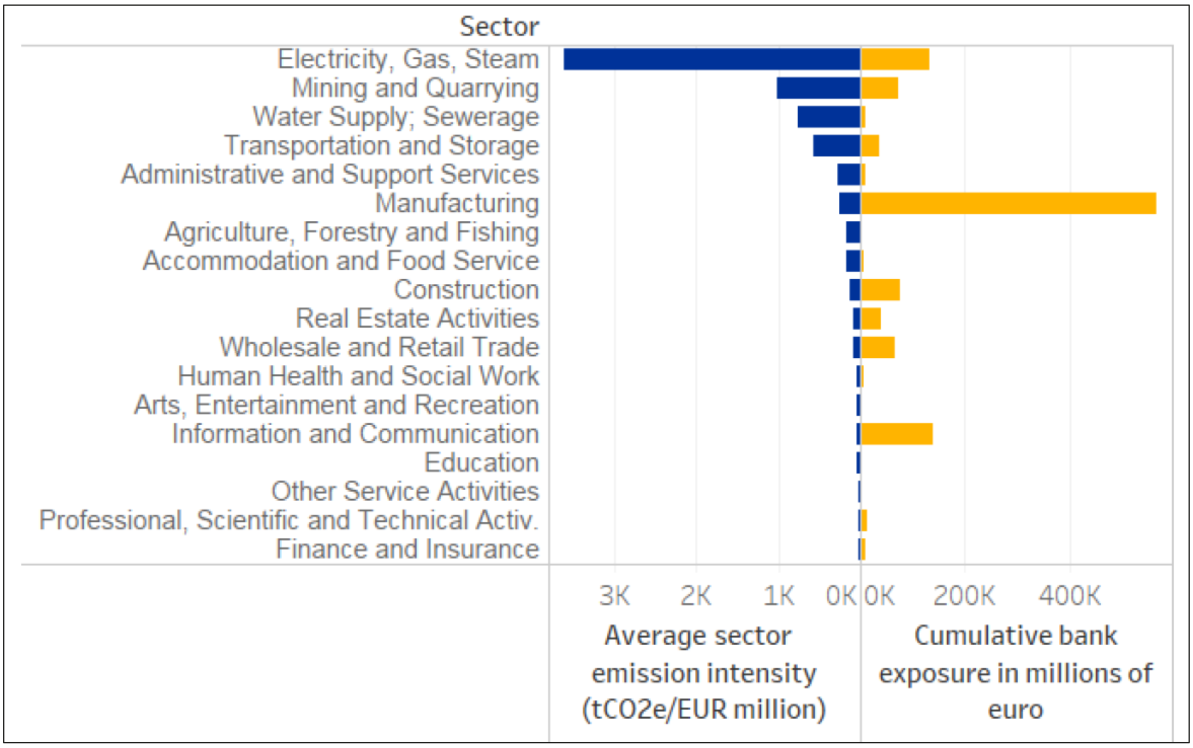

Figure 5: Cumulative CO2 air emissions intensity and bank exposures, by economic activity (2018).

Source: Despres, M. and Hiebert P. (2020), Positively green: Measuring climate change risks to financial stability.

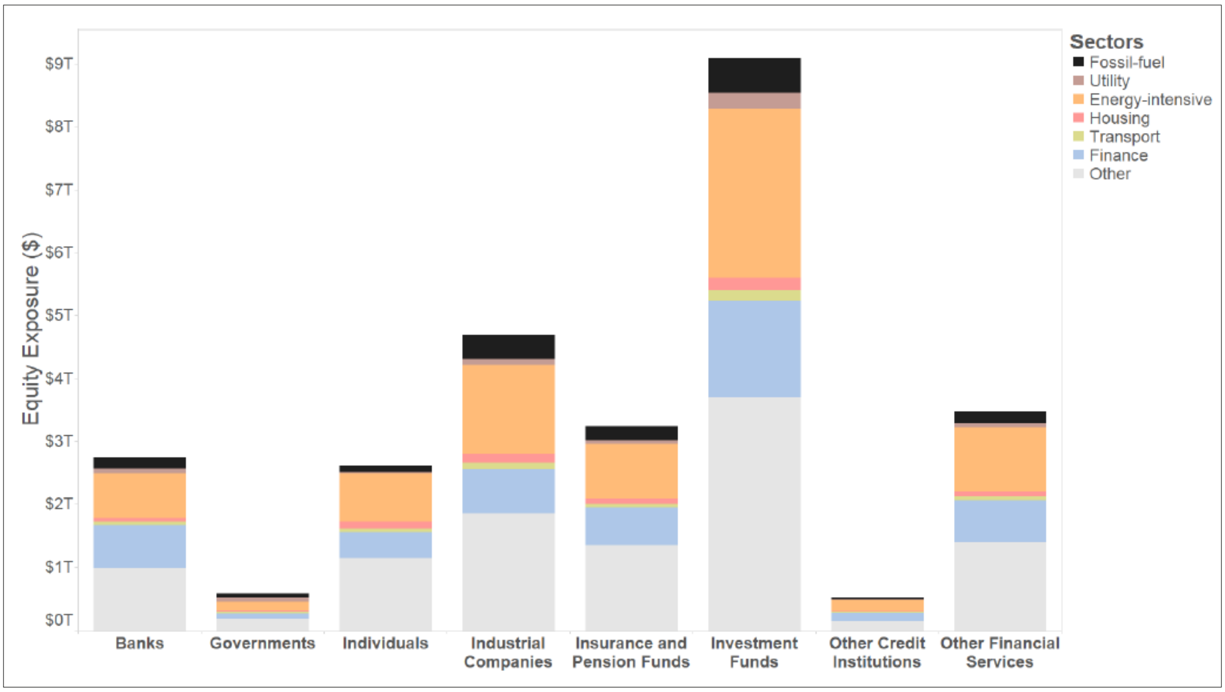

Figure 6: Sectoral breakdown of European financial institutions' equity holdings in listed companies (US/EU), by type of institution

Source: Battiston et al (2017), A climate stress-test of the financial system.

As far as physical risks are concerned, the exposures of French banks' portfolios are essentially concentrated in Europe, at 75.8%, including 52.9% in France[21] in 2018 (see **Figure 7**). For credit risk alone, large French banks are exposed at 60%[22] to French counterparties, although there is considerable heterogeneity and varying degrees of international exposure depending on the player. The ACPR notes that the majority of commitments are located in temperate zones and therefore appear to be "moderately exposed without being spared". However, such indicators are still limited in capturing all risks, especially acute, unpredictable risks that are still beyond the reach of physical impact projections.

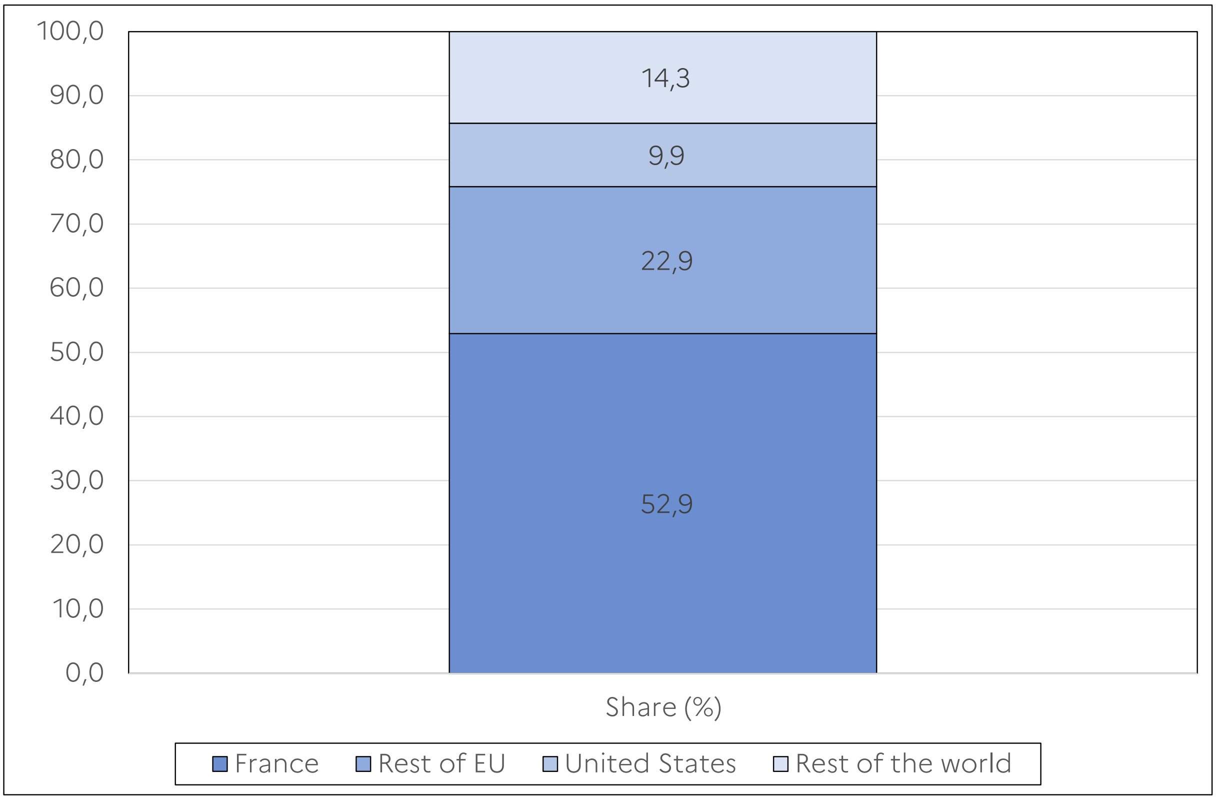

Figure 7: Breakdown of total gross commitments of the main French banking institutions by geographic area, as of June 30, 2018

Source: ACPR (2019), French banking groups facing climate risk.

Note: the banks analyzed in the ACPR sample are: BNP Paribas, BPCE, Crédit Agricole, Crédit Mutuel, HSBC France, La Banque Postale, Société Générale.

It should be noted that the distribution of risks between the banking and insurance sectors is not subject to any kind of consensus yet and seems to depend on the magnitude of the physical risks to which the portfolios are exposed. In its pilot exercise, the ACPR (2020) assumes that the physical risks are borne solely by the insurance sector; moreover, it asserts that "banks and insurance companies seem to have little exposure", due to their low exposure to areas deemed vulnerable and the existence of an effective system for taking natural disasters into account. For its part, the IMF Financial Sector Assessment Program (FSAP) for the Bahamas considers that natural disasters can affect the banking sector through household employment, particularly in the tourism sector, where disruptions in activity would lead to higher unemployment and losses on mortgages and consumer credit (IMF, 2019).

The European Insurance and Occupational Pensions Authority (EIOPA) identifies several factors affecting the distribution of physical risks between economic actors and causing a gap in insurance protection for climate risks (protection gap): overall, 35% of losses caused by extreme temperature waves and climatic

[21] Apart from the United States, the main exposure outside Europe is Japan.
[22] ADEME's estimates are based on the EBA's transparency exercise as of June 30, 2020, using the *original exposure* value valuation method.

events would currently be uncovered by insurance (EIOPA, 2019). The European countries would have very heterogeneous cover depending on the risks (see **Table 12**). Some countries have a public or private reinsurance system to fill this insurance gap[23]. The stress-testing exercises carried out tend to show most European physical risks would be borne by reinsurance (reinsurers and insurers involved in these activities), with more than half of the financial losses being transferred to these organizations[24].

	Protection gap	Earthquake	Flooding	Fire	Storm
Germany	1,6	1,6	2,6	1,0	1,1
Austria	2,0	1,8	3,4	2,6	0,0
Belgium	1,7	1,3	1,9	2,0	1,6
Bulgaria	2,0	3,2	1,7	2,0	1,2
Cyprus	1,9	2,5	1,0	3,0	1,0
Croatia	2,4	2,8	2,0	3,0	1,6
Denmark	0,0	0,0	0,0	0,0	0,0
Spain	0,9	0,0	0,0	2,0	1,4
Estonia	1,1	0,0	0,0	3,0	1,5
Finland	0,7	0,0	1,0	0,0	1,8
France	0,5	0,0	0,0	2,0	0,0
Greece	2,2	3,5	1,7	2,0	1,6
Hungary	1,3	1,3	1,9	1,0	1,1
Ireland	0,7	0,0	0,0	1,0	1,9
Iceland	1,0	1,0	1,0	n/a	1,0
Italy	2,4	3,5	1,7	2,0	2,5
Latvia	0,9	0,0	1,0	1,0	1,7
Lithuania	1,3	0,0	1,0	2,0	2,0
Luxembourg	1,6	1,3	2,0	2,0	1,1
Malta	2,3	2,8	1,7	3,0	1,6
Norway	0,0	0,0	0,0	0,0	0,0
Netherlands	1,9	2,0	4,0	0,0	1,6
Poland	1,6	2,0	1,0	1,0	2,3
Portugal	2,0	1,8	1,6	3,0	1,7
Czech Republic	1,9	1,8	2,0	2,0	1,6
Romania	1,7	3,1	1,6	1,0	1,2
Slovakia	2,4	1,9	3,0	3,0	1,6
Slovenia	1,5	2,4	1,3	1,0	1,2
Sweden	0,4	0,0	0,0	0,0	1,6
EU	1,0	1,0	1,0	1,6	1,0

Table 12: Insurance protection gaps in Europe

Source: EIOPA (2020), The pilot dashboard on insurance protection gap for natural catastrophes in a nutshel.

Note: A score of 0 corresponds to a non-existent protection gap, a score of 4 to a very high gap. It is calculated as an average between three scores: risk exposure, vulnerability and insurance coverage. According to EOIPA, a protection gap below 3 is not considered significant.

[23] For example, the Caisse Centrale de Réassurance in France.

[24] EIOPA indicates that the events simulated in these stress tests are not specifically the result of climate change. The exercises therefore do not model the consequences of such scenarios, but indicate the effects of an increase in the severity and intensity of natural catastrophes.

3. Definition of a climate stress-test scenario

3.1. A forward-looking vision of climate, society and economy by the IPCC

A stress-testing approach must be based on a prior analysis of the main risks to which institutions are exposed, well as on the identification of the channels through which risks are transmitted to the economy. These risks can be seen in the five major shared socio-economic trajectories of the IPCC, known as "SSPs"[25], and the comparison of scenarios, based on the "matrix" architecture (see **Appendix 1**).

Each SSP family is defined by the same socio-economic narrative and by the same set of quantitative data (GDP, population, urbanization rate). The shared socio-economic trajectories are based on a set of integrated assessment models (known as "IAM" models) developed by the scientific and academic community and translate the implications of these narratives in terms of energy, land use and, subsequently, the resulting greenhouse gas and air pollutant emission trajectories. Each SSP scenario is associated to a marker model, aimed at representing a reference trajectory for each scenario and guided by a concern for model consistency and their ability to adapt to specific narratives.

Several mitigation strategies are associated with each baseline scenario. The common policy assumptions, known as "SPAs"[26], reflect the effects of several policy scenarios (international cooperation agreements, regional agreements, land use sector coverage) through a set of measures affecting energy, industry or LULUCF[27] .

The matrix architecture then makes it possible to define different degrees of public action, the efforts to be made to achieve emission reductions and radiative forcing targets in line with the climate objectives (see **Figure 9**).

Scenario	Name	Mitigation/adaptation issues	Description
SSP1	Sustainability *Taking the Green Road*	Low	Strong international cooperation, giving priority to sustainable development
SSP2	Middle of the Road	Means	Continuation of historical trends
SSP3	Regional Rivalry *A Rocky Road*	Raised	Fragmented world affected by competition between countries, slow economic growth, policies oriented towards security and industrial production and little concern for the environment
SSP4	Inequality *A Road Divided*	Low/High	Great inequalities between and within countries
SSP5	Fossil-fueled Development *Taking the Highway*	High/Low	Traditional and rapid development of developing countries, based on high energy consumption and carbon-emitting technologies

Figure 8: Description of the SSP scenarios and their narrative

Source: Riahi et al. (2017), The Shared Socioeconomic Pathways and their energy, land use and greenhouse gas emissions implications: An overview.

[25] *Shared Socioeconomic Pathways.*
[26] *Shared Policy Assumptions.*
[27] Land use, land use change and forestry.

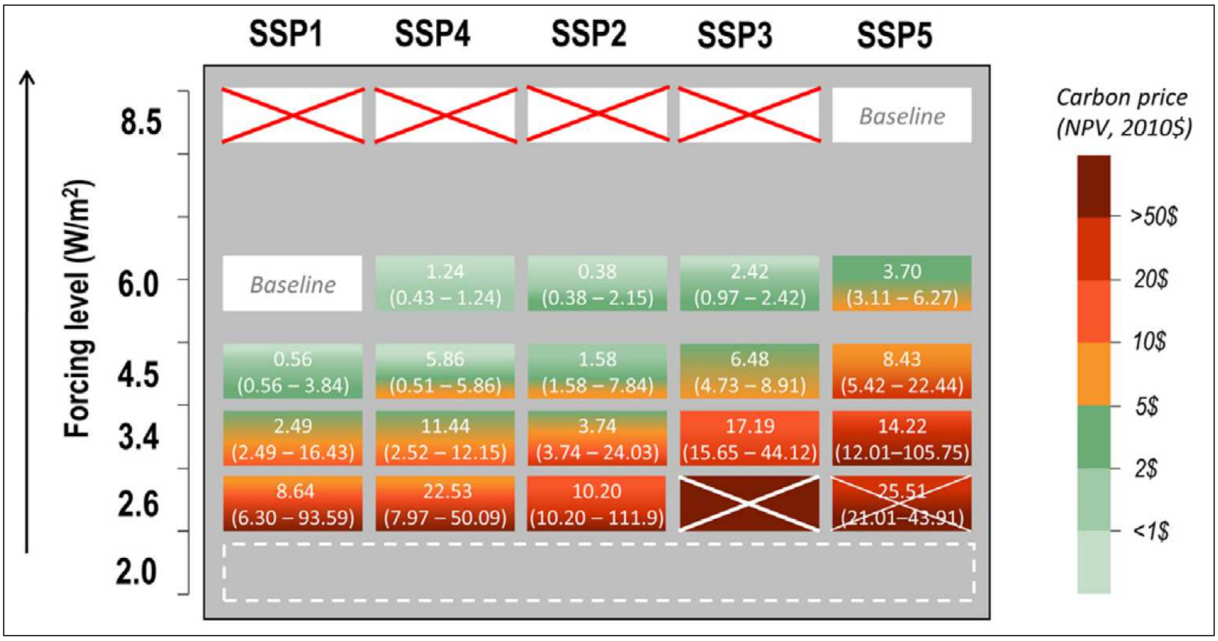

Figure 9: Attainability of radiative forcing targets (RFTs) among the SSP scenarios

Source: Riahi et al. (2017).

Note: white boxes indicate the position of the baseline scenarios; empty boxes represent an absence of achievability for all models (crosses, an absence for at least one); colors represent the average level of discounted carbon prices over the 2010-2100 period of the marker scenario (in constant 2010 euros), with the panel of values for all scenarios in parentheses The columns are ordered by increasing mitigation stakes: low stakes (SSP1/SSP4), intermediate stakes (SSP2), high stakes (SSP3/SSP5).

3.2. Narrative methods for developing climate scenarios

Several narrative methods can be applied to represent a climate scenario applicable to a stress test:

- In the prospective (or normative) approach, the trajectory is defined from a predefined target at a future date (for example, a temperature or emissions target); the trajectory is a declination of exogenous hypotheses allowing to reach this objective (e.g. IPCC scenarios of the international community, high level reference scenarios of the NGFS, "Sustainable Development" scenario of the IEA).
- The enumerative approach aims at precisely and exhaustively listing all existing or announced policy measures and their associated socio-economic impacts, through budgetary laws, multiannual programs or long-term strategies; in particular, such an approach requires a fine distinction between measures according to their credibility and the realism of their implementation (e.g., the IEA's "Stated Policies Scenario") and could, if necessary, be used as a baseline scenario.
- The historical approach aims to reproduce as closely as possible a past economic shock; however, economists lack hindsight on the effects of climate change that have already materialized, although some experiments can already be evaluated.
- The hypothetical approach aims at implementing one or several severe shocks, without any preconceived idea of their probability of occurrence.

These approaches differ according to the knowledge upstream of the scenario and on the determinant of the narrative (see **Table 13** and **Figure 10**)

		A priori knowledge of the scenario	
		Unknown scenario	Known scenario
Narrative determinant	from the risk factor	*Hypothetical*	*Enumerative*
	from a predefined target	*Prospective*	*Historical*

Table 13: Classes of narrative approaches according to their determinant and upstream knowledge of the scenario

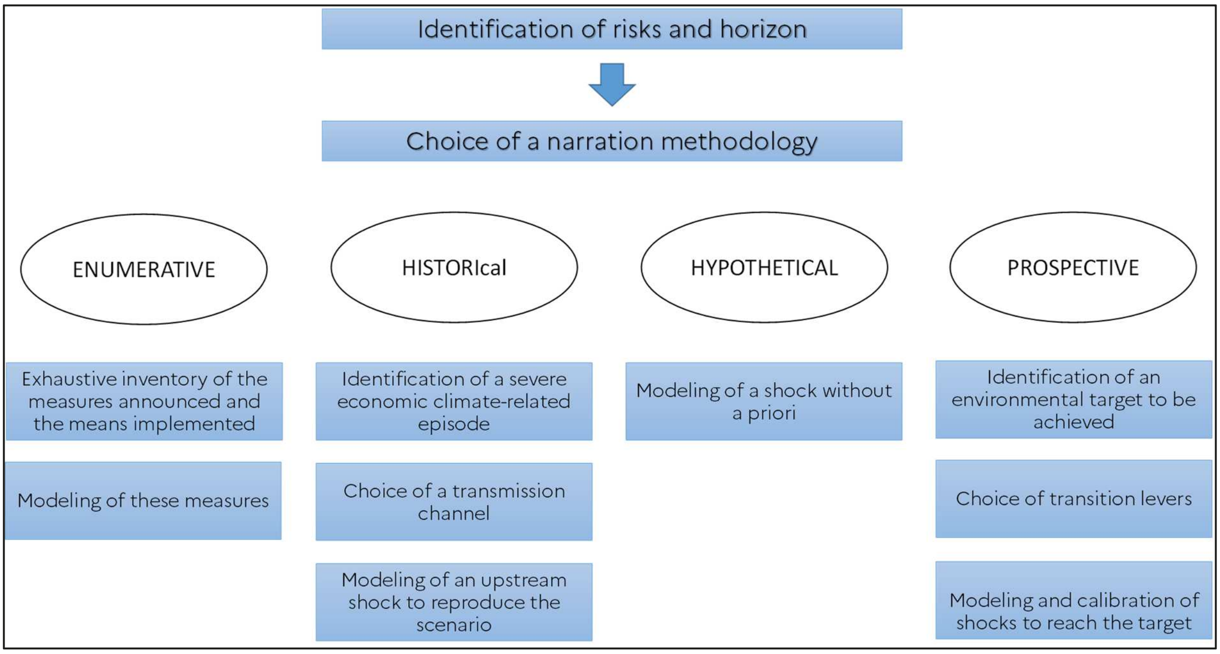

Figure 10: Declination of the narrative approach of a climate stress test

Source: author.

3.3. The climate scenarios of international institutions and their limitations

Scenarios are supposed to be based on narratives that clearly explain how the scenario incorporates all the risks to be assessed. In the case of a stress test, the scenarios must be "severe but plausible". This is why the use of past experiences, in particular economic and financial crises, is a fundamental contribution of stress tests, as it provides a realistic metric for future severe states of the economy, unlike more exploratory scenarios whose narrative may sometimes seem less realistic (see **Box 2**).

In the case of climate risks, the narratives are subject to additional modeling difficulties because of radical uncertainties and lack of historical information. The documentation of financial impacts does not cover all identified risks, despite the beginning of the materialization of physical risks (ACPR, 2019). The various scientific projections maintain a high degree of uncertainty about climate change: the extent and speed of global warming, the diversity and uncertainty of impacts on all physical and environmental parameters. According to surveys conducted by the French Treasury, climate change could, in the absence of a proactive policy to reduce emissions, reduce world GDP by between 4 and 30% by 2100 (Lancesseur, Labrousse, Valdenaire, & Nakaa, 2020). Finally, the economic effects of climate change are still subject to a high degree of uncertainty, particularly with regard to the transmission vectors of physical phenomena to socio-economic systems, as well as to the expected public actions of mitigation and adaptation to this change. This is why scenario analysis is by definition limited in the evaluation of these risks, insofar as the events are

Box 2: Declination of a solvency stress test scenario
The implementation of solvency stress tests[28] can be analyzed from several perspectives:

(i) Type of analysis

The term "stress testing" encompasses a broad spectrum of modeling techniques, classified into two types of programs. **Sensitivity testing** is the basic level of a stress-testing program and includes processes that aim to determine the impact of a single risk factor on the institution and its portfolio (or a given asset). They are often not directly related to a global economic or financial context[29]. They require few resources, are simple to implement, and can quickly identify the main risks in a portfolio[30]. **Scenario analyses** assess the impact of a set of risk factors on a financial portfolio and describe a dynamic and prospective state of the rest of the economy. They represent the evolution of one or more simultaneous parameters, including potential spillover effects from the economy's feedback loops, and over longer time horizons (from a few months to two years).

(ii) The narrative of the scenario

The events simulated during the exercise are most often based on **historical scenarios**, which reproduce past economic or financial crises. They present a realistic framework and incorporate both the probability of occurrence of the shock, its magnitude and the overall consistency between the evolution of the different variables at stake, although the expected shocks may be inadequate and underestimate the actual risk to come. In contrast, **hypothetical scenarios** seek to explore potential future states of the economy. They are more flexible and can explore new risks and shocks, especially with respect to vulnerabilities identified by financial institutions. Scenarios that are too extreme or too innovative, however, may be perceived as implausible by institutions (BIS, 2009).

(iii) Statistical modeling

Deterministic scenarios are defined *a priori* and without taking into account their probability of occurrence. They often include *at least* two scenarios: a central scenario ("*business as usual*" or "*best estimate*") and a *downturn scenario* representing the economic or financial shock. The stress-test then aims to measure the impact of a "severe but plausible" event. These scenarios are easier to implement than **stochastic scenarios** that are randomly generated to produce a probabilistic distribution for one or more key variables. This approach requires advanced modeling capabilities and is rather limited to internal risk assessments by institutions (Ionescu & Yermo, 2014).

(iv) The objective of the exercise

Microprudential exercises are supervisory exercises aimed at ensuring the financial resilience of individual institutions. **Macroprudential exercises** are conducted within an overall supervisory framework and aim to ensure the stability of the financial system as a whole and prevent systemic risk[31]. This approach differs in two important respects: the so-called "constant balance sheet" assumption can be relaxed and allows the banking sector in the model to adjust its balance sheet to the economic environment; and it assesses contagion effects[32] in the financial sector and feedback between the financial sector and the real economy ("second-round" effects), for example, using macroeconomic models developed with a financial block.

(v) The level of granularity

In **"top-down" approaches**, the exposures of financial institutions are aggregated into homogeneous sets and the supervisor assesses the impact of adverse scenarios without the direct participation of the institutions. On the contrary, **"bottom-up" approaches** consider exposures in a fine-grained way and the exercises are carried out by the institutions based on of their internal models and granular data, under the supervision of the supervisor and the implementation of its scenarios.

[28] Specific liquidity stress tests are also carried out and focus on banks' liabilities.
[29] For example, the instantaneous drop in an interest rate, not linked to a specific narrative.
[30] Sensitivity testing is most appropriate when the fluctuations of a portfolio depend on a single market parameter.
[31] Systemic risks are risks of threats to financial stability that impair the functioning of a large part of the financial system and have significant negative effects on the economy in general.
[32] Contagion effects are direct (cross-exposures between institutions) or indirect (correlated exposures).

unpredictable with respect to the past and can have an extreme magnitude[33], and would necessarily be prospective. Moreover, climate risks are endogenous, insofar as the materialization of the risk depends on the perception and reaction of economic agents, and must therefore involve a large number of scenarios.

To limit the uncertainty of the effects of climate change, supervisors can rely on the long-term scenarios carried out by the various international institutions offering a relevant framing for a risk assessment exercise. Developed by the global academic community, the IPCC's **Shared Socioeconomic Pathways** describe a set of global and regional economic trajectories, their articulation with concentration and temperature trajectories and thus the issues associated with mitigation and adaptation policies (Riahi, et al., 2017). The **WEO** (World Energy Outlook) and **ETP** (Energy Technology Perspective) scenarios, produced by the International Energy Agency, describe long-term energy projections, based on a systematic review of current and future policies affecting energy markets (IEA, 2020). These two families of long-term scenarios, which are used as a reference by various actors at the international level, have the advantage of integrating both projections with little mitigation action (e.g. IEA Stated Policies Scenario) and projections with strong mitigation action associated with targets set by international commitments (e.g. IEA Sustainable Development Scenario). Such an approach makes it possible to define the contours of a reference scenario and to evaluate the relative effects of one or more severe shocks in the transition from one scenario to another, which are necessary elements for the implementation of a stress test. In addition to these international prospective visions, there are also programs or plans, carried out at the national or local level, which aim to translate commitments on emissions into coherent macroeconomic projections. In France, the **National Low-Carbon Strategy** (Ministère de la Transition Ecologique et Solidaire, 2020) translates the national objectives in terms of greenhouse gas emission reductions to achieve carbon neutrality by 2050, the remaining carbon budgets for the major economic sectors and the macroeconomic trajectory underlying these ambitions.

In particular, a specific range of scenarios has been developed for the purpose of framing climate stress tests: the **NGFS high-level reference scenarios** (cf. **Box 3** and **Appendix 1**) aim at translating in socio-economic terms several economic trajectories according to (i) the implementation of the transition (ordered or disordered) (ii) the achievement or non-achievement of several climate targets in 2050 (compliance with 1.5°C, compliance with 2°C, non-achievement of the target) and (iii) the maturity of carbon capture and sequestration technologies. These scenarios include integrated and cross-case modeling of transition risks and chronic physical risks[34], notably based on macroeconomic models and general circulation models used by the IPCC. In particular, the economic projections are based on the central trajectory of the shared socio-economic trajectories, known as the SSP2 "middle-of-the-road" trajectory, which guarantees their consistency and comparability with the IPCC work.

All of these scenarios are therefore of interest in the application of a climate stress test insofar as they propose a set of coherent and realistic economic trajectories for a financial institution. As an example, the PACTA for Banks methodology makes it possible, based on the various IEA projections, to link the financial exposures of banks to the real economy, to evaluate and compare the alignment of portfolios with the objectives of the Paris Agreement between these scenarios (2DII, 2020). Used as they are, however, they seem insufficient to carry out a microprudential stress-testing exercise, notably because of the specificity of climate risks, and reveal several methodological limitations:

- In terms of coherence, most of these scenarios are prospective and conditional on the achievement of a climate objective; they may be unrealistic, as they do not take into account all of the concrete measures and effective means, particularly financial means, to implement this political ambition; For example, ADEME notes that the trajectory of the SNBC 2 includes "fictitious prices that are not backed by any public policy measure (...) in order to achieve the energy consumption targets of the SNBC 2, in particular to compensate for the freezing of the carbon tax [in 2019]; this approach represents an approximation that may lead to an optimistic estimate of the economic effects of the transition" (ADEME - G. Callonnec, H. Gouëdard, P. Jolivet, 2020).

[33] Climate risks can be described as "green swans", in contrast to the black swans theorized by the statistician Nassim Nicholas Taleb (Bolton, Després, Pereira da Silva, Samama, & Svartzman, 2020).
[34] Only chronic risks were estimated in Phase I. Extreme events are assumed to be included in Phase II.

- In terms of severity, most of the models and tools chosen to achieve such objectives are defined for planning purposes and for finding an optimal economic, political and social trajectory to achieve a set of objectives defined upstream by economists. They are essentially centered on public policy scenarios, viewed as the most economically optimal way to achieve the transition. Designed to be optimal both sectorally and geographically, they define a scenario that is useful for policy dialogue but not very realistic for steering and even less so for risk measurement. For example, the SSP scenarios consider the GDP trajectory as a driver of the scenarios (see for example the documentation of the REMIND model[35]), which does not allow for an accurate assessment of the macroeconomic cost of a mitigation action.

- In terms of scope, the projections are currently difficult to apply to stress-testing exercises (lack of financial variables in particular) and to climate exercises (rather crude modeling of economic sectors, although certain sectors such as energy or agriculture can be finely represented). At the level of geographical granularity, they are also too concentrated to be used in a stress test conducted at the national level (see **Table 2**) for the assessment of physical and transitional risks in specific countries.

Models	Africa	America	Asia	Europe	Oceania
GCAM – 32 regions	North Africa, South Africa, West Africa, East Africa	Central America and Caribbean, Latin America (South), Latin America (North), Argentina, Brazil, Canada, Colombia, Mexico, United States	Central Asia, South Asia, South East Asia, China, India, Indonesia, Japan, Middle East, Pakistan, Russia, South Korea, Taiwan	EU12, EU15, Europe outside the EU, Europe outside Schengen, Western Europe, Eastern Europe	Australia and New Zealand
GLOBIOM MESSAGE - 11 regions	Africa	Latin America, North America	Southeast Asia, China, India, MEA, former USSR	Western Europe, Central and Western Europe	OECD Pacific
REMIND MAgPIE – 11 regions	Sub-Saharan Africa	Latin America, USA	Brazil, China, India, Japan, MEA, Middle East, Russia, Other Asia	European Union	

Table 14: Geographic granularity of three IPCC integrated assessment models

Source: GCAM, MESSAGE GLOBIOM, REMIND technical documentation.

Note: these three models contributed to the development of the IPCC shared socio-economic trajectories and were retained for the synthesis of the NGFS high-level reference scenarios.

[35] To reproduce the narrative of the SSP scenario, GDP was calibrated by an iterative procedure of productivity gains: "To calibrate GDP, which is an endogenous result of the growth engine in REMIND, we calibrate labor productivity parameters in an iterative procedure so as to reproduce the OECD's GDP reference scenarios. » (Luderer, et al., 2015).

Box 3: NGFS analytical framework and high-level reference scenarios

In order to share best practices and help identify, measure and mitigate climate-related financial risks, in 2020, the Network for Greening the Financial System (NGFS) proposed a first scenario-based analytical framework for supervisors and central banks. This guide is intended to be a first tool to support the consideration of climate change through the various missions of its members (microprudential and macroprudential policy, macroeconomic forecasting, monetary policy, economic research...). In particular, this analytical framework distinguishes four families of scenarios according to the extent of public action taken (objectives achieved or not) and the degree of uncertainty about the transition (ordered or disordered), see **Figure 11**.

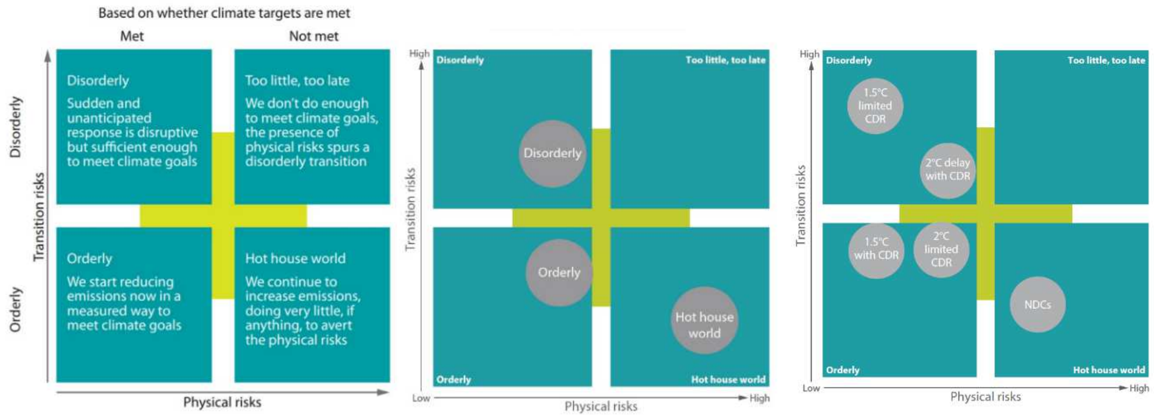

Figure 11: NGFS matrix and articulation between representative and alternative scenarios

Source: NGFS (2020), NGFS Climate Scenarios for central banks and supervisors.

A first set of quantitative scenarios has been proposed to cover the whole analytical framework and to project a wide range of potential risks, using socio-economic assumptions aligned with the IPCC's SSP2 "middle-of-the-road" scenario (GDP, population, urbanization, but also technological progress, international cooperation and resource use). They differ, according to the four axes of the matrix but also according to the achievement of more ambitious climate targets and the degree of development of carbon capture and sequestration technologies. In their current phase of development, these scenarios include the economic impact of chronic risks but not those of acute risks.

As they stand, such scenarios are difficult to apply to stress testing exercises (notably because of the absence of macro-financial assumptions and a lack of geographic and sectoral granularity), but they can serve as a relevant anchor for the development of new, more refined scenarios. For example, in the three scenarios of the French pilot exercise, ACPR retains the carbon price trajectory as a climate action lever, and aligns productivity gains to replicate the growth assumptions of the high-level baseline scenarios from the NiGEM macroeconometric model (see Allen et al., 2020). Similarly, the Bank of England's biennial exercise (BES) represents three exploratory scenarios incorporating both the economic consequences of climate change and the ecological transition, based on the NGFS framework (Bank of England, 2019).

The development of such a systematic approach to climate scenarios can provide a global view of climate-related financial risks, offer a sufficiently wide range of possible futures, and allow actors to target the risks they wish to explore, depending on the conditions of the exercise.

3.4. How to develop stress-test scenarios on transition risk?

To develop long-term scenarios, several options can be declined, at the discretion of the supervisors, through the various detailed policy levers (e.g., carbon price) and transition characteristics. The NGFS identifies two drivers for these scenarios:

- The materialization of the transition, either orderly (gradual, anticipated, continuous and efficient) or disorderly (sudden, unanticipated, unpredictable and discontinuous); this transition may also differ according to technological advances, the degree of global coordination and resource use;
- The materialization of physical risks, depending on the extent of mitigation measures implemented to reduce GHGs, which determines whether or not climate objectives will be met.

These scenarios can then be compared to a single baseline scenario. According to the Bank for International Settlements, a baseline scenario for a stress test defines a set of financial and economic conditions consistent with economic and financial projections, without incorporating a specific stress. In practice, these projections are based on (and extended if necessary) the main existing macroeconomic forecasts (central banks, statistical and economic institutes, economic ministries, consensus forecasts, etc.). When the supervisor is in charge of conducting the stress-testing exercise, it may rely on or extend macroeconomic forecasts made by national or community institutions, generally over a horizon of one to three years[36]. At relatively short time horizons, these forecasting exercises are generally the subject of a consensus between the various public and private institutes in charge of this exercise.

In the case of long-term climate scenarios, the choice of the reference scenario is much more complex, given the radical uncertainty surrounding the climate future and the lack of consensus among markets and institutions. This is why the prospective exercises carried out by international institutions, rather than talking about forecasts, prefer to talk about projections reflecting a wide range of possibilities. Moreover, it appears that any central scenario, depending on the modeling and the time horizon selected, may ultimately prove to be more adverse than the adverse scenarios selected. In light of the supervisors' initial exploratory exercises and the variety of options tested, it appears first of all that this choice depends on the objective sought, and in particular whether the supervisor is carrying out a forward-looking exercise or a specific risk assessment exercise (see **Table 15**).

<u>If the research objective is prospective</u>
In this case, the explicit definition of a reference scenario appears to be a weak element of the exercise.

First of all, it appears that the definition of a central scenario is of limited use in conducting a climate stress test, particularly in the absence of regulatory capital requirements[37]. For example, the Bank of England (2020) does not explicitly define a baseline. The exercise consists of projecting losses under all scenarios and comparing a range of possibilities, without necessarily measuring the effects of the materialization of a specific risk. This forward-looking approach also makes sense because it is based on consistent physical and transition risk scenarios.

The baseline scenario could be based on the long-term socio-economic trajectories produced by community or national agencies. These scenarios outline several possible hypothetical futures for the world economy. However, there is no one scenario that the scientific or academic community considers more likely than another. Such an approach could be based on the assumptions of the Nationally Determined Contributions (NDCs), the IEA's Stated Policies Scenario or the IPCC's SSP2 middle of the road scenario, in which the economic, social and technological trajectory follows observed historical trends, or the transition scenarios prepared at the national level.

[36] In the 2016 EBA stress test, the central scenario follows the European Commission's macroeconomic forecasts (2016-2018)
[37] In the case of a traditional stress test, a bank is assumed to have made provisions for the current fiscal year for the losses expected in the absence of stress.

If the objective is the evaluation of a risk

In this case, the reference scenario would essentially serve to evaluate the relative deviation of an adverse scenario and thus capture the specific effect of the materialization of a risk. This choice depends on the objectives of the supervisors in the exercise and on the theoretical representation of the most likely future; the associated risks, however, depend strongly on the models used and the prospective choices of the modelers. One of the difficulties is then, in ensuring the realism of the scenarios, to model trajectories that will appear adverse in relation to the counterfactual, which will depend on the choice of modeling tools. Several options appear from the first exercises carried out:

(i) Central scenario of no risk

In order to specifically assess the hidden and unknown risks, a central scenario could reflect the absence of both physical and transition risks, which would correspond to a total "*status quos*" scenario. Such an option would allow a simple simulation of an adverse scenario (by a transition shock or a physical shock), but would appear to be unrealistic, because of the necessary interdependence between physical and transition risks: a lack of mitigation policy would result in very large physical damages. Moreover, even in the presence of a proactive public policy, all IPCC projections predict physical damage, which limits the methodological developments of such an approach. However, it would appear to be relevant for very short-term scenarios, where chronic physical risks do not change significantly, such as the IMF scenario for Norway (2020).

(ii) Central scenario with unchanged policy, integrating the concrete actions announced

A status quo scenario could also be interpreted as an unchanged policy scenario, although market expectations tend to point to an increase in the burden of public action (even if insufficient). In the field of policy evaluation, the traditional way of assessing the effect of an external shock is to refer to a no policy change counterfactual, which would translate here into a limited mitigation policy and a high physical risk. However, such an approach would not allow for a proper assessment of the physical impacts, as the scenario would have the most disastrous climate consequences; it could then be considered as a potential adverse scenario.

For example, the Bank of Canada (2020) defines a central BAU scenario including no climate action (assuming a freeze in the price of carbon over the entire stress horizon), associated with a drastic increase in the level of emissions and average temperature. It is based in the short term on IMF projections (World Economic Outlook), and in the medium and long term on World Bank and United Nations projections (although these projections do not include the economic damage of climate change).

(iii) Central scenario of successful orderly Transition

To specifically target the materialization of transition risk, the central scenario could represent an orderly transition path, defined here as an economically optimal path to meet climate targets.

The four-family matrix defined by the NGFS allows, for example, comparison of scenarios that include risks of disordered transition (versus ordered transition) and physical risk (depending on whether climate targets are met). The ACPR pilot exercise is based on a central scenario of orderly transition (consistent with the NGFS); this is a relevant counterfactual to highlight the risk of disordered transition because, in this context, orderly transition corresponds to the least adverse scenario (Allen, et al., 2020).

3.5. How to develop stress-test scenarios on physical risk?

As explained above, it may be appropriate, for the sake of readability, to clearly separate transition and physical climate stress tests, in order to be able to assess the level of exposure for each of the institutions evaluated. To date, most of the exploratory exercises (DNB, Bank of Canada) have focused on transition risk; only the Banque de France has proposed a single central physical risk scenario. Such an exercise aims at measuring the direct impact of the most adverse path underlying the RCP 8.5 scenario (without a counterfactual scenario). This scenario remains consistent with the SSP2 "*middle of the road*" scenario family.

(i) Representing the physical risk over a time horizon comparable to that of the transition risk (1 to 30 years)

The projection of such a scenario could be more akin to an exercise in measuring the macroeconomic impacts of climate change (the central scenario being a no-risk scenario, although this would be unrealistic). This choice, made by the Banque de France (2020), is all the more credible as it materializes on time horizons that can be assimilated by institutions and limit the uncertainty on the materialization of physical risks, as the temperature increase trajectories are relatively close in all IPCC scenarios at this horizon (climate inertia phenomenon, see for example **Figure 18** in the appendix). As such, financial institutions will be able to assess their resilience and direct vulnerabilities to the consequences of climate change.

(ii) Representing physical risk in the longer term (20 to 80 years)

This choice is in line with the standards of a stress test and the time horizon. It is at this horizon that global warming adopts different trajectories and becomes even more dependent on the mitigation policies implemented in this interval, and that there is a potential and severe risk to assess. Yet, the horizon of materialization is relatively distinct from that of transition risks and could be the occasion to carry out stress tests integrating both physical risks and transition risks and their inversely correlated evolutions. That is precisely what the Bank of England did during its exercise on life and non-life insurance (Bank of England, 2019) or during its biennial exercise (2021). In addition to being difficult to articulate with the short-term horizons of institutions, a physical scenario over a very long period would combine a multitude of uncertainties that would make the exploitation of its results extremely limited, because of:

- the uncertainty related to the mitigation actions implemented to achieve carbon neutrality,
- climate sensitivity, which represents the temperature increase linked to the evolution of concentrations in the atmosphere;
- physical impacts, consequences of temperature increase and climate variations;
- a very strong model risk, especially on the last two uncertainties mentioned.

In any case, the physical risks in such long-term scenarios have so far been modeled essentially as trends; they do not include the occurrence of large and unanticipated shocks, which are mainly restricted to short-term exercises.

Supervisors are most often accustomed to this type of short-term exercise, particularly in the non-life insurance sector (Bank of England, 2019). The IMF also reproduces macroeconomic scenarios of natural disasters during its Financial Sector Assessment Program in exposed regions: Samoa (2015), Jamaica (2018) or Bahamas (2019). Such exercises, often calibrated from historical data, are for the time being conducted in a different framework than climate change, and do not specifically assess climate change-related financial risks. Their narrative method could nevertheless serve as a basis for future short-term exercises to simulate the effect of the occurrence of acute physical risks (see **Table 16**).

	Baseline	Adverse scenario(s)	Narrative method	Horizon
		Transition risks alone		
Netherlands (2018)	BAU	Increase in carbon prices Increase in the renewable mix Double increase (price and mix) Shock in household confidence	Hypothetical	5 years
Canada (2020)	BAU	*National Determined Contributions* Orderly transition Disorderly transition	Enumerative (NDC) Prospective	2050
France (2020)	Orderly transition	Delayed disorderly transition Sudden and accelerated disorderly transition	Prospective	2050
IMF - Norway (2020)	BAU	Oil price shock	Hypothetical	3 years
		Physical risks alone		
France (2020)	RCP Scenario 8.5		Enumerative	2050
		Scenarios combining physical and transition risks		
England (2019) - Life and non-life insurance	Sudden disorderly transition (temperature rise less than 2°C) Orderly transition (temperature rise much less than 2°C) No transition (temperature rise more than 4°C)		Prospective	20222050 2100
England (2021)	*Business as usual* (2°C target exceeded) Orderly transition (2°C target met) Disorderly transition (2°C target met)		Prospective	2050

Table 15: Narratives and scenarios from the first supervisors' climate change exercises

Source: Publications of central banks and supervisors (see bibliographic references).

	Central scenario	Adverse scenario(s)	Narrative method	Horizon
IMF - Samoa (2015)	WEO (October 2014)	Class 4 cyclone (similar to Cyclone Evan in 2012) Two class 4 cyclones and recessions in Australia and New Zealand	Historical Hypothetical	4 years (2015-2018)
IMF - Jamaica (2018)	WEO (October 2017)	Major hurricane (similar to Hurricane Gilbert in 1988)	Historical	5 years (2018-2022)
IMF - Bahamas (2019)	WEO (October 2018)	Major hurricane Perfect storm scenario (major hurricane and US recession)	Historical	3 years (2019-2021)
England (2019) - Non-life insurance	Historical average of insurance liabilities	Three hurricanes (USA) Earthquake and aftershock (California) Earthquake and Tsunami (Japan) Storm and flood (UK)	Historical Historical Hypothetical	5 years (2019-2023)

Table 16: Examples of natural disaster narratives and stress-test scenarios

Source: Publications of central banks and supervisors (see bibliographic references).

4. Macroeconomic modeling of a climate stress test

4.1. Contribution of a macroeconomic model

Macroeconomic models can be used to simulate the economic effects of a climate trajectory, under various assumptions (demographic, technological...) at different geographical and sectoral levels. These models have several characteristics that make them particularly suitable for scenario analysis, both in the context of studying the impact of specific public actions (De Williencourt & Jacquetin, 2019) and for risk analysis for financial institutions (Appeddu, Suarez-Lledo, Licari, & Juan, 2012) :

- They present a dynamic framework, making it possible to evaluate short, medium and long-term impacts as well as the time and cost of adjustment required for the transition of the economy.
- They are based on a coherent accounting framework (input-output representation) that provides a clear and legible view of the economic situation and ensures the coherence of the evolution of the variables of interest.
- Most of the variables are interdependent, which makes it possible to take into account feedback loops. Supply influences demand which in turn determines supply. This makes it possible, for the analysis of the energy transition, to model the rebound effects linked to a variation in energy prices, or within the framework of the analysis of market risks, to model in a rigorous way the cross-correlations between assets.

On the contrary, some prospective work has been based on partial equilibrium analyses based on cost and price projections by sector following the implementation of a carbon tax (BNP Paribas, 2016) in order to estimate loss projections. These approaches present the advantage of being able to integrate the market power of the sectors, by estimating the carbon pass-through[38], but they do not integrate the various economic adjustment mechanisms (decrease in purchasing power and competitiveness, upward wage pressure, changes in production) and the dynamic effects of the transition.

4.2. Classes of relevant models

Several families of models can be used to simulate the economic effects of climate scenarios[39]. However, they require the integration of at least three dimensions closely linked to such an exercise:

- A temporal and dynamic dimension, linked both to the commitments of nations to achieve climate objectives within the framework of international agreements and to the projected increase in climate damage over the very long term; the stress tests are therefore very different from the traditional horizons (1 to 2 years). The models may depend on the anticipation and preparation of public action, assume perfect or imperfect visibility of economic agents[40].
- A sectoral dimension, including specific modeling of the interactions between the economic environment and nature; the possibility of trade-offs and synergies between several goods and services or technologies; and technological advances, particularly those affecting the energy sector (NGFS, 2019). Transition often consists of a transfer of activity from one sector to another. However, these sectors do not have the same labor intensity, nor the same propensity to export or import. These variations have an impact on GDP, which in turn affects the various sectors in a heterogeneous way. The modeler must define the optimal level of disaggregation of the model between sectors, in order to limit the bias in forecasting and to allow actors to easily interpret the results of the scenarios.
- An international dimension, linked to the activity of the institutions tested and the exposure of the portfolios; sectoral and geographical granularity can then be combined, insofar as the carbon

[38] Pass-through, generally associated with the effects of a change in the exchange rate, is the phenomenon whereby the rising cost of a good or factor (in this case carbon) affects prices in an economy.

[39] The NGFS provides a comprehensive list of these and their respective advantages and limitations (see the technical supplement referenced below).

[40] DSGE (*Dynamic Stochastic General Equilibrium*) models can, in particular, introduce uncertainty and actions not anticipated by agents by introducing stochastic shocks.

intensity of the sectors can vary greatly from one country to another (e.g. the electricity market in France and Germany)

Historically, Integrated Assessment Models (IAMs), dedicated to the economic study of climate change, were the preferred candidates for such exercises. They are composed of a macroeconomic module, one or several technical modules (energy and land use in particular) and a climate module. However, most of them have a too low level of sectoral and geographical disaggregation, which makes them inapplicable to define fine transition and physical risk scenarios. The economy-climate loop, defined successively by the relationship between concentrations and temperature (climate sensitivity) and between temperature rise and economic impact (damage function), is subject to the criticism of Pindyck (Pindyck, 2017) who considers the structure of certain equations as arbitrary and the calibration of certain parameters sensitive to the properties of the model: preference for the present, climate sensitivity, damage function (Landa Rivera, Malliet, Saussay, & Reynès, 2018). The economic properties of these models are extremely heterogeneous (see **Appendix 1**): some do not represent the economic costs of climate change, such as the REMIND model[41] (which relies on the MAGICC climate model[42] to translate emissions into climate impact); in others, the GDP paths are exogenous (e.g. GCAM).

Two other categories of models have also emerged, both in the work of the NGFS and in exploratory exercises conducted by various institutions:

- Computable General Equilibrium (CGE) models, which represent the sectoral and regional disaggregation of the economy, the interconnections between sectors and the resolution of a set of supply and demand equilibria based on a system of relative prices (labor market, goods and services market); they represent the link between sectoral activities and emission levels (often with a fine representation of the energy sector) and allow for a precise analysis of the transition scenarios towards a decarbonized economy; however, they must integrate the cost of climate damage (such as the OECD's ENV-LINKAGES model) and their potential variation, otherwise the long-term benefits of proactive mitigation policies would be underestimated.
- Macroeconometric models, based a national accounting framework and a set of econometrically estimated behavioural equations to forecast the evolution of the main aggregates (demand, imports, prices and wages); their dynamics are based on a gradual adjustment towards a new state of equilibrium and take into account, as do some CGEs, the inertia of the adjustment processes of prices and quantities; However, they are constructed and estimated on the basis of past data and are ineffective, according to Lucas's criticism[43], in properly assessing the effect of new environmental policies aimed at modifying the structure and functioning of the economy in the long run (e.g., the NIESR NiGEM[44] model); like most current CGE models, they are silent on the issue of physical risks.

While these two families have common properties (disaggregation, accounting identities), economic behaviours derive from different economic frameworks, which have strong implications for scenario analysis: in CGEs, optimization ensures that all resources are fully utilized, so it is theoretically not possible to increase output and employment by adding regulation; on the contrary, macroeconometric models allow the use of additional capital and labor and make it possible to further sustain the economy (Cambridge Econometrics, 2019).

Although multiple models have been applied to conduct such analyses, it appears that none of them can capture all the characteristics specific to climate risks. In particular, they are still used separately and specifically for certain categories of risks (CGE and macroeconometric models for transition risks, IAM for physical risks), and are sometimes associated with complementary modules that make it possible to specify the detailed effects. Other families (input-output models, multi-agent models, stock-flow consistent models, overlapping generational models), which are less common, also seem complex to apply to stress-test scenarios.

[41] "In contrast to RICE, REMIND does not monetize climate damages, and therefore is not applied to determine a (hypothetical) economically optimal level of climate change mitigation ("cost-benefit mode"), but rather efficient strategies to attain an exogenously prescribed climate target ("cost-effectiveness mode")."

[42] Model for the Assessment of Greenhouse Gas Induced Climate Change.

[43] According to Lucas, evaluating the effects of public policies requires the use of structural models, based on parameters that are robust and invariant to the economic environment: "Given that the structure of an econometric model consists of optimal decision rules of economic agents, and that optimal decision rules vary systematically with changes in the structure of series relevant to the decision maker, it follows that any change in policy will systematically alter the structure of econometric models. (Lucas, 1976).

[44] National Institute Global Econometric Model.

A-theoretical and statistical models, subject to Lucas' criticism, are not widely used for this type of exercise, which requires an in-depth analysis of the evolution of the mechanisms governing the economy in the long run; however, their contribution can be relevant for very short-term national exercises: for example, the IMF has developed a structural VAR (Vector Autoregression) model in order to analyze the impact of an increase in carbon prices on oil revenues, GDP and bank losses on loan portfolios over a three-year horizon in Norway (Grippa & Mann, 2020).

	Description	Relevance for studying climate risks	Examples
IAM	Description of the interactions between socio-economic, technical and climatic environments	Low sectoral disaggregation International and regional dimension Physical representation, sometimes cost of damage (emissions, concentration, radiative forcing, temperature and damage)	DICE/RICE (Nordhaus) MESSAGE (IIASA) REMIND-MAgPIE (PIK) WITCH (FEEM)
CGE	Description of the economy as a set of monetary flows between agents and sectors according to general equilibrium principles[45] Microfounded behavior of economic agents resulting from a constrained optimization	Strong sectoral disaggregation International and regional dimension Lack of physical representation	AIM/CGE (NIES) ENV-LINKAGES (OECD) EPPA (MIT) G-CUBED (Australian University) GEM-E3 (JRC) GTAP (Purdue University) Imaclim-R (CIRED) Three-ME (OFCE-ADEME)
Macroeconometric models	Description of the economy as a set of relationships between aggregate economic variables Behaviors projected by econometric equations estimated on past data[46]	Variable sectoral disaggregation International and regional dimension Lack of physical representation Models subject to the Lucas critique	E3ME (Cambridge Econometrics) NEMESIS (ERASME-Seureco) NiGEM (NIESR)

Table 17: Models for climate-related financial risk assessment

Source: author, from NGFS (2019). Models where GDP is exogenous (e.g., GCAM) are not included.

As an example, the multi-country NiGEM model is used for both the Dutch Bank exercise and the ACPR pilot exercise (see **Table 18**). It is widely used among public actors and various financial institutions, and is already used by supervisors in the context of classic stress tests. It has the advantage of being able to provide transition scenarios at the global level, to represent the impacts at the level of each country. It is also the subject of the development of an energy block (Kara, 2019). However, it represents a single productive sector and does not allow for a more granular level of analysis. This *top-down* modeling (i.e.,

[45] Chen *et al.* (2015) make explicit the three agent-specific features of a typical CGE model: (i) *zero-profit conditions* (in equilibrium, marginal cost equals marginal profit), (ii) *market-clearing conditions* (price balances supply and demand in all markets), and (iii) *income-balance conditions* (each agent's expenditure equals its income).
[46] These behaviors are not necessarily optimal.

based on aggregate macroeconomic shocks affecting sectors in an undifferentiated way) tends to neglect certain aspects specific to the energy transition (sectoral specificities, transfers of activity from one sector to another, incentives for energy efficiency investments and incentives for energy sobriety). This is why economists introduce the evolution of the major aggregates thus estimated into sectoral models in order to distribute the macroeconomic effect observed at a finer level according to the sector's exposure to carbon emissions, as in the exercise carried out by DNB (Vermeulen, et al., 2018) or the ACPR's pilot exercise (Devulder & Lisack, 2020). This method may present a forward-looking bias, since the heterogeneity of sectoral results directly affects the evolution of aggregates (employment, trade balance, investment, consumption and GDP).

	Model	Sectoral granularity	Geographic granularity	Transition instruments	Revenue recycling
Netherlands (2018)	NiGEM+ sectoral ventilation rule	56 sectors	Multi-country *Declination: Netherlands*	Carbon price Productivity Consumption Cost of capital	No recycling
Canada (2020)	EPPA (CGE)	13 sectors	18 regions	Carbon price	100% households
France (2020)	NiGEM+ sector model	55 sectors	Multi-country *Declination: France, EU (except France), USA, rest of the world*	Carbon price Productivity	100% households (income tax credit)
IMF - Norway (2020)	Structural VAR	-	-	Oil revenues (via carbon price)	-

Table 18: Models and assumptions of the first exercises of central banks and supervisors

Source: Central banks and supervisor publications.

Computable general equilibrium (CGE) macroeconomic models used for energy transition assessment purposes could have an important contribution to make in establishing climate stress tests. For example, the Bank of Canada has used the Emissions Prediction and Policy Analysis (EPPA) model developed by the MIT, a dynamic and recursive multi-country model. In France, the Three-ME[47] (OFCE-ADEME[48]), Imaclim (CIRED[49]) and Nemesis[50] (SEURECO-ERASME[51]) models make it possible to accurately model transition scenarios. They are based on a fine sectoral granularity and on several production functions, model energy as a production factor in its own right and combine technical-economic approaches that take into account the particular characteristics of energy as a complementary consumption good (these are called hybrid models). They also reproduce sectoral emissions and carbon taxation, which makes them particularly well suited to assessing the levels of exposure of each sector to transition risk. Finally, they do not incorporate physical risk modelling yet, which is still limited to the scope of IAMs. As they were not originally developed for financial institutions, it is difficult to articulate their projections with the different modules of a stress test (Direction Générale du Trésor, 2017), notably because of the macro-financial environment of a stress test and the specific variables that depend on it (e.g. fine modeling of interest rates).

However, these models are most often used on the basis of the backcasting method, which consists of synthesizing a scenario that is consistent with a target defined upstream, as it was done in France when estimating the tutelary value of carbon (France Stratégie, 2019). The energy transition models are then specifically calibrated to find an optimal way to reduce CO2 emissions, define a set of policies allowing this reduction and estimate the costs and opportunities (Douillard, Epaulard, & Le Hir, 2016). The relevance of these models for specific risk analysis purposes should be assessed through further research.

[47] Multisectoral Macroeconomic Model for the Evaluation of Environmental and Energy Policies.
[48] French Observatory of Economic Conjunctures - Agency for Ecological Transition.
[49] International Center for Research on Environment and Development.
[50] *New Econometric Model of Evaluation by Sectoral Interdependency and Supply*.
[51] SEURECO (Société Européenne d'ECOnomie) is a company serving the ERASME research team specialized in economic modeling.

Finally, some models are specifically designed to assess the impact of a policy at the national level: this is the case of the Three-ME model, which reproduces the model of a small open economy and takes the rest of the world as exogenous. In this representation, world demand and world prices are not influenced by the different shocks, which is a limitation when evaluating a globally coordinated transition action.

4.3. Properties of a model applied to transition risk

As explained above, at this stage, it appears difficult to integrate all risks through a single tool. Few models seem to have the properties necessary to assess the two categories of risk presented. As far as physical risks are concerned, the use of a single model is subject to a radical uncertainty, coming at the same time from the uncertainty on the mitigation policies (scenario uncertainty), an uncertainty on the evolution of the climate (climate uncertainty), the physical impacts resulting from it (physical uncertainty) and a model risk for the whole exercise (inherent criticisms of the climate sensitivity functions and the damage functions). This area requires further work and research, by both supervisors and the academic community. To date, few climate scenarios have integrated all these dimensions in a single tool. Rather than a macroeconomic scenario, the ACPR has, for instance, relied on modeling the direct impact of the RCP 8.5 scenario through weather and health variables and their impact on insurance liabilities.

On the contrary, the modeling of transition risks is a field that is particularly open to macroeconomic modeling and to the evaluation of the impact of environmental policies. As explained above, several categories of models already seem to be able to apprehend these risks, and in particular computable general equilibrium models. These models have a particularly fine sectoral disaggregation and make it possible to apprehend the heterogeneity of transition policies according to the sectors considered, as well as the transfers of activity from one sector to another (in terms of employment, investment or imports in particular).

(i) Sectoral and regional disaggregation

These models must be disaggregated to levels that are both sufficiently fine and consistent to account for this heterogeneity, at a level that is sufficiently relevant for a risk analysis. This disaggregation depends on the nature and importance of the risks to be assessed, which can be seen in (i) the direct exposure to a mitigation policy, for example through carbon intensity, (ii) the place in the economic (and notably energy) supply chain, (iii) the sector's capacity to adapt to the transition, both in terms of its ability to substitute its carbon-based production methods, its market power (its ability to pass on or not pass on the cost increases induced by environmental policy measures, particularly in a context of strong international competition), and even the possibilities of modifying the composition or the production methods of its goods and services

It therefore appears necessary to specify the criteria for the sectoral disaggregation underlying the model, in order to identify the channels of diffusion of transition risks on the different macroeconomic and sectoral values. Used for the evaluation of energy and environmental policies, the Three-ME model (Reynès, Yeddir-Tamsamani, & Callonnec, 2011) defines a set of four preferred criteria for the choice of disaggregation:

- the relative energy intensity of the sector, which distinguishes between sectors according to the weight of their carbon-based energy consumption and their contribution to anthropogenic CO2 emissions[52];
- the possibility of benefiting from a tax exemption (total or partial), in particular in a framework of analysis of the transition risks linked to the implementation of a carbon tax[53];
- the degree of openness to international competition, which makes it possible to estimate the effects of a new environmental constraint on the competitiveness of the sectors; in a risk analysis framework, this criterion would be all the more relevant as the scenarios incorporate non-cooperative transition policies between countries and distort relative export prices;

[52] In the Three-ME model, anthropogenic CO2 emissions are derived from the combustion of fossil fuels and from industrial processes of decarbonization of non-mineral metal products (in the glass and ceramics production sector). They are assumed to be proportional to the volume of intermediate consumption used in the process.

[53] In practice, these sectors have been defined according to the criteria of the European energy directives, which exempt from tax the energy sectors, the industrial sectors consuming dual-use fuels, the sectors producing non-metallic mineral goods and the sectors subject to the European Union Emission Trading Scheme (EU-ETS).

- the homogeneity of each sector, which remains the main accounting criterion for sectoral breakdown.

Thus, productive activities with similar energy intensity and CO_2 emission factors are grouped together in the same sector, which ensures the overall coherence of the production structure, distinguishes the main sectors of the national accounts according to the current nomenclatures of activities, and reduces as much as possible the size of the model while preserving its explanatory power.

Finally, the fine disaggregation of production functions, based on a model with one or more levels of production factors (nested CES), or, as in the Three-ME model, on a generalized GCES model[54] (Generalized Constant Elasticity of Substitution), makes it possible to take into account the capacity of each sector to substitute (between fossil fuels and green energies, but also between energy and capital) and to adapt in the face of the adoption of new environmental constraints.

It should be noted, however, as the ACPR (2020) points out, that it could be even more relevant to go down to a finer level: the level of the company (in the same sector, several companies can have very heterogeneous levels of emissions), or even the nature of its investments. Such precision, which is difficult to envision within the framework of traditional macroeconomic models, would have the advantage of encouraging investments by companies in an emitting sector towards climate-friendly actions and projects, while exposing the transition risks of institutions.

(ii) The place of energy

The representation of energy in the models seems to be decisive for achieving a transition scenario, as it is the source of more than 90% of CO_2 emissions in France and Europe. Most macroeconomic models do not include energy as a sector in its own right; when that is the case, it is often endowed with the properties of an ordinary consumer good, whose demand by agents evolves more or less proportionally to their net disposable income. As highlighted by Lancaster in his new theory of consumption (Lancaster, 1966), the demand for energy does not derive from its direct utility, but rather from its intrinsic characteristics, and in particular from the service it provides when its use is combined with certain capital goods (transport vehicle, housing). Such a model has several advantages and allows to link energy consumption and capital stock, but also to impose saturation rules based on physical criteria (Landa Rivera, Malliet, Saussay, & Reynès, 2018). It then appears necessary to divide the energy sectors according to the types of energy and their renewable or non-renewable character. Such granularity, however, increases the number of parameters to be estimated by economists, such as the elasticities of substitution between factors of production, which are often poorly documented but whose values are crucial for the properties of the model.

(iii) The macroeconomic and financial refinement of a stress test

Macroeconomic models, which were not originally designed for a financial stress-testing exercise, need to be given special attention in order to be able to propose a set of relevant variables that can be articulated with the internal models of financial institutions (with the exception of the sectoral framework, which can be the subject of specific development work by financial institutions, for example in the specific calculation of infra-sectoral probabilities of default)

As an example, the list of scenarios and variables submitted to banks and insurance companies by the ACPR during the French pilot exercise (2020) is presented below, as is the capacity of the Three-ME model (OFCE-ADEME) to provide such detailed information (see **Table 19**). It appears that the international dimension of the scenarios and models, in addition to accurately reflecting the heterogeneity of impacts across regions, also allows for the development of consistent macro-financial scenarios that can be applied by actors. Indeed, many French macroeconomic models are dedicated to the evaluation of national economic policies and are thus constructed as small open economies, with an international environment assumed to be exogenous; such an approach ensures that the results can be read all other things being equal, but does not allow for the definition of a narrative for the main macro-financial variables whose evolution is guided by the balances and imbalances on global markets (interest rates on sovereign securities, exchange rates, oil prices, etc.).

[54] This modeling thus overcomes the restrictions of classical production functions (CES), which impose the same elasticity of substitution between all factor pairs (see Callonnec *et al*, 2013).

While this level of detail seems essential for risk assessment exercises with long time horizons (which would take into account all global actions to achieve carbon neutrality, or the trend effects of climate change), less detailed models can be considered to simulate violent shocks in a short time horizon, at the scale of a region or a country. For example, the IMF uses a VAR model to simulate the short-term effect of a rise in carbon prices on Norway's oil revenues, on national GDP and then on loan defaults, with the counterparties assumed to be mostly located at the national level (Grippa & Mann, 2020). Similarly, the simulation of a hurricane in the Bahamas was carried out, based on a historical scenario, using a highly aggregated DSGE model focused on the local economy (IMF, 2019).

As this is a new exercise for financial institutions, internal models are not yet able to fully incorporate scenarios for climate risk analysis; the list of variables and their articulation with models can therefore be subject to scenario expansions[55] by institutions and further exchanges and feedback between supervisors and institutions, as advocated by the Bank of England, in order to identify the key variables in the modeling process (Bank of England, 2020).

<table>
<tr><th>Macrofinancial variables of the ACPR pilot exercise</th><th>Presence in Three-ME</th><th>Comments</th></tr>
<tr><td>Gross Domestic Product</td><td>Yes</td><td></td></tr>
<tr><td>Unemployment rate</td><td>Yes</td><td></td></tr>
<tr><td>Inflation rate</td><td>Yes</td><td></td></tr>
<tr><td>Carbon price</td><td>Yes</td><td></td></tr>
<tr><td>Oil price</td><td>No</td><td>Exogenous</td></tr>
<tr><td>Public deficit</td><td>Yes</td><td></td></tr>
<tr><td>Public debt</td><td>Yes</td><td></td></tr>
<tr><td>Sovereign rates</td><td rowspan="3">No</td><td rowspan="3">No modeling</td></tr>
<tr><td>EIOPA</td></tr>
<tr><td>Long rates</td></tr>
<tr><td>Short rate</td><td>Yes</td><td>Short-term interest rate determined by the ECB (Taylor rule)</td></tr>
<tr><td>Exchange rates</td><td>No</td><td>Exogenous</td></tr>
<tr><td>Value added by sector (in level and %)</td><td>Yes</td><td></td></tr>
<tr><td>Production by sector (in level and %)</td><td>Yes</td><td></td></tr>
</table>

Table 19: Refinement of a CGE model applied to a climate stress test

Source: ACPR (2020), Scénarios et hypothèses principales de l'exercice-pilote climatique.

[55] For a financial institution, scenario expansion involves taking a scenario provided by the supervisor and interpolating or extrapolating additional variables necessary to estimate the impacts on individual counterparties.

4.4. Energy transition and model risks

The representation of the mechanisms specific to the energy transition is complex, in particular because of the multiple interactions between the economic system and the specific nature of energy. Three effects are often mentioned when it comes to transition scenarios: energy sobriety (reduction of energy consumption), energy efficiency (reduction of the amount of energy needed to meet a given energy service) and the substitution of emitting activities for more sustainable ones. While macroeconomic models are starting to integrate the issue of energy transition, there is not a large consensus over the expected macroeconomic impacts of transition actions (Boitier, et al., 2015). This is particularly true for environmental taxation, which is considered to be the most effective public policy tool for achieving carbon neutrality.

Modelers tend to think that environmental have a negative impact on activity (see **Table 20**), via an increase in production costs and a decrease in household purchasing power. The double dividend theory assumes that it can simultaneously achieve two objectives: an environmental objective (reduction of emissions) and an economic objective[56] that offsets or exceeds the initial cost. This benefit is realized through the recycling of new budgetary resources that allow to get out of a suboptimal equilibrium point. In the models, the translation of these effects is very heterogeneous and depends on many assumptions: initial situation of the economy (involuntary unemployment, fiscal distortions), modeling of the labor market, method of recycling revenues, fuel import rate (see **Figure 12**).

in % deviation from baseline	Permanent 10% increase in fossil fuel prices				Permanent increase of the carbon tax of 1% of GDP *ex ante*			
	3 years	5 years	10 years	LR[57]	3 years	5 years	10 years	LR
Mésange (French Treasury)	-0,2	-0,3	-0,3		-0,6	-0,7	-0,7	-0,7
Three-ME - *Wage Setting*	-0,3	-0,3	-0,3	-0,3	-0,8	-0,8	-0,7	-0,9
Three-ME - *Phillips Curve*	-0,3	-0,3	-0,3	-0,2	-0,8	-0,8	-0,8	-0,8
Nemesis (Seureco)	-0,3	-0,3	-0,3	-0,3	-1,2	-1,2	-1,3	-1,3
Imaclim-R (CIRED)	-0,7	-0,6	-0,4	0,0	-2,0	-1,8	-1,2	-0,1

Table 20: Impact on French GDP of transition shocks using macroeconomic models

Source: Boitier et al (2015), La transition énergétique vue par les modèles macroéconomiques.

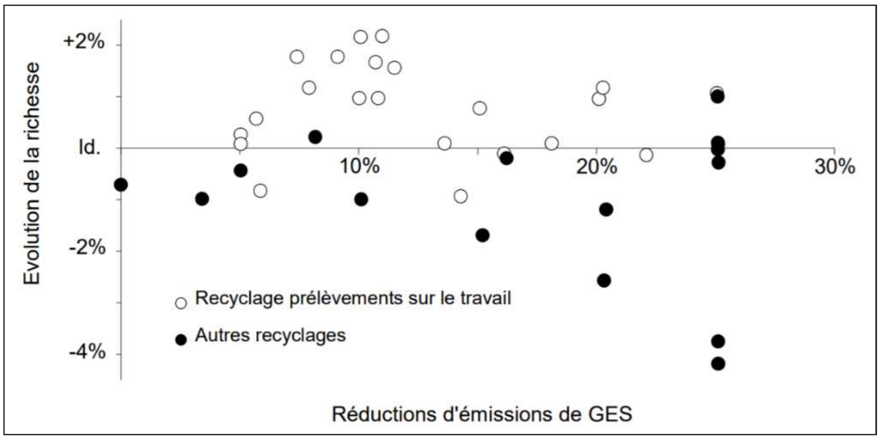

Figure 12: Heterogeneity of economic and environmental impacts of carbon taxes in the EU

Source: Conseil économique pour le développement durable (2009).

[56] According to Ekins (1997), three types of economic dividend can be distinguished: an increase in GDP or employment (this is the one generally considered in macroeconomic models), but also an increase in collective well-being or a decrease in inequality.

[57] Long-run.

The models can also incorporate to varying degrees transition investments, which help offset the negative effects of the initial tax action. Carbon taxes are likely to trigger energy efficiency investments[58], which become profitable through the new rise in energy costs, but also through the potential resolution of pre-existing market failures[59], while limiting the rise in costs for companies (Hebbink, et al., 2018) provided that the crowding-out effect between investments is low, which is the case in models that take into account the possibility of money creation. In countries that are net importers of fossil fuels, it would also allow for a redirection of demand for goods and investments towards domestic producers, in particular when the models make a distinction between fossil fuels and green energies (Callonnec & Combaud, 2019). However, such mechanisms remain subject to strong economic uncertainties on which there is no consensus in modeling: adjustment costs, presence of long-term contracts, real possibilities of substitution solutions[60]; they also depend on the granularity of the production functions and their different inputs (intensity of each sector in each production factor, particularly energy sectors, propensity to import and export).

The macroeconomic scenarios are also impacted by the possible multiplier effects of changes in demand (linked to the possible recycling of revenues, but also to changes in employment or to new investments in energy renovation). In neo-classical supply models, where interest rates ensure the balance between savings and investment, changes in demand linked to transition actions would be partly crowded out. In neo-Keynesian supply-demand models, investment is not constrained by the stock of savings, and changes in income then lead to multiplier effects that amplify the initial economic effects.

Finally, the modeling of carbon pass-through also seems to be decisive (see **Figure 13**). In response to higher carbon prices, firms adjust both their factor demand and their prices. The decision to absorb all costs without adjustment (no pass-through assumption) directly penalizes the financial results of companies and has direct consequences on asset portfolios. On the contrary, mitigating this additional cost on sales prices (no pass-through assumption) limits direct losses but affects internal demand (to a greater or lesser extent depending on the degree of wage-price indexation) and external demand addressed to firms, and would have recessionary effects in the longer run. For example, the ADEME Three-ME model represents a unitary carbon pass-through in the long run[61].

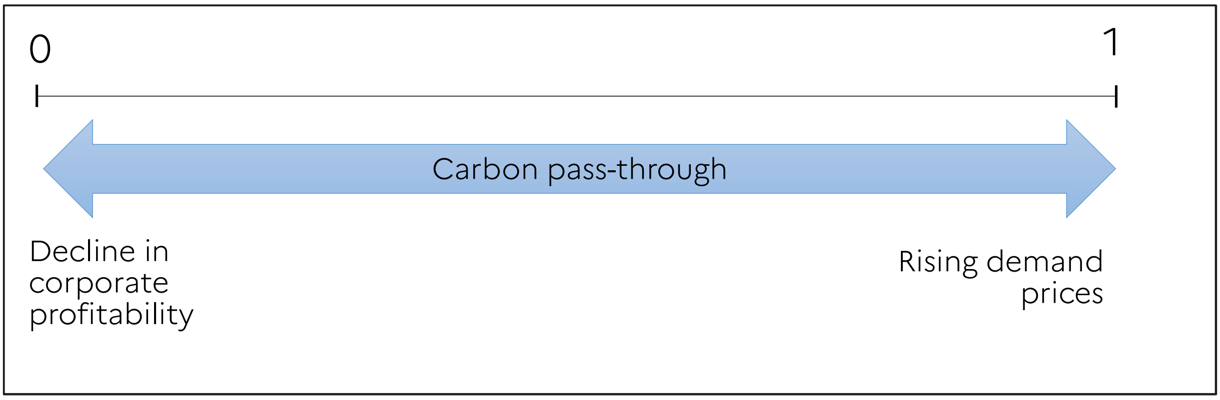

Figure 13: Carbon pass-through and direct economic effects

Central bank-state modeling also plays a role: through monetary policy (interest rate reaction to an inflationary measure) and fiscal policy (for example, through the indexation or not of social transfers to prices). However, these parameters are often left to the modellers.

[58] In practice, companies would replace their machines with more expensive but more energy-efficient equipment. On the household side, this would translate into investments in energy renovation or the purchase of less polluting vehicles.
[59] These failures may be due to poor anticipation of future energy prices or to the short-sightedness of the players, which prevents them from evaluating the long-term profitability of a potential investment.
[60] The parameters of the production functions, such as substitution elasticities, then need to be quantified very precisely by the modelers, as their values can strongly influence transition scenarios (see for example Hebbink et al., 2018).
[61] The assumption of long-run unitary carbon pass-through is often the norm in macroeconomic models based on the neo-classical theory of the producer (profit maximization) and the absence of long-run markup behavior. The ex ante increase in production costs can only be compensated by substitutions towards other production factors.

4.5. The contribution of integrated assessment modelling to physical risk evaluation

Economic modelling of climate change has historically been based on integrated assessment models (IAM), which is based on a multidisciplinary approach to model the interactions between the economy, technology and climate[62]. The first of these was the Dynamic Integrated model of Climate and the Economy (DICE) developed in 1992 by the Bank of Sweden prize-winner William Nordhaus. The first generation of IAMs included optimization models aimed at defining economically and socially optimal mitigation policies (cost-benefit analysis). The second generation, composed of evaluation models, seeks to assess the impact of mitigation measures and their effectiveness in achieving the climate objectives set beforehand (cost-efficiency analysis[63]); it includes, for example, the models used by the IPCC to produce its shared socio-economic pathways.

The IAMs present very heterogeneous structures. Five characteristics appear common to the first generation (NGFS, 2020) These are the GHG emissions trajectory, the average temperature (climate sensitivity), a measure of social well-being, an emissions abatement cost function and the economic costs of climate change (damage function). However, they remain highly debated by the academic community, whose main objections can be found in the virulent critique of Pindyck (2017). In particular, the structure of certain equations and the calibration of their parameters, considered to be crucial for the properties of the models, are judged to be arbitrary: the representation of well-being and the rate of preference for the present (which defines the preference of agents between the present costs of climate action and the distant consequences of warming), the climate sensitivity (which links atmospheric concentrations and temperature rise), and finally the damage function[64] (which represents the economic cost of climate damage). The second generation bracketed the feedback of climate on the economy and developed more explicitly the interaction between technologies, physical systems (energy, land use) and climate.

Approaches to integrating the economic, technical and climate environment together have multiplied, to the point where the boundaries between IAMs and conventional models have become blurred. While some IPCC models explicitly consider GDP as exogenous (e.g. GCAM), some of them may incorporate an economic block in its own right, for example in the form of a CGE (e.g. AIM/CGE). By contrast, some macroeconomic models have been improved to take into account physical and technical specificities: this is the case of the EPPA model (MIT), CGE whose latest version (2015) integrates the energy system, the land use sector, the use of natural resources or even emission levels at a fine granular level, or the macroeconometric model E3ME (Cambridge Econometrics).

The realization of climate stress tests encourages the further development of macroeconomic models through integrated assessment approaches, for example to integrate the economic cost of climate change in a bottom-up approach: loss of labor productivity, decrease in agricultural yields, destruction of capital... These approaches can be based on damage functions, as well as on shocks calibrated ad hoc to reproduce the estimated losses in a given scenario. For example, NIESR seeks to integrate into the NIGEM model the chronic physical risks affecting agricultural productivity (through labor productivity) and acute risks related to floods (through a risk premium) associated with the NGFS scenarios (NIESR, 2020). Such a model would allow the synthesis of climate scenarios combining transitional and physical risks in a coherent and detailed way by explaining precisely the transmission channels at the relevant granular levels, in connection with the technological assumptions and the mitigation actions implemented.

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[62] See for example Weyant's (1996) definition of integrated assessment: "Integrated assessment is distinguished from disciplinary research by its purpose, which is to inform policy and decision making rather than to advance knowledge for its intrinsic value. Integrated assessment is identified by the breadth of knowledge sources and the variety of disciplines from which it draws. It is to be distinguished from those (infrequent) instances in which a significant policy issue can be well informed by clear presentation of a body of knowledge held within a single discipline. "

[63] These two approaches can overlap: optimization models can be used to make projections, while evaluation models can be used to compare multiple actions (Nordhaus & Sztorc, 2013).

[64] The structure of the functions (linear, quadratic, polynomial...) would lead to an underestimation of the impact of extreme events and tipping points that would increase significantly with increasing temperature (Weitzman, 2011).

5. **Conclusion**

The initiatives of central banks and supervisors to address climate change have opened up a new field for economic research and the integration of scenario analysis into supervisory tools, a field that was previously reserved to public policy and futurists. The survey of methodologies and tools has highlighted several additional dimensions of such exercises compared to traditional stress tests:

- the international and shared dimension of climate change risks and commitments to collective and coordinated decarbonization actions;
- the sectoral dimension, linked to the heterogeneous dependence of companies and sectors on greenhouse gas emissions, as well as to sectors particularly exposed to climate change (agriculture);
- the remote materiality of events, which implies projecting scenarios to time horizons further away than those of a classic stress test;
- the radical uncertainty around the risks, both in terms of the implementation of future mitigation actions, climate change and the materialization of physical damage on the economy, which limit the use of historical scenarios; but also on the ability of models to represent all these events;
- the extreme amplitude of risks (fat tail risks) linked to non-linearities, domino effects, positive feedback loops and tipping points, limiting the usual approaches to stress tests by historical scenarios analysis;
- The interdependence of events, with an increase (decrease) in decarbonization actions materializing in the future as weaker (resp. stronger) climatic and physical damages ;
- Finally, economic and financial actors can benefit from the emergence of sectors and activities with a low environmental impact (renewable sector).

Macroeconomic modellers are faced with a set of practical and theoretical difficulties. In conclusion of this non-exhaustive reference, ADEME proposes a first vision of what a climate stress-test scenario could look like, according to the different objectives of the supervisors, which turned out to be of very different natures and horizons (see **Table 21**). Very long-term forward-looking exercises, similar to those of the Bank of England, make it possible to ensure consistency between physical and transitional risks, but do not make it possible to assess precisely the impact of the emergence of one risk in relation to another. The latest generations of IAM models make it possible to carry out such scenarios, such as the Banque de France's ACCL model, which endogenizes long-term growth as a function of changes in energy prices (Alestra, Cette, Chouard, & Lecat, 2020). Such tools allow for a comparison of long-run costs and benefits but remain subject to radical uncertainty and a lack of granular detail.

On the contrary, medium and long term exercises, centered on carbon neutrality horizons (2050), allow to separate physical risks and transition risks, insofar as warming trajectories are very similar in all future scenarios and this independently of future climate actions (climate inertia phenomenon). They are closer to the characteristics of a stress test, but remain subject to many uncertainties. In particular, the assumption of a dynamic balance, which seems essential for the coherence of the exercise, and the difficulty to clearly define more plausible scenarios, seem to be strong limits to the application of new regulatory requirements.

Possible regulatory capital requirements could be associated with very short-term exercises, which would reflect the abrupt materialization of a climate event or a sudden and unanticipated public action, in response to the materialization of a new event or to public pressure, but these would require extensive research into relevant historical experience and data to best simulate the expected future risks

	Prospective exercise	Risk assessment exercise		Prudential exercise	
Horizon	~2100	~2050		3 to 5 years	
Risks	Transition and physics	Transition and/or physical		Transition	Physics
Risk analysis (trigger)	Mitigation policies implemented	Mitigation policies implemented	RCP 8.5	Climate action following the materialization of a risk	Natural disaster
Mechanisms in play	Inter-temporal trade-off between anticipated climate action and future damage	Assessment of the risks and opportunities of one or more transition scenarios and of the adjustment mechanisms of the economy		Direct consequences of an environmental lever, without adjustment of the economy	Economic consequences of a climate-related disaster
Choice of the baseline	No central scenario indicated	Enumerative or No Policy Change Scenario Forward-looking scenario of orderly transition	No physical risk	Business as usual	Absence of climatic event
Choice of adverse scenarios	Prospective scenarios reflecting the materialization of climate policies and announced ambitions	Enumerative or hypothetical scenarios Prospective scenarios reflecting a disorderly transition	Climate and physical impact trend scenario	Hypothetical or historical: Sudden environmental action	Hypothetical or historical as reflecting a past disaster
Choice of a model	Sectoral and geographical modeling integrating: - energy dependency and emission levels- climate change costs	Fine sectoral modeling integrating energy dependency and emission levels	Climate and physical scenario Economic scenario integrating the costs of climate change	Statistical or macroeconomic modeling	
Applicable models	IAM	CGE	IAM or similar Non-model physical scenarios	Statistical models (VAR), Macroeconometric models, DSGE/CGE	
Level of uncertainty	Scenarios (radical), model (radical)	Scenarios (moderate), model (moderate)	Model (radical)	Scenarios (moderate), model (low)	
Balance sheet modeling	Dynamics	Static and/or dynamic		Static	
Regulatory capital requirements	No	No		Yes	

Table 21: The stated objectives of a climate scenario, according to the time horizon considered

Source: author.

Appendix 1: Overview of the different socio-economic scenarios produced by international institutions

a) Shared socio-economic pathways (IPCC)

Socio-economic scenarios describe potential trajectories of[65] future economic development and its consequences for the environment. At the time of the various IPCC reports (1990, 1995, 2001, 2007, 2014), these scenarios were developed in conjunction with two other categories of scenarios with interrelated assumptions, inputs, and boundary conditions:

- Climate change scenarios, which project the possible consequences of human activities on the climate system, in particular through trajectories of greenhouse gas concentrations in the atmosphere;

- Climate impact scenarios, which project the possible consequences of climate change on a given system (e.g. temperature, sea level, precipitation level, etc.).

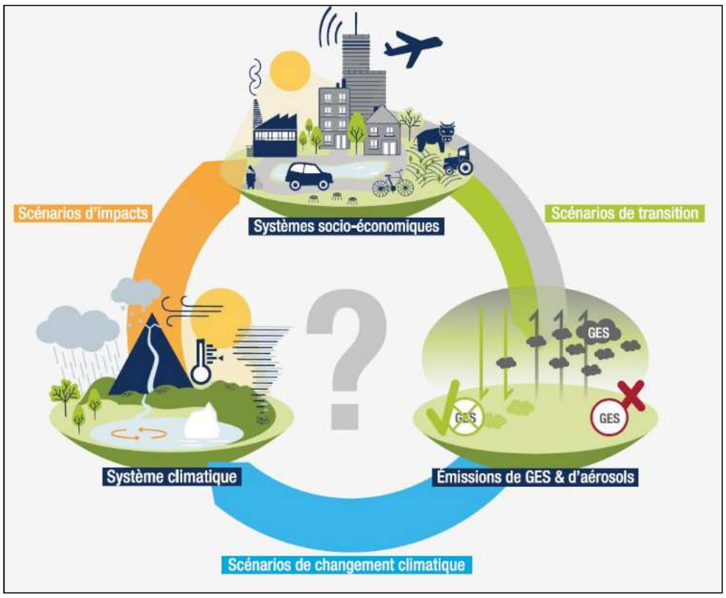

Figure 14: The three categories of scenarios produced by the IPCC

Source: I4CE (2020), Understanding Transition Scenarios - Eight Steps to Reading and Interpreting Scenarios

As part of its assessment reports, the IPCC has been developing a set of scenarios since 1988 (first report), evaluating a range of "possible futures" for a set of determinants. During the 4th report (2007), these scenarios were developed following a sequential logic that successively mobilized three working groups:

- Based on a set of socio-economic determinants, IPCC Group III (in charge of climate change mitigation studies) proposed greenhouse gas emissions trajectories;
- From these emissions, the IPCC Group I (in charge of the scientific elements of climate physics) projected global and regional climate evolutions;
- Group II (in charge of consequences, adaptation and vulnerability to climate change) finally used models to simulate the effects of climate change.

[65] The term scenario refers to a comprehensive description of the future of the climate system, including qualitative and quantitative information. The term "trajectory" describes the composition of the scenario, such as atmospheric concentration or socio-economic developments (macroeconomics, technology, demography).

For the first two IPCC 2000g reports, 4 main families of scenarios[66] were developed (A1, B1, A2, B2). However, since the 2000s, this family of scenarios no longer seems to be appropriate for assessing socio-economic trajectories. The reasons are multidisciplinary and are for example detailed by Moss (2010) or by Guivarch and Rozenberg (2013):

- changes in socio-economic determinants (growth of emerging countries, downward revision of demographic projections) ;
- no inclusion of climate policies;
- evolution of physical climate models (computing power and resolution) and the need for more detailed and finer information on emission sources (e.g. aerosols) and geography (e.g. land use);
- lack of elements necessary for impact and adaptation studies (e.g. urbanization dynamics, changes in governance);
- the overlap of models having increased, there is a need for increased coordination for consistency and harmonization between all the modellers (assumptions, data, boundary conditions).

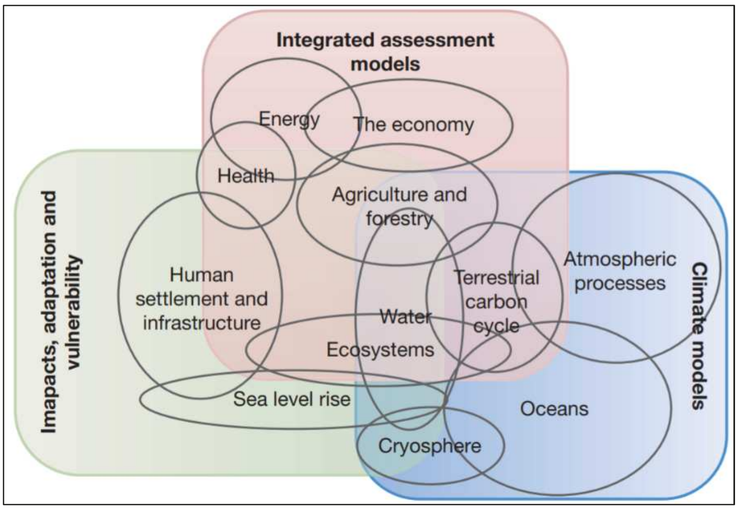

Figure 15: Interactions between the economy, climate and environment

Source: Moss et al (2010), The Next Generation of Scenarios for Climate Change Research and Assessment, Nature Vol. 463.

In 2006, the IPCC decided to leave the development of economic scenarios to the scientific community and, from the fifth report (2013) onwards, a new generation of scenarios to analyze all the mechanisms that contribute to climate change. The IPCC has defined four reference scenarios, the so-called "RCP" (Representative Concentration Pathways) scenarios, each representing possible evolution profiles of greenhouse gas (GHG) concentrations according to the evolution of radiative forcing[67] over the period from 2006 to 2100. In parallel to this work, five scenarios of socio-economic developments are being developed by economists, the so-called "SSP" (Shared Socioeconomic Pathways) scenarios, based on a so-called "matrix" architecture that translates the means to be implemented, at the global level, to reach the different concentration targets defined in the RCPs. By decoupling the climate scenarios from the economic scenarios, such a process allows climate scientists and economists to work in parallel and in coherence to analyze the impacts and costs of adaptation and mitigation of climate change. Certain classes of scenarios are then associated, when they are compatible, with RCP emissions profiles.

These models were applied in three successive steps:

- translation of the narratives into a set of "input tables" (e.g. availability of resources, technological developments, changes in lifestyles, etc.);

[66] These four SRES scenarios were distinguished according to the pace of globalization (axis 1) and the pursuit of more economic or environmental objectives (axis 2).
[67] Radiative forcing is the change in the radiation balance (downwelling radiation minus upwelling radiation) at the top of the troposphere related to climate change factors, including greenhouse gas concentration.

- translation of narratives into projections of socio-economic assumptions (including economic activity, population and urbanization);
- Use of a combination of IAMs to match input tables and narratives, and derive associated energy, land use and emissions projections.

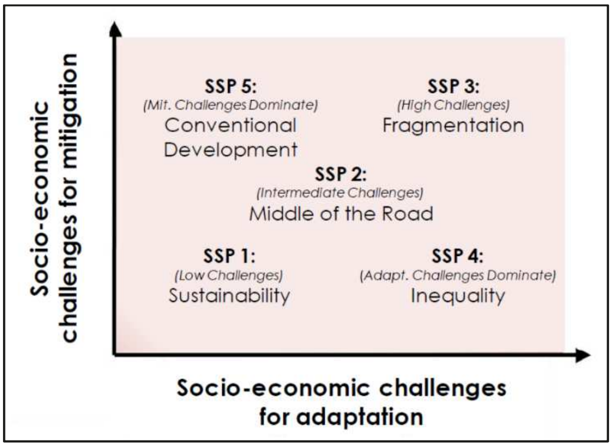

Figure 16: Shared socio-economic pathways according to mitigation and adaptation issues

Source: French Directorate General for Energy and Climate (2013)

Model	Institution	Marker	Scenario coverage	Class of model
AIM/CGE [68]	NIES [69]	*SSP3*	SSP1, SSP2, SSP3, SSP4, SSP5 (22 scenarios)	General equilibrium
GCAM [70]	PNNL [71]	*SSP4*	SSP1, SSP2, SSP3, SSP4 (20 scenarios)	Partial equilibrium
IMAGE [72]	PBL [73]	*SSP1*	SSP1, SPP2, SSP3 (13 scenarios)	Hybrid
MESSAGE-GLOBIOM [74]	IIASA [75]	*SSP2*	SSP1, SSP2, SSP3 (13 scenarios)	Hybrid
REMIND-MAgPIE [76]	PIK [77]	*SSP5*	SSP1, SSP2, SSP5 (14 scenarios)	General equilibrium
WITCH-GLOBIOM [78]	FEEM [79]	-	SSP1, SSP2, SSP3, SSP4, SSP5 (23 scenarios)	General equilibrium

Figure 17: Integrated assessment models used for the synthesis of shared socio-economic pathways

Source: Riahi et al. (2017).

[68] Asia Pacific Integrated Model/Computable General Equilibrium.
[69] National Institute for Environmental Studies (NIES), Tsukuba, Japan.
[70] Global Change Assessment Model.
[71] Pacific Northwest National Laboratory, Joint Global Change Research Institute at the University of Maryland-College Park (USA)
[72] Integrated Model to Assess the Global Environment
[73] PBL Netherlands Environmental Assessment Agency, Bilthoven (Netherlands)
[74] Association of the energy model MESSAGE (Model for Energy Supply Systems And their General Environmental Impacts) and the land use model GLOBIOM (Global Biosphere Management Model).
[75] International Institute for Applied Systems Analysis, Laxenburg, Austria.
[76] Combination of the REMIND (REgional Model of Investment and Development) macroeconomic model and the MAgPIE (Model of Agricultural Production and its Impacts on the Environment) agricultural model.
[77] Potsdam Institute for Climate Impact Research, Potsdam, Germany.
[78] Association of the WITCH (World Induced Technical Change Hybrid) model and the GLOBIOM land usemodel.
[79] Fondazione Eni Enrico Mattei, Milan (Italy).

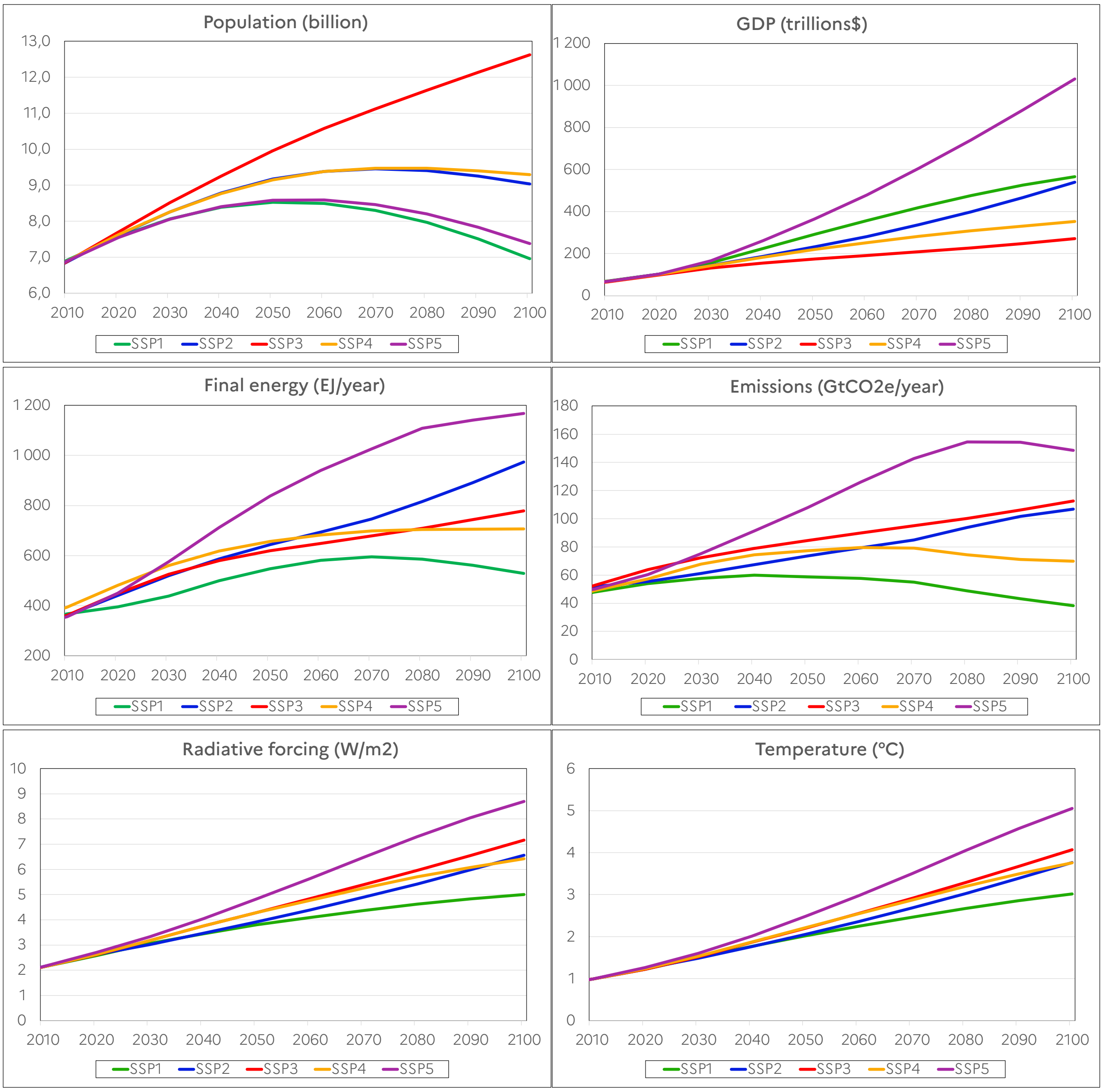

Figure 18: Shared socio-economic pathways

Source: Riahi et al. (2017).

Note: The trajectories represent the baseline global scenarios of each SSP family. Final energy demand is expressed in exajoules (10^{18} joules). Emissions include all greenhouse gases listed by the Kyoto Protocol, including carbon sinks, and are expressed in "CO2 equivalents", a unit that allows to compare the impact of different GHGs and to cumulate their respective emissions. The radiative forcing used is that induced by all greenhouse gases as well as the negative radiative forcing of aerosols. The average temperature increase is related to the average of the pre-industrial period (1850-1900). GDP is expressed at purchasing power parity, in trillions of dollars and at constant prices (base year: 2005). Each trajectory is associated with its marker model (see **Figure 17**). *The carbon price is zero over the entire horizon of the reference trajectories.*

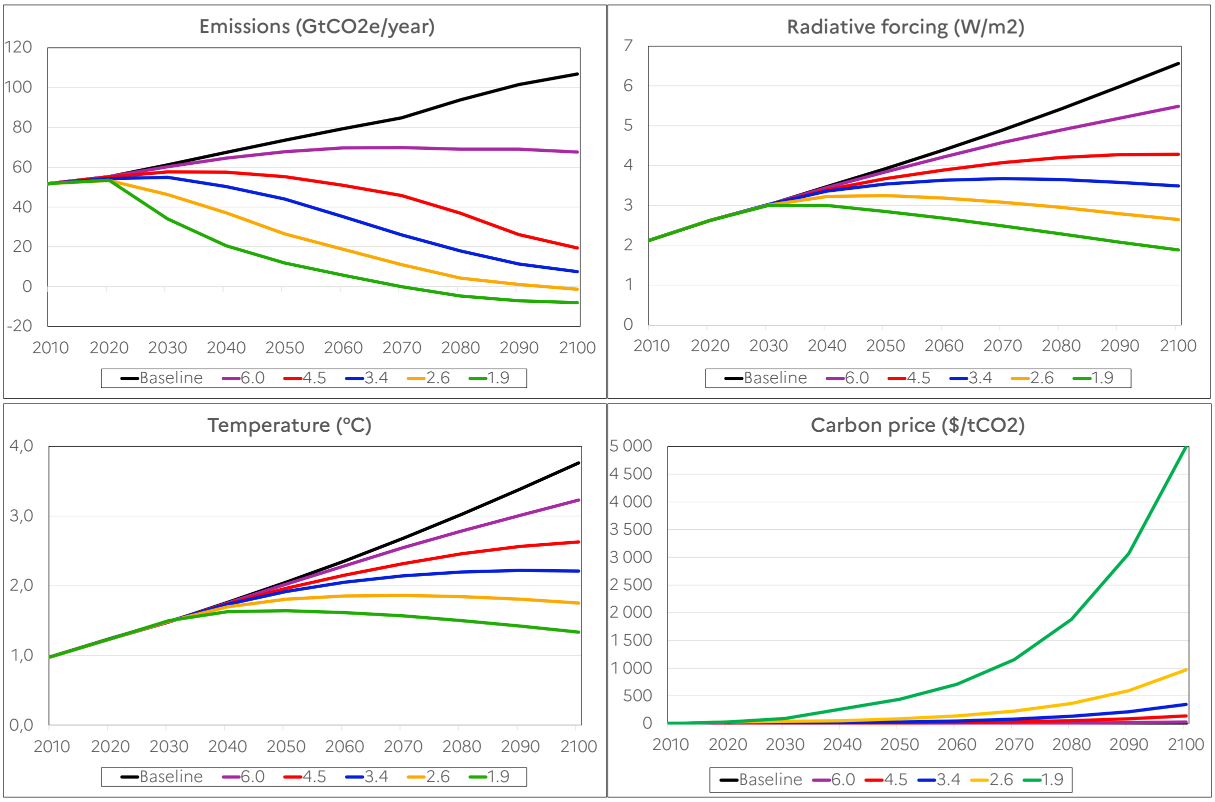

Figure 19: Breakdown of the SSP2 "middle of the road" scenario by environmental action

Source: Riahi et al. (2017).

Note: the trajectories are associated with the "SSP2" scenario marker model (MESSAGE-GLOBIOM). Carbon prices are expressed in constant dollars (base year: 2005), i.e. in dollars corrected for price changes since the base year.

b) The scenarios of the International Energy Agency (IEA)

The International Energy Agency has been producing a set of energy projections since 1993. They do not represent forecasts as such, but hypothetical futures as well as the actions (or inactions) that lead to these futures and the links and connections that exist between the different socio-economic variables. They are based on the World Energy Model (WEM), which is composed of three modules: final energy consumption (residential consumption, services, agriculture, industry, transport and non-energy uses), energy transformation (electricity and heat production, refining and other transformations) and energy supply. The model provides energy trajectories, investment needs, production costs, CO2 emissions and final energy prices. The latest version of the model covers energy trajectories to 2050 for 26 regions.

Four scenarios were summarized in 2020:

- Stated Policies Scenario (SPEPS)

This is the IEA's central scenario; it incorporates all measures and public policies taken up to the day of its publication (as well as their long-term effects).

- Delayed Recovery Scenario (DRS)

This specific scenario was introduced to include the effects of the Covid crisis and its uncertainties on the world economy. It includes a spreading crisis and a slower economic recovery than in the SPEPS. It includes the same measures as those specified in the SPEPS.

- Sustainable Development Scenario (SDS)

This scenario reflects an evolution of the energy sector in line with the United Nations Sustainable Development Goals (SDGs) [80]and aims to both:

- universal access to energy services by the world's population by 2030;
- the achievement of international climate objectives (including the Paris Agreements);
- reducing emissions of other air pollutants from the energy sector;
- for WEO 2020, green stimulus policies to support the economy after the Covid crisis.

- Net Zero Emissions by 2050 Scenario (NZE2050)

This scenario complements the SDS scenario by the achievement of carbon neutrality by advanced economies by 2050 and by the rest of the world by 2070, and sets out the measures and policies associated with achieving these objectives.

	Stated Policies Scenario (SPEPS)	Sustainable Development Scenario (SDS)	Delayed Recovery Scenario (DRS)
Definitions	Cautious modeling of existing policies, commitments and formalized plans, including those requiring formal adoption	Integrated scenario providing a trajectory to: ensure access to sustainable, modern, affordable and secure energy services by 2030, reduce air pollution, implement effective measures to tackle climate change	Scenario in which the pandemic lengthens and catch-up is slower than in SPEPS
Objectives	Reference scenario for assessing the impact and limits of new energy and climate measures	Propose a plausible trajectory for achieving universal energy access, meeting the goals of the Paris Agreement on climate change, and reducing air pollution	Exploring the uncertainties raised by the Covid-19 crisis

Figure 20: Definitions and objectives of the WEO-2020 scenarios

Source: IEA (2020), World Energy Model Documentation (2020 Version).

c) The high-level reference scenarios (NGFS)

The NGFS climate scenarios aim to provide a common basis for the analysis of the diffusion of climate risks to the economy and the financial sector, both for central banks and supervisors but also for financial institutions and academia. They are not presented as forecasts, but as a sufficiently broad panel of potential future states of the economy.

They are the result of a first iteration by the 2nd working group on "macro-financial aspects and the impact of climate-related risks on financial stability", in conjunction with the Potsdam Institute for Climate Impact Research (PIK), the International Institute for Applied Systems Analysis (IIASA), the University of Maryland (UMD), Climate Analytics (CA) and the Swiss Federal Institute of Technology in Zurich (ETHZ). Three models were selected for scenario synthesis: GCAM (PNNL), MESSAGE-GLOBIOM (IIASA) and REMIND-MAgPIE (PIK).

Three representative scenarios were conducted, based on a distinction between implementing the transition and achieving the climate goals[81]:

- a business as usual (or hothouse world) scenario;
- an orderly transition scenario: rapid and ambitious action to achieve carbon neutrality;

[80] UN Sustainable Development Goals (SDGs)
[81] Under this framework, a fourth "*too little, too late*" scenario combining both physical and transition risks could have been included but was not for the first iteration.

- a disorderly transition scenario: delayed, disruptive, sudden and unanticipated action.

The uncertainty inherent in the modelling of the scenarios has been taken into account through the development of five alternative scenarios, depending on the emission reduction trajectories and the deployment of carbon capture and sequestration (CCS) technology. A final scenario includes the implementation by governments of National Determined Contributions (NDCs).

Finally, uncertainty was also modeled through the joint use of several integrated assessment models for the same scenario; however, only one model was retained as a "marker model" (see **Table 22**).

NGFS scenarios	Representative and alternative scenarios	Models
Hothouse world	**Current Policies** Nationally Determined Contributions	GCAM, **MESSAGE**, REMIND MESSAGE, REMIND
Orderly transition	**Immediate (2°C) with CCS** Immediate (2°C) with limited CCS Immediate (1.5°C) with CCS	**GCAM**, MESSAGE, REMIND MESSAGE, REMIND MESSAGE, REMIND
Disorderly transition	**Delayed (2°C) with limited CSC** Delayed (2°C) with CCS Immediate (1.5°C) with limited CCS	**REMIND** MESSAGE, REMIND MESSAGE, REMIND

Table 22: NGFS scenarios, characteristics and marker models

Source: NGFS (2020), NGFS Climate Scenarios for central banks and supervisors.

Reading: the scenarios in bold are the representative scenarios; each scenario is associated with the models used (in bold the "marker" model of the representative scenario).

The scenarios produce time series in 5-year steps (up to 2100), integrating both transition risks (represented by IAM models) and physical risks (based on climate and general circulation impact models and a damage function) through the following variables:

- energy demand;
- energy capacities;
- energy investments ;
- energy prices;
- carbon pricing;
- CO2 and GHG emissions;
- temperatures;
- agriculture-related variables;
- GDP (in purchasing power parity or exchange rate).

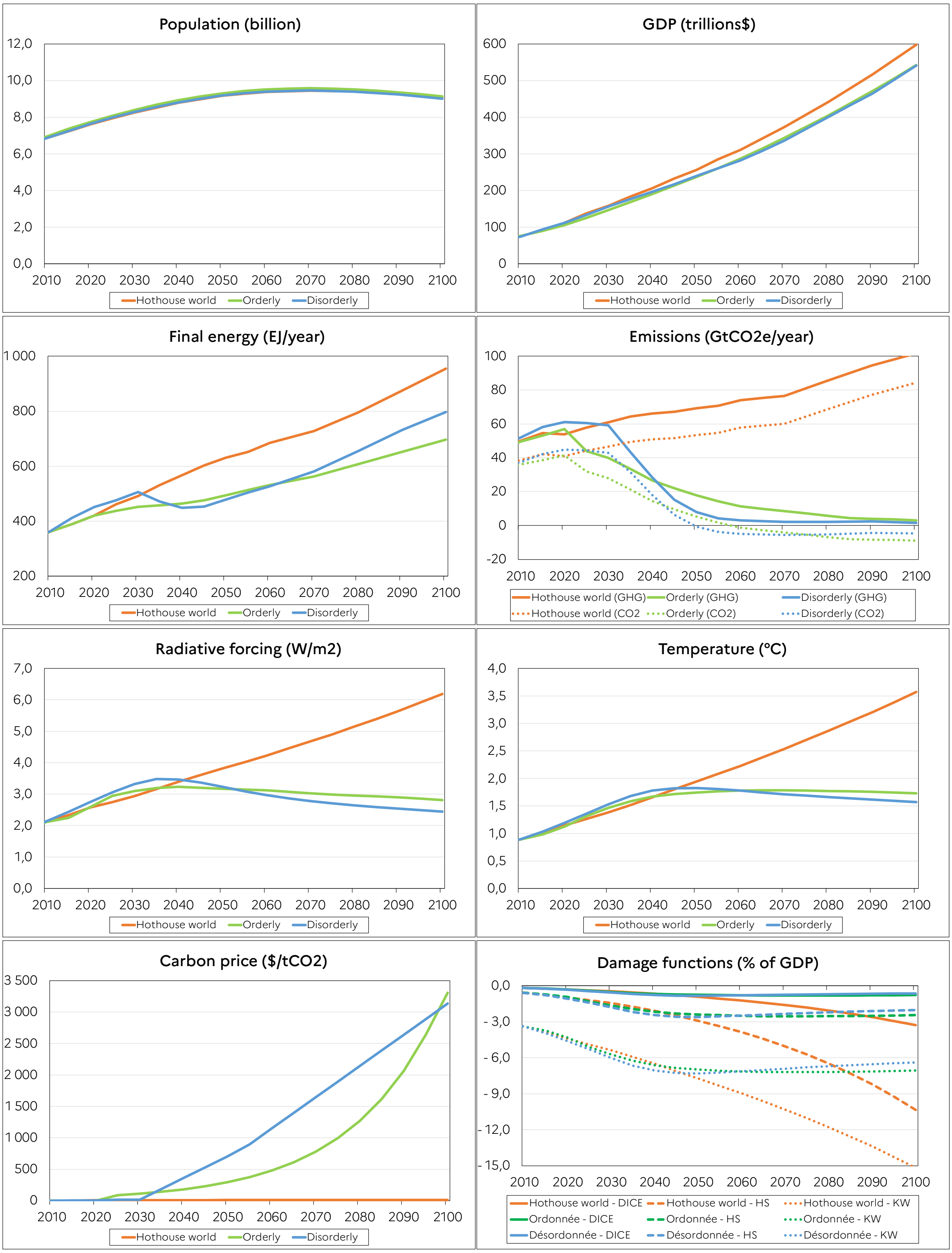

Figure 21: NGFS high-level reference scenarios

Source: NGFS (2020), NGFS Climate Scenarios for central banks and supervisors.

Note: the trajectories are associated with the corresponding representative scenario and their marker model (see **Table 22)**. *GDP is expressed at purchasing power parity, in trillions of dollars and at constant prices (base 2010). Carbon prices are expressed in constant (2010) dollars. Economic losses are estimated based on several damage functions from the literature: Nordhaus (2017), Howard & Sterner (2017) and Kalkuhl & Welz (2020).*

Appendix 2: French prospective scenarios

The National Low-Carbon Strategy (Ministry of Ecological Transition)

The National Low Carbon Strategy (SNBC) is defined in application of the law on energy transition for green growth (LTECV), in article 173, as a steering tool to lead and monitor the policy of decarbonization of the French economy and transformation of its energy model. The low-carbon strategy is one of the government's instruments to implement the objectives defined at the European and national levels and translated into article L100-4 of the Energy Code.

The first SNBC published in 2015 (SNBC 1) aimed at dividing greenhouse gas (GHG) emissions by four by 2050 compared to 1990 (Factor 4) with an intermediate target defined by the LTECV of a 40% reduction, compared to 1990, by 2030, in line with European objectives.

The second and final version (SNBC 2) aims at a more ambitious objective of carbon neutrality by 2050, in addition to the previous objectives of the LTECV already integrated in the SNBC 1 (50% reduction of final energy consumption in 2050 compared to the 2012 baseline, distribution of the carbon budget by major sectors over each of the periods 2019-2023, 2024-2028, 2029-2033). It is linked to and complements a series of national programs and plans, such as the Multiannual Energy Program[82]. The SNBC is based on a socio-economic scenario (known as the "SNBC-PPE") developed during a modeling exercise. This scenario, known as "With Additional Measures" (AMS), integrates public policy measures, in addition to those existing today, which would enable France to meet its short, medium and long-term climate and energy objectives. It outlines a possible trajectory for reducing greenhouse gas emissions until carbon neutrality is achieved in 2050, from which carbon budgets are defined. In particular, it is compared to a trend scenario in the absence of these additional measures after July 2017, a scenario called "With Existing Measures" (AME) in a common demographic and macroeconomic framework, particularly in terms of trend economic growth before measures.

The SNBC-PPE scenario was carried out separately by two modeling teams: on the one hand CIRED with the Imaclim model, and on the other hand ADEME and CGDD with the Three-ME model. A macroeconomic assessment compares the scenario underlying the SNBC (the so-called AMS scenario) with a trend trajectory in the absence of additional measures after July 2017 (the so-called "AME" scenario). This assessment does not include the impact of future climate change consequences. According to both models, the SNBC would generate a similar GDP gain, in the order of 3 to 4 points by 2050 (Ministère de la Transition Ecologique et Solidaire, 2020).

Other national foresight exercises

At the French level, other studies are being conducted upstream or in parallel with the SNBC and can be considered as complementary to this trajectory:

- ADEME's visions;
- the negaWatt scenario;
- RTE's electricity scenarios;
- GRT gaz and GrDF gas scenarios.

[82] For a complete list of these plans, please refer to the strategic environmental assessment of the National Low Carbon Strategy (2020).

Appendix 3: The Three-ME Model

The Three-ME model, developed since 2008 by OFCE and ADEME, and co-used by the Ministry of Ecological Transition since 2013, is a computable general equilibrium model that represents an overview of the French economy, based on a complete system of markets where agents interact by making microeconomic decisions to maximize their profit or utility. This model is specifically intended for the evaluation of the impacts of energy and environmental policies in France. The fine level of sectoral detail and the structure of taxation allows to highlight the potentially strong heterogeneity of the effects of transition shocks according to the sectors considered.

The Three-ME model is a Keynesian model in the sense that the dynamics of prices and money supply account for transitory imbalances in markets. The model is neo-Keynesian: unlike Walrasian models, prices do not adjust instantaneously to balance supply and demand in the markets. In the goods market, the notional price is obtained by applying a mark-up to unit production costs (mark-up theory). The mark-ups themselves depend on the variation in volume demand from firms. In the labor market, wages do not instantly adjust supply and demand for employment. There may therefore be an equilibrium of chronic underemployment and involuntary unemployment. The wage is determined by a Wage-Setting curve, i.e. by negotiations between employees and employers in the labor market. It assumes that labor compensation depends on the bargaining power of employees, which depends on the inflation rate, the evolution of the unemployment rate and labor productivity. In the capital market, interest rates do not instantaneously balance savings and investment because it is assumed that investments can be financed not only by savings but also by bank loans, in other words by money creation. This characteristic limits the possible crowding-out effects found in Walrasian models, where for a given amount of savings, the increase in investment by some is financed at the expense of others. The monetary authority set the interest rate according to the evolution of inflation and economic activity (Taylor rule).

The Three-ME model is multi-sectoral (see **Figure 23**): it represents 37 economic sectors (including 17 energy sectors and 4 transport sectors), which makes it possible to analyze the effects of activity transfers from one sector to another (in terms of employment, investment, imports, etc.). Finally, the Three-ME model considers four factors of production: capital, labor, intermediate consumption, and different energies (oil, biofuel, nuclear, gas, geothermal, wind, etc.) that are more or less substitutable. The choice of factors of production results from three trade-offs (see **Figure 22**): between capital, labor, energy and intermediate goods (level 1), between types of energy, capital, intermediate goods or transport (level 2), and between domestic and imported goods (level 3). Substitution between the different factors of production is given by elasticities of substitution for each of the three levels.

The Three-ME model is a hybrid model in the sense that it juxtaposes a "top-down" macroeconomic approach with a "bottom-up" (or technical-economic) sectoral approach to determining energy demand. This makes it possible to take into account the specific nature of energy, which is never demanded for its own sake, but as a complement to other demand (housing, transport), which is itself linked to the ownership of certain goods (housing and vehicles). It evolves according to transport or heating needs and according to variations in the energy performance of the housing and vehicle stock. Households make trade-offs between different energy classes of buildings and vehicles according to their respective usage costs. This modeling choice allows for a fine-grained measurement of the economy's CO_2 emissions, which depend on the stocks of buildings and vehicles, not on the flows. Households' choice between other consumer goods is simulated via an elasticity of substitution.

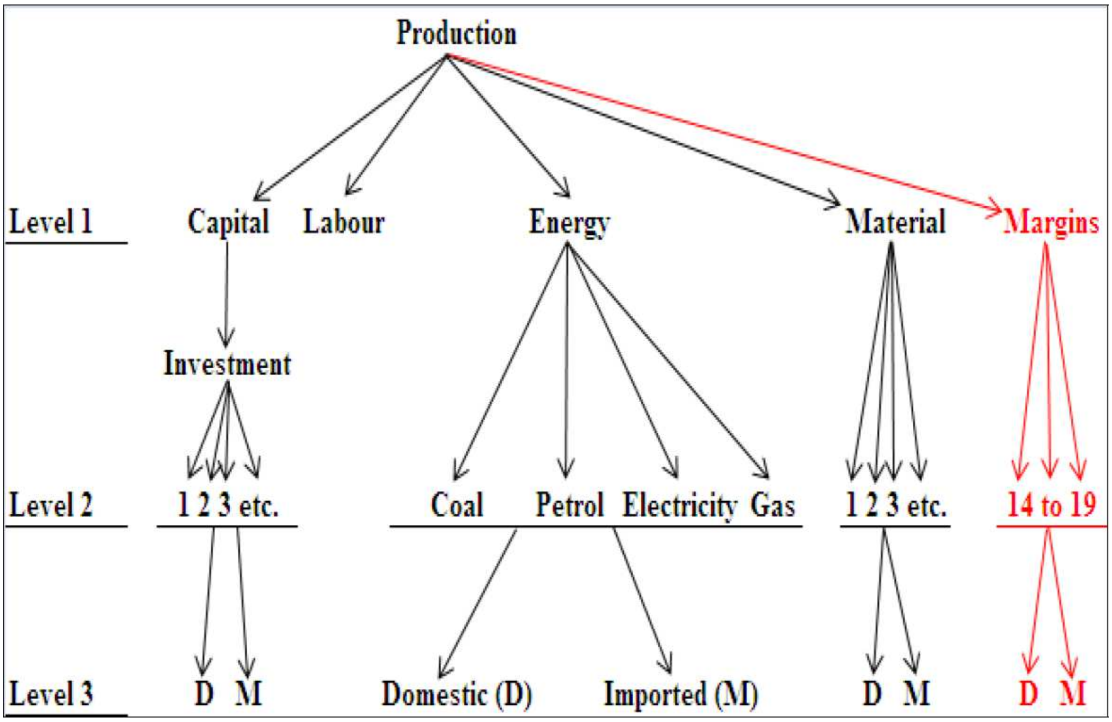

Figure 22: Production structure in the Three-ME model

Source: Reynès et al. (2011), Presentation of the Three-ME model.

Index	Sectors	NAF 118 code
1	Agriculture, forestry and fishing	GA01-03
2	Manufacture of food products and beverages	GB01-06
3	Manufacture of motor vehicles, trailers and semi-trailers	GD01-02
4	Manufacture of glass and glass products	GF13
5	Manufacture of ceramic products and building materials	GF14
6	Manufacture of articles of paper and paperboard	GF32-33
7	Manufacture of inorganic basic chemicals	GF41
8	Manufacture of organic basic chemicals	GF42
9	Manufacture of plastics products	GF46
10	Manufacture of basic iron and steel and of ferro-alloys	GF51
11	Manufacture of non-ferrous metals	GF52
12	Other industries	GC11-12, GC20, GC31-32, GC41-46, GE11-14, GE21-28, GE31-35, GF11-12, GF21-23, GF31, GF43-45, GF53-56, GF61-62, GG12-14, GG22
13	Construction of buildings and Civil engineering	GH01-02
14	Rail transport (Passenger and Freight)	GK01
15	Passenger transport by road	GK02
16	Freight transport by road and transport via pipeline	GK03
17	Water transport	GK04
18	Air transport	GK05
19	Business services	GJ10, GJ20, GJ30, GK07-08, GK69, GL01-03, GM01-02, GN10, GN21-25, GN31-34, GN4A, GP10, GP21, GP2A, GP2B, GP31-32, GQ1A, GQ2A, GQ2C, GQ2D
20	Public services	GN4B, GQ1B, GQ2B, GQ2E, GR10, GR20
21	Mining of coal and lignite	GG11
22	Manufacture of refined petroleum products	GG15
23	Electric power generation, transmission and distribution	GG2A
24	Manufacture and distribution of gas	GG2B

Figure 23: Sector disaggregation of the Three-ME model, distribution of production by sector

Source: Reynès et al. (2011), Presentation of the Three-ME model.

Annex 4: Survey of the economic consequences of climate change in France

(i) RCP scenarios and global temperature increase relative to 1850 - 1900 (in °C)

	Period	Temperature rise (average)	Temperature rise (interval)
RCP 2.6	2016 - 2035	1,1	0,9 - 1,3
	2046 - 2065	1,6	1 - 2,2
	2081 - 2100	1,6	0,9 - 2,3
RCP 4.5	2016 - 2035	1,1	0,9 - 1,3
	2046 - 2065	2	1,5 - 2,6
	2081 - 2100	2,4	1,7 - 3,2
RCP 6.0	2016 - 2035	1,1	0,9 - 1,3
	2046 - 2065	1,9	1,4 - 2,4
	2081 - 2100	2,8	2 - 3,7
RCP 8.5	2016 - 2035	1,1	0,9 - 1,3
	2046 - 2065	2,6	2 - 3,2
	2081 - 2100	4,3	3,2 - 5,4

Source: IPCC.

(ii) Physical risks related to the increase in the frequency and amplitude of chronic or trend events

IMPACT	ECONOMIC CHANNEL	ECONOMIC VARIABLE	UNIT	2016-2035	2046-2065	2081-2100	Comment
Sea level rise	Loss of capital	Expected annual costs (EAD)	Bn€/year	0,93	3,94	[23,6 ; 96]	RCP 8.5 - SSP5 - With adaptation
		Insurance losses	M€/year		[43 ; 78]		RCP 8.5 - Without adaptation
		Number of people affected per year	additional % affected by flooding		[10 % ; 50%]		RCP 6.0 - Without adaptation
Increase in air temperature and change in precipitation regime	Energy demand	Energy demand	Changes in demand in % (compared to the period 1961-1990)			-16 %	RCP 8.5 - Without adaptation
	Energy yields	Wind farm	Evolution of productivity in % (compared to 2012 potential)	-2 %	-3 %	-4 %	RCP 8.5 - Without adaptation
		PV Park		-1 %	-1,2 %	-1,5 %	RCP 8.5 - Without adaptation
		Hydraulic power plants		2,8 %	-1 %	-6 %	RCP 8.5 - Without adaptation

		Thermal power plants		-5,5 %	-8 %	-14,5 %	RCP 8.5 - Without adaptation
	Tourism revenues	Number of overnight stays from May to October	Evolution of the number of overnight stays in % (compared to 1980-2005)	[+5% ; +10%]	[+10% ; +20%]		RCP 4.5/8.5 - Without adaptation
		Number of overnight stays in winter		[-1.5% ; -0.5%]	[-2% ; -0.6%]		RCP 4.5/8.5 - Without adaptation
		Operational capacity of ski resorts over the ski season: % of resorts with low snow cover	Operational capacity in %.		28 %	0 %	RCP 8.5 - Without adaptation
					75 %	28 %	RCP 8.5 - With adaptation
	Agricultural yields	Area of arable land (km²)	Change in surface area in % (compared to reference climate 1960-1990)		-50 %		RCP 8.5 - Without adaptation
		Grassland area (km²)			50 %		RCP 8.5 - Without adaptation
		Area of land under intensive agriculture (km²)			-50 %		RCP 8.5 - Without adaptation
		Poultry farming (number of animals)	Evolution of livestock in % compared to 2020	-4 %	-15 %		RCP 8.5 - SSP2 - Without adaptation
		Milk production (number of animals)		-9 %	-32 %		RCP 8.5 - SSP2 - Without adaptation
		Beef farming (number of animals)		-1 %	-8 %		RCP 8.5 - SSP2 - Without adaptation
		Wheat yield	Evolution of yields in % compared to 2020	1 %	4 %		RCP 8.5 - SSP2 - Without adaptation
		Irrigated corn yield		6 %	21 %		RCP 8.5 - SSP2 - Without adaptation
		Barley yield		-1 %	-4 %		RCP 8.5 - SSP2 - Without adaptation
		Millet yield		9 %	26 %		RCP 8.5 - SSP2 - Without adaptation
		Rice yield		7 %	25 %		RCP 8.5 - SSP2 - Without adaptation
		Sorghum yields		17 %	68 %		RCP 8.5 - SSP2 - Without adaptation
		Oil yields (rapeseed, soybean, sunflower)		13 %	30 %		RCP 8.5 - SSP2 - Without adaptation
		Vegetable yields		10 %	26 %		RCP 8.5 - SSP2 - Without adaptation
		Fruit yields		8 %	21 %		RCP 8.5 - SSP2 - Without adaptation
	Silvicultural yields	Evolution of productivity	Change in area in % (compared to 1960-1990)		-50 %		RCP 8.5 - Without adaptation

		Wind-related production loss	Evolution of the loss in % (compared to 2000-2010)	38 %			RCP 4.5 - Without adaptation
		Loss of production due to bark beetles		24 %			RCP 4.5 - Without adaptation
		Loss of production due to forest fires		25 %			RCP 4.5 - Without adaptation
	Workplace productivity	Indoor work productivity	Evolution of productivity in % compared to 1985-2005		[0% ; +2%]	[-10% ; -2%]	RCP 8.5 - Without adaptation
		Labor productivity (industry sector)			[-10% ; -5%]		RCP 8.5 - Without adaptation
		Outdoor work productivity			[-5% ; 0%]	[-12% ; -2%]	RCP 8.5 - Without adaptation
		Labor productivity (construction)			-10 %		RCP 8.5 - Without adaptation
		Outdoor work productivity			0 %	[-0.5% ; 0%]	RCP 8.5 - With adaptation
		Changes in urban production	Billions of euros per year (Bn€/year)		[0,5 ; 2,3]	[0,65 ; 2,5}	RCP 8.5 - Without adaptation
		Changes in urban production				[0,156 ; 0,08]	RCP 8.5 - With adaptation
Disease	Workplace productivity	Number of working days lost due to climate change	Number of days / year	21 333	25 600	29 866	RCP 6.0 - Without adaptation
Increase in temperature and change in pH of the sea	Fish yields	Animal biomass	Evolution in % in 2100 compared to 1990-2000			[0% ; +50%]	RCP 8.5 - Without adaptation
		Potential of catch in the open sea	Evolution in % compared to 2019	[-6% ; -3%]	[-20% ; -5%]	[-64% ; -16%]	RCP 8.5 - Without adaptation
		Change in NPV for the fishing sector	Evolution in % compared to 1980-2005		-10 %		RCP 8.5 - Without adaptation

Source: ADEME internal report.

(iii) Physical risks related to the increase of extreme climatic events

IMPACT	ECONOMIC CHANNEL	ECONOMIC VARIABLE	UNIT	2016-2035	2046-2065	2081-2100	Comment
Drought, heat waves, cold waves, coastal flooding and floods	Workplace productivity	Corporate supply Chain productivity	Evolution of productivity in % compared to 1990-2015	-12,41 %	-14,75 %	-14,75 %	RCP 4.5 - Without adaptation
Flooding, high water	Loss of capital	Expected annual costs (EAD)	Billions of euros / year (Bn€/year)	0,5	3	20	RCP 8.5 - SSP2 - Without adaptation
				[0,5 ; 3,1]	[2,5 ; 8,5]	[5 ; 10,4]	RCP 8.5 - SSP3 - Without adaptation
				[0,5 ; 3,8}	[3,5 ; 6]	[9 ; 33,9]	RECP 8.5 - SSP5 - Without adaptation
				[0,5 ; 2,5}	[0,5 ; 2,5}	[1,3 ; 6,6]	RECP 8.5 - Without adaptation
All types of disasters (floods, droughts, heat waves, storms, fires etc.)				5,623	7,592	20,872	RECP 6.0 - Without adaptation
Flooding, high water					13,5	67,5	RCP 8.5 - SSP5 - With adaptation
				1,109	1,444	4,618	RCP 6.0 - With adaptation
		Compensation costs		1			RCP 6.0 - With adaptation
Dryness		Average annual cost				1,5	RCP 8.5 - With adaptation -
		Compensation costs			0,503		RCP 8.5 - Without adaptation
		Average annual cost		8			RCP 8.5 - Without adaptation -

Source: ADEME internal report.

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ABBREVIATIONS AND ACRONYMS

2DII	2 Degrees Investing Initiative
EBA	European Banking Authority
ACPR	Autorité de contrôle prudentiel et de résolution
ADEME	Agency for Ecological Transition
IEA	International Energy Agency
ECB	European Central Bank
BIS	Bank for International Settlements
CGE	Computable general equilibrium model
CCS	Carbon capture and sequestration
DNB	Central Bank of the Netherlands
EIOPA	European Insurance and Occupational Pensions Authority
ESG	Environmental, social and governance criteria
ESRB	European Systemic Risk Board
EU-ETS	EU Emissions Trading Scheme
IMF	International Monetary Fund
FSAP	Financial Sector Assessment Program
GHG	Greenhouse gases
IPCC	Intergovernmental Panel on Climate Change
I4CE	Institute for Climate Economics
IAM	Integrated assessment model
NACE	Statistical classification of economic activities in the European Community
NGFS	Network of central banks and supervisors for greening the financial system
NIESR	National Institute of Economic and Social Research (British Economic Research Institute)
NiGEM	National Institute Global Econometric Model (NIESR macroeconometric model)
OECD	Organisation for Economic Cooperation and Development
CPR	Representative concentration profile
RWA	Risk-weighted assets
SNBC	National Low-Carbon Strategy
SPA	Shared Policy Assumptions
SSP	Shared socio-economic pathways
TCFD	Task Force on Climate-related Financial Disclosures
THREE-ME	Multi-sector Macroeconomic Model for the Evaluation of Environmental and Energy Policy
UTCATF	Land use, land use change and forestry
VAR	Vector autoregressive model
VaR	Value at risk

ADEME IN BRIEF

At ADEME - the French Agency for Ecological Transition - we are firmly committed to the fight against global warming and resource degradation.

On all fronts, we are mobilizing citizens, economic players and regions, giving them the means to move towards a resource-efficient, low-carbon, fairer and more harmonious society.

In all areas - energy, air, circular economy, food, waste, soil, etc., we advise, facilitate and help finance many projects, from research to sharing solutions.

At all levels, we put our expertise and foresight capacities at the service of public policy.

ADEME is a public institution under the supervision of the Ministry of Ecological Transition and the Ministry of Higher Education, Research and Innovation.

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FACTS AND FIGURES
The ADEME referent: It provides objective analyses based on regularly updated numerical indicators.

KEYS TO ACTION
ADEME facilitator: It develops practical guides to help actors implement their projects in a methodical manner and/or in compliance with regulations.

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The ADEME catalyst: The actors testify of their experiences and share their expertise.

EXPERTISE
ADEME expert: It reports on the results of research, studies and collective achievements carried out under its supervision

HORIZONS
ADEME looks to the future: It offers a forward-looking and realistic vision of the challenges of the energy and ecological transition, for a desirable future to be built together.

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EXPERTISES

SCENARIO-BASED CLIMATE STRESS TESTING FROM RISK ANALYSIS TO MODELING

This working paper presents a review of the state of the art on the conduct of climate stress tests by central banks, supervisors and international institutions and on the macroeconomic modeling of climate scenarios that they require. These risk management tools, commonly used by financial institutions to measure their resilience to the materialization of short-term economic and financial risk, require structural adaptations to be extended to climate risks, whether physical, transition or responsibility. Specific issues must be considered: long term horizons, fine granularity of scenarios to take into account the numerous international and sectoral specificities, radical uncertainty and extreme amplitude of risks, interdependence of physical and transitional risks.

The work carried out by ADEME aims to make proposals and recommendations based on the agency's macroeconomic, prospective and sectoral expertise.

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