I4CE
INSTITUTE FOR CLIMATE ECONOMICS
Une initiative de la Caisse des Dépôts et de l'Agence Française de Développement

Towards an alternative approach in finance to climate risks:

Taking uncertainties fully into account

November 2019

Vivian **Dépoues** (I4CE) | Vincent **Bouchet** (Groupe Caisse des Dépôts & Chaire Energie et Prospérité) | Michel **Cardona** (I4CE) | Morgane **Nicol** (I4CE)

SOMMAIRE

> *While ignorance of uncertainty leads to error, certainty of uncertainty leads to strategy.*
>
> *E. Morin*

Introduction

It is no easy task to take climate risks – transition risks and physical risks – into account in financial management practices. As this note shows from the example of banking activities, the intrinsic characteristics of these risks – which are long-term, cannot be assigned a probability and for which there are no historical data – are often difficult to reconcile with standard processes based on probabilities established from the past. But uncertainty cannot be a pretext for inaction. The framework of decision-making theory in an uncertain world provides alternative approaches and tools for making decisions despite uncertainties. Although these approaches have been developed in contexts that differ from financial activities, we defend the idea that what underpins them – and in particular the importance given to the criteria of adaptability and robustness of management choices – could be used by financial players. We suggest avenues for discussion in this regard concerning both banking strategy and regulation.

In the first part of this note, we give an overview of the transition risks and the physical climate risks and the three main sources of uncertainty associated with them. We then look at the standard risk management processes that banks use before showing why it is particularly difficult to factor in climate risks. We then review several decision-support tools used in other sectors. Lastly, in the conclusion, we suggest ways to adapt these tools to the finance sector.

This document is intended to serve as a basis for exchange between banking sector risk management practitioners and the regulator, as well as operatives and researchers who have already applied exploratory approaches in other areas. We believe it is crucial to discuss the conditions that must be met to make such developments possible in order to improve the consideration of climate risks in the financing of the economy. Although this work is exploratory, it also opens up avenues for case studies to be conducted.

1. Climate risks: certainties and uncertainties

Given the very complexity of climate and economic systems, it is not possible to accurately predict either the form of an energy transition or the future climate. What we know is that extrapolating historical trends and acting as if nothing changed is a very bad approximation that can only lead to a poor assessment of financial risks (Röttmer, Mintenig, and Sussams 2018). The challenge therefore lies in making, political, strategic or financial decisions in a context of uncertainty inherent in climate issues. To do so, we first have to become aware of the certainties currently established regarding the reality of these risks:

1.1. Climate transition risks

Transition risks are the financial impacts that result from the effects of the implementation of a low-carbon economic model on economic actors (Carney 2015; Gros *et al.* 2016; TCFD 2017). These may be risks of regulatory, technological or market changes or reputational risks in a context where the stakeholders of many organisations are increasingly aware about climate impacts. Since the Paris Climate Agreement was signed in 2015, there have indeed been major changes in the regulatory and economic environments. In ten years, for example, there has been an increase from 10 to 50 national carbon prices worldwide (World Bank Group 2018; Métivier, Bultheel, and Postic 2020). Awareness and preferences are changing on the consumption side too; combined with green innovation, they can lead to dazzling changes. In 2017, renewable energy accounted for more than 85% of new installed electricity capacity in Europe. The installation costs for solar and wind installations have fallen sharply: since 2010, they have fallen by 70% for new photovoltaic solar installations and by 25% for wind energy. Although the form and speed of the transition are not yet entirely clear, this growing momentum should not be ignored.

1.2. Physical climate risks

Physical climate risks are the financial impacts resulting from the effects of climate change (change in average temperatures and rainfall patterns, increase in the frequency and severity of extreme climate events, etc.) on economic actors and on asset portfolios (Carney 2015; Nicol *et al.* 2017; TCFD 2017). There is now ample and robust scientific evidence that the climate is changing at an unprecedented speed (IPCC 2014, 2018). The average global warming has reached +1°C since the pre-industrial period, leading in particular to a 17 to 21 cm increase in the sea level between 1901 and 2010. These phenomena have high degree of inertia and are difficult to reverse – these trends should therefore be confirmed in the years and decades to come. The consequences of these changes are already widely felt and described around the world. They are spreading to the financial sector by directly affecting its counterparties in the real economy (directly exposed assets, performance of results, value chains (Hubert, Evain, and Nicol 2018; CICERO 2017; World Economic Forum 2019)). Climate events already have increasing costs: for example, 153 billion hours of work were lost in 2017 due to heat in the world (World Health Organization 2018). The cost of climate-related disasters rose from $895 billion between 1978 and 1997 to $2,245 billion between 1998 and 2017, an increase of 151% in 20 years. In 2017 alone, natural disasters costed the US economy a record $307 billion (Swiss Re Institute 2017; CRED-UNISDR 2017).

All indicators show that we are emerging from the window of relative climate stability in which modern economies have developed. While we have been able to forget the relationship of many activities with the climate, and also their reliance on the climate, these will suddenly resurface. Accordingly, it is becoming urgent to re-examine the stability assumptions implicitly used in the risk management strategies. Not taking these dynamics into account means concealing major trends and taking the risk of being stuck in deadlocks.

1.3. Three sources of radical uncertainties

While trends are increasingly certain, the exact shape of the various changes underway is surrounded by uncertainties[1]:

1. Socio-economic uncertainties

The first and main source of uncertainty linked to these risks is of a socio-economic nature: will the decarbonisation of the economy really materialise in the coming decades, at what pace, and in what forms?

Although the energy transition that the global economy will follow is already underway, it is very difficult to predict. Despite the existence of a variety of scenarios (Vailles and Métivier 2019), its pace and shape (which technologies, which instruments, etc.) remain largely uncertain. This endogenous socio-economic uncertainty is not of a very different nature from many other uncertainties that economic and financial decision-makers face. It resembles, for example, the evolution of the geopolitical context or technological innovation trajectories, all dependent on the sum of political and economic choices at the global level. Although it is not very discriminating in the short term, the socio-economic development trajectory is the main source of indeterminacy in the long term (**Figure 1**).

This source of uncertainty directly affects both transition risks and physical risks. Climate models have been designed as tools to test the climate response to different scenarios of greenhouse gas concentrations in the atmosphere. However, this concentration depends directly on the economy's emissions. There are therefore several sets of projections, with no probability assigned, representing the changes that can be expected depending on the global emission trajectory over the 21th century[2].

2. Scientific uncertainties

The climate system is extremely complex, involving thousands of interactions between highly diverse atmospheric, biological and oceanological components. It is therefore not possible to give an exhaustive description. Scientists are therefore working on models that are simplified representations of this reality.

These models enable them to project possible climate changes. From one team to another, and from one simulation to another, the results of these projections largely overlap, which is what makes it possible to say that there is an extremely solid consensus on the major trends (overall temperatures, sea level, etc.). On more specific or more local aspects, however, the results may differ. It is therefore possible to obtain fairly affirmative answers on the evolution of certain phenomena such as the risk of heatwaves in Europe (which are becoming more frequent) and more cautious answers on others such as the evolution of tropical storms:

> *"It should be remembered that the average climate changes inexorably while extreme weather events occur randomly, but with a law that depends on this average climate".*
>
> *(Yiou and Jouzel 2015)*

Similarly, even if we were able to know exactly the major characteristics of the transformation of our energy model, it would be materially impossible to model all the consequences in the economy.

3. The natural variability of the climate

Although climate models are becoming increasingly precise and we have an increasing understanding of the climate system, there will always be a measure of uncertainty related to the natural variability of the climate. The reason is that the climate system presents a chaotic behaviour. By nature, it evolves according to non-linear and non-deterministic relationships. This means that despite all the scientific efforts that can be made, it will never be possible to predict with certainty what it will look like tomorrow, especially as we move away from the known areas[3].

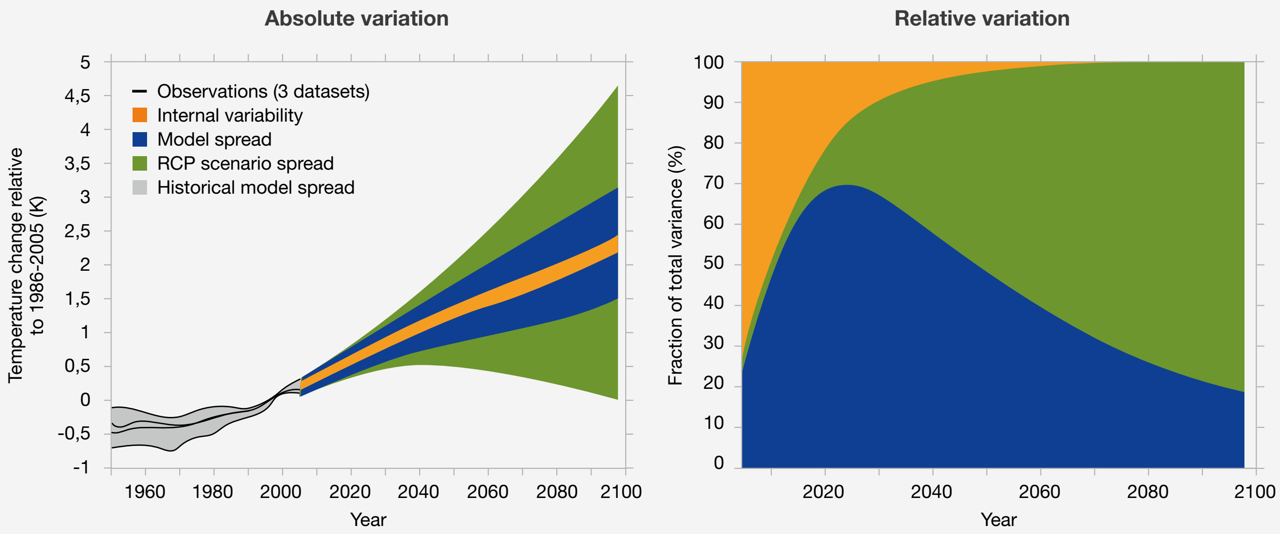
While some of these uncertainties can be reduced over time (for example by increasing the scientific capacity to represent certain phenomena), many will remain and will only dissipate when the future – political and technological choices and climate reactions – materialises. They are described as radical or deep uncertainties, because no probability can be assigned to them and they are irreducible– at least in the short term.

1 The concept of uncertainty has been distinguished from that of risk (Knight 1921) on the basis of this impossibility of constructing a probability distribution of possible cases: 'The practical difference between the two categories, risk and uncertainty, is that in the former the distribution of the outcome in a group of instances is known (either through calculation a priori or from statistics of past experience), while in the case of uncertainty that is not true, the reason being in general that it is impossible to form a group of instances, because the situation dealt with is in a high degree unique'.

2 The RCP scenarios

3 On these characteristics of the climate system causing scientific uncertainties (linked to our ability to understand and model the climate that may change over time) and ontological uncertainties (linked to the very nature of the climate and cannot be reduced) see: (Dessai and Van der Sluijs 2007; Henry 2013; IPCC 2014; R. J. Lempert *et al.* 2004; Van Bree and Van der Sluijs 2014; Van der Sluijs 1997, 2010).

FIGURE 1. RELATIVE IMPORTANCE OF EACH SOURCE OF UNCERTAINTY IN THE TEMPERATURE CHANGE PROJECTIONS OVER THE 21ST CENTURY



Source: (Hawkins and Sutton 2009)

TABLE 1. SUMMARY OF THE THREE SOURCES OF RADICAL UNCERTAINTY IN THE EVOLUTION OF THE CLIMATE

Source of uncertainty	Natural variability of climate (stochastic/ontological uncertainties)	Scientific (or epistemic) uncertainties	Socio-economic uncertainties
Associated risks	Physical risks	Physical risks	Physical and transition risks
Origin and nature of uncertainty	The climate is a chaotic system with non-linear and non-deterministic behaviour. Differences from one simulation to another, even with the same model and scenario.	The climate is a complex system that we can only partially describe and represent. Modelling limit. Differences between the results of different models even with the same scenario.	Relating to the global economy's greenhouse gas emissions trajectory (what transition to low carbon?)
Outlook for changes in the level of uncertainty	Essentially non-reducible uncertainty	Uncertainties that could be reduced with the progress of modelling (both in terms of computing power and understanding of dynamics). However, scientific advances are not linear.	Depends on political and economic scenarios and their interpretation (perceived credibility) by economic actors
Time horizon at which this source of uncertainty predominates	Short term	Medium term	Long term
Ability to manage uncertainty	Known unknowns: there are certain variables and dimensions on which we know the intrinsic limitations or those linked to lack of understanding/ modelling choices of the projections made. But also unknowns, *i.e.* components of the system that could present disruptive behaviours and surprises, particularly when moving away from the common areas of variability.		Scenarios can be drawn up that can identify limits to what is possible, but not to assign probabilities

Source: authors

2. Inadequate traditional financial risk management approaches

To better understand the challenge of integrating these risks with the uncertainties surrounding them, this section reviews the main indicators and decision-making processes in financial risk management. For the sake of clarity and accuracy, this note focuses on the management of risks by banking institutions, *i.e.* players whose main activity is to receive deposits from the public and to grant loans[4]. However, the reasoning followed could be extended by looking at other types of financial practices.

2.1. Overview of financial risk management indicators and decision-making processes

Risk management in the banking sector has several characteristics. It was initially only integrated into lending or investment decisions (both in terms of tools, processes and actors involved), but in the 1990s it was structured using the three lines of defence model:

1. The first line of defence corresponds to the front office functions. Whether granting a loan or investing in a financial security, the banker or the manager incorporates a risk component in his or her decisions, which depends in particular on the institution's risk appetite and the rules defined by the second line of defence;
2. The second line of defence corresponds to the specific functions of the risk department, which is responsible for monitoring the risks taken by the front office and ensuring compliance with the institution's own risk appetite framework and regulatory requirements;
3. Lastly, the third line of defence corresponds to internal audit, which is responsible for controlling risk management processes.

We first present the main risks that a banking institution faces, then the processes, indicators and decisions that take these risks into account[5].

- **Credit risk.** This is the risk that the borrower will default and not repay its loan in full when due. At the regulatory level (*i.e.* for the calculation of regulatory capital requirements), banks may adopt a "standard" approach or internal ratings-based (IRB) approaches. In the latter case, the capital requirement is calculated on the basis of the probabilities of default associated with each counterparty, the exposure to default and the estimated losses given default. A probability of default is generally calculated at a one-year horizon and is based on the counterparty's rating (*e.g.* BB+), which may be derived from a quantitative model (regression on a track record of financial data specific to the counterparty) supplemented by qualitative analysis.
- **Market risk.** This is the risk of fluctuations in the prices of the financial securities that make up a portfolio. This fluctuation may be linked to share prices, interest rates, foreign exchange rates or commodity prices such as oil. The requirement for market risks to be covered by regulatory capital (included in the denominator of the solvency ratio) is generally calculated on the basis of value-at-risk and stress indicators, over a 10-day horizon. Market risks relate in particular to market portfolios (or trading portfolios) that are valued on the basis of market prices.
- **Solvency risk.** This is the risk that the bank will no longer be able to pay its debts or even its deposits. There is a solvency risk when the capital is no longer sufficient to deal with the risks at a 1-year horizon, covered by the assets
- **Liquidity risk.** This is the risk of being unable to meet its short-term commitments (cash outflows) by using its liquid assets. Liquidity risk stems from a short-term mismatch between the maturities of assets and liabilities.
- **Transformation risk.** This is the risk that results from an excessive imbalance between the duration of assets and the duration of liabilities. It is linked to overall interest rate risk and may generate liquidity risk in the future.
- **Overall interest rate risk.** This is the risk, for income and for the market valuation of the balance sheet, in the event of a change in interest rates due to all balance sheet and off-balance sheet transactions.

The various risks presented above are not independent. Risk management decisions, processes and indicators often include several types of risk. Similarly, the economic (formalised by the «risk appetite framework» defined by the banks' governance bodies) and regulatory (Basel) requirements are sometimes integrated jointly into the processes and decisions[6]. We present below a simplified typology of decision-making processes in the context of a traditional banking activity.

4 These institutions may also carry out other related transactions, including securities management, foreign exchange transactions, etc.
5 Operational risk will not be considered in this note.
6 See overview of banking regulations in the appendix

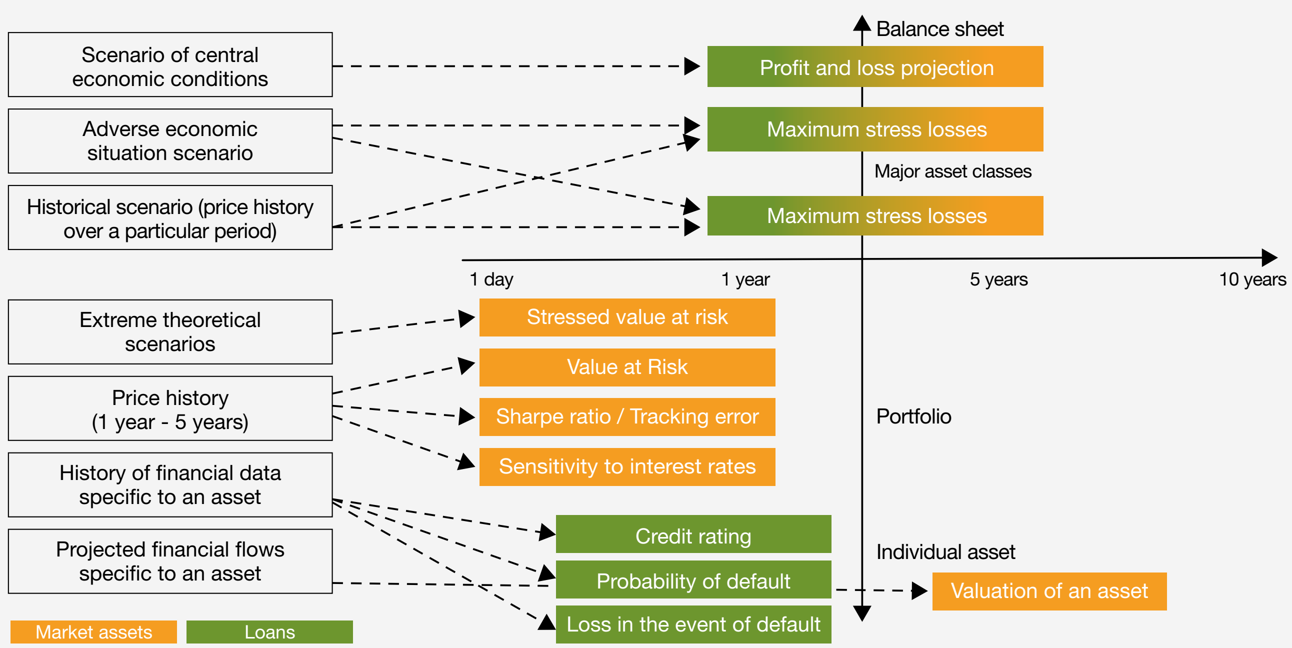
TABLE 2. SIMPLIFIED TYPOLOGY OF DECISION-MAKING PROCESSES IN THE CONTEXT OF A TRADITIONAL BANKING ACTIVITY

	Process / decision	
Level	**First line of defence**	**Second line of defence**
Banking portfolio	• Lending	• Setting a loan limit
		• Making provisions for losses (IFRS 9 standards)
	• Changing the composition of a bank loan portfolio	• Checking portfolio compliance with risk appetite framework
Market portfolio	• Increasing or reducing a position	• Setting an investment limit
	• Changing the composition of a market portfolio	• Checking portfolio compliance with risk appetite framework
Assets and liabilities	• Defining the optimal allocation between major asset classes • Defining the optimal financing of the institution	• Checking the solvency of the institution (compliance with the risk appetite framework and the regulatory ratio)
		• Checking the liquidity of the institution (compliance with the risk appetite framework and with the LCR and NSFR regulatory ratios)
		• Checking compliance with stress tests (internal and regulatory)

Source: authors

These decision-making processes are based, inter alia, on indicators, model results and/or analyses. The type of indicator and the way to achieve it are partly standardised by the regulations. However, each institution refines these models according to its characteristics and risk appetite framework. We present above the main indicators, depending on the level of analysis to which they apply (the analysis of an asset in the institution's entire balance sheet) and the time horizon associated with each indicator. Some of these indicators are risk management indicators (*e.g.* maximum stress losses), others are indicators incorporating a risk component (*e.g.* valuation of an asset).

FIGURE 2. MAIN INDICATORS ACCORDING TO THE LEVEL OF ANALYSIS TO WHICH THEY APPLY AND THE TIME HORIZON ASSOCIATED WITH EACH INDICATOR



Source: authors

EXAMPLE OF AN INDICATOR: VALUE AT RISK (VAR)

The value at risk corresponds to the worst expected loss at a given horizon (generally less than one year) and with a given probability (generally 95% or 99%). The distribution can be estimated parametrically, *i.e.* by associating a formula with the distribution curve (e.g. using a “normal” distribution), estimated directly from historical data (e.g. by considering the daily profitability of a portfolio over the last 250 days to estimate one-day VaR) or by simulations calibrated on historical data (e.g. using the Monte Carlo method). Regardless of the method, VaR uses retrospective data and only takes into account events already observed. However, most of the phenomena related to climate change (whether physical risks or transition risks) have not been observed in the past with distributions comparable to the forecasts of the different climate scenarios. On the other hand, VaR does not provide information on the distribution of losses above the threshold used (95% or 99%).

Traditional approaches to risk management in the banking sector are therefore characterised by an increased use of quantitative indicators, based on historical data and on assumptions of normal distributions. However, recent crises have shown the limits of these indicators, and have led banks to develop stress test methods based on historical and theoretical scenarios. Banking risk management is also characterised by constantly changing regulatory requirements.

2.2. Difficulties in integrating climate risks into traditional approaches

So far, much of the work that seeks to improve financial players’ handling of physical climate and transition risks has sought to integrate them into existing processes. Several steps are needed to achieve this. Monnin, working on credit risk, maps three steps (**Table 3**).

TABLE 3. STEPS FOR INTEGRATING PHYSICAL CLIMATE RISK INTO CREDIT RISK ASSESSMENT PROCESSES

1. Defining climate scenarios	2. Estimating economic and financial impacts	3. Translating financial impacts into credit risk measures
“The estimation of the impact of climate change and of the transition to a low-carbon economy on credit risk relies first on the definition of physical scenarios for climate change and for the transition. These scenarios define how climate change will impact the variables that are relevant for economic activities, how a transition will mitigate these impacts and which measures are taken to steer the transition.”	“Once the impact of climate change on the variables relevant for economic activities has been estimated, its consequences must be translated into economic terms though macro and microeconomic simulations. This step basically assesses the direct and indirect repercussions of climate change and the transition to a low-carbon economy in economic terms and identifies which actors are affected by them and by how much. Once the economic effects on actors have been identified, the next step is to estimate the impact of these effects on both their cash flows and their balance sheets.”	“Based on this assessment of financial impacts on firms and households, the next step is to compute how changes in cash flows and balance sheets will affect their credit worthiness in terms of probability of default and loss given default –and thus also in their credit ratings.”

Source: authors from (Monnin 2018)

Various projects have thus endeavoured to make available the input factors required for this analysis, ranging from transition or climate change scenarios to financial information. Examples include the E.T Risk project on transition risk scenarios (Röttmer, Mintenig, and Sussams 2018; Raynaud *et al.* 2018), UNEP-FI analyses (UNEP FI and Acclimatise 2018; UNEP FI and Carbon Delta 2019; Wyman 2018) and the ClimInvest project on the definition of physical risk indicators (Hubert, Evain, and Nicol 2018).

However, several obstacles have emerged[7]:

1. Incompatible time horizons

The horizons considered in current analyses are often too short compared to those of climate scenarios, which tend to be ignored. Furthermore, standard financial analysis tends to reduce the weight of the future in the decision by using high discount rates. For example, credit ratings can be determined on the basis of an analysis of the current economic cycle, the time horizon of which is estimated to be between three and five years. Regulations also require that they be reviewed every year, which does not encourage long-term thinking. And even if we consider that these ratings say something about the probabilities of default over the entire life of the loans granted, it is once again only on the basis of claims tables defined according to the analysis of the past.

2. Granulometry and contextualisation of input data

Existing risk assessment tools are built to consider certain predetermined variables with a certain granulometry of the information presented in a certain form. However, the relationship between climate and these variables is not always direct and often complex to represent. For example, the physical risk to an activity depends not only on its exposure but also on its vulnerability and its capacity for resilience and adaptability. The ability to respond to a disruption can thus be greater or lesser from one company to another and for the same asset. Moreover, the accuracy of the information available is far from being homogeneous from one location to another, from one sector to another, or from one hazard to another. The data provided by climate service providers are very heterogeneous and not immediately usable (Hubert, Evain, and Nicol 2018).

3. Assigning probabilities to scenarios

In general, risk is assessed by existing tools on the basis of distributions of probability of possible futures. This is how the tools were designed, in a context where historical decline made it possible to have quantified distributions of risks. However, due to the uncertainties described above, the climate change scenarios generally cannot be assigned probabilities because there are no statistics for the future. As the authors of the E.T. project also point out regarding transition risks: “To factor the risk of transition to 2°C into current valuation models, analysts should assign a probability to the results of specific scenarios in order to establish a weighted average. However, scenarios are not forecasts and scenario designers do not assign them probabilities. There are an infinite number of plausible ways to achieve the objective of limiting climate change to 2°C. It is therefore very difficult to integrate the results of scenario analysis into current assessment models” (Röttmer, Mintenig, and Sussams 2018; Raynaud *et al.* 2018).

4. Representation of disruption dynamics

By construction, traditional risk assessment models represent a normal functioning of the financial system, close to known areas of variability. They are not at all designed to account for non-linear consequences or possible disruptive effects that could result from structural changes to the system. However, with climate change, this possibility cannot be ruled out a priori.

Given these problems encountered in the only route explored until now, and in the absence of an obligation or a challenge to the functioning of standard processes, the analyses are mainly business as usual, which means these new risk factors are not – or barely – taken into account.

7 Various specific studies describe them in detail, we just list them briefly here.

3. Alternative approaches: learning from other sectors

These obstacles and uncertainty cannot, however, be a pretext for inaction. It is not because the available information does not resemble the information usually used that it is not feasible to take this into account.

As this information is unambiguous about the existence of risks, it could even be recognised that financial players are responsible for their fiduciary obligation to take them into account. Indeed, the European Commission's Action Plan for Sustainable Finance recognises that «current EU rules on the duty of institutional investors and asset managers to consider sustainability factors and risks in the investment decision process are neither sufficiently clear nor consistent across sectors» and must therefore be quickly clarified (European Commission 2018).

In non-financial sectors, different methodological frameworks have been developed and are used to achieve this (Marchau *et al.* 2019). While these tools can only very rarely be used as they are in a financial management context, it is possible to draw inspiration from their operation to imagine other approaches adapted to this sector.

3.1. General principles of exploratory approaches

These analytical frameworks are at odds with conventional risk assessment. They consist of leaving aside the desire to model risks and the possibility of optimising choices according to a likely future (predict-then-act approaches[8]) to explore a diversity of possible futures and assess the performance of different management options with regard to this diversity (de Haan *et al.* 2016; Hallegatte *et al.* 2012; Maier *et al.* 2016). Such approaches aim to answer the question: *How to think systematically in the face of a wide range of potentially contradictory assumptions and decision parameters?* They value non-probabilistic logics that do not directly lead to a decision but help understand the relationships between the risks considered and its activity. The underlying principle is then no longer to decide based on predefined indicators, but to adopt a strategic behaviour based on this understanding of the dynamics. Such approaches are based on an analysis of the relationship between one's own activity and the climate and the transition to identify the conditions under which one is at risk.

3.2. From scenario analysis to scalable and robust decisions

Scenario analysis is the first tool we think of for conducting this type of procedure. But in a context of numerous and radical uncertainties, it may be difficult to identify or construct the small number of relevant scenarios. Moreover, to be useful, a scenario analysis must be part of a more comprehensive management approach (Trutnevyte *et al.* 2016; de Haan *et al.* 2016).

The solution is to no longer seek to identify the reference future, but to have variants capable of showing the dynamics of risk transmission and the way the system responds to them. To do this, we can use:

- Qualitative approaches, relying on consultation with stakeholders, for example through collective scenario construction approaches (Malekpour *et al.* 2017; Malekpour, de Haan, and Brown 2016; Wardekker *et al.* 2010; Dessai *et al.* 2018; van Bruggen, Nikolic, and Kwakkel 2019).
- Quantitative approaches relying on digital tools such as scenario-discovery algorithms (Dittrich, Wreford, and Moran 2016; Bryant and Lempert 2010; R. Lempert 2013) to identify from among a large number of simulations that cause the conditions of the future environment to vary, the situations in which the proposed decision proves to be at risk. This type of exercise makes it possible to identify the combinations of factors that would lead to the default of the chosen option and therefore to adjust its action accordingly.

Having multiple scenarios then makes it possible to assess how different strategic options could behave in a variety of future conditions and thereby decide, according to its priorities, by valuing in particular two criteria complementary to performance:

1. Adaptability

The main danger in a volatile and uncertain universe is to become locked in trajectories that could prove to be non-efficient in the future, which will be realised without the possibility of exiting. A first response to this risk is to factor in the temporal dynamics into the management strategy by considering: the reversibility of choices and their flexibility or adaptability, *i.e.* reserving the possibility of taking into account new information to adjust or correct them. Various tools have been developed in this regard, including Real option analysis and Dynamic adaptation pathways.

8 Reflecting the classical theory that a decision is a process of maximising expected utility. Most traditional risk analysis and decision support methods are designed to identify optimal strategies based on uncertainty characterisation that obey known probabilities.

Real option analysis (ROA) makes it possible to assess the costs and benefits associated with each management option envisaged. It is used when the question is no longer just to invest or not to invest, but to invest now or to invest later with more information. ROA does not differ from conventional cost-benefit analysis, except that an explicit value is attributed to open or closed opportunities[9]. It makes it possible to sequence decisions by factoring in, in the best possible way, information that gradually becomes available to optimise the cost/benefit ratio over the lifetime. The costs and benefits of postponing the decision are compared with the costs and benefits of anticipating. Real option analysis, which is difficult to implement (heavy and data-intensive analysis), is particularly useful for decisions involving significant capital costs and low reversibility that can be taken now or in the future, when uncertainty is more dynamic than radical (Dittrich, Wreford, and Moran 2016; Hallegatte *et al.* 2012; Watkiss *et al.* 2015; Buurman and Babovic 2016; Woodward *et al.* 2014).

Dynamic adaptation pathways (Haasnoot *et al.* 2013) is a tool that combines adaptive management approaches and work on adaptation tipping points. It is used in particular in flood protection as illustrated by the example of the City of London (box). In the Netherlands, it is at the heart of national policy in this area (Haasnoot *et al.* 2013; Woodward *et al.* 2014). The approach followed is as follows (Kwakkel, Haasnoot, and Walker 2016; Watkiss *et al.* 2015; Walker, Haasnoot, and Kwakkel 2013; Buurman and Babovic 2016; Haasnoot *et al.* 2013; Werners *et al.* 2013; Walker *et al.* 2001):

1. Explain the final objective and its horizon, *i.e.* how do we define the success of a decision/strategy at the end? (*e.g.* ability of a dike to protect from a 100-year flood by the end of the century).

2. Identify, among the risk factors considered, the threshold values from which this success is no longer guaranteed – based on expert opinions or simulations as previously presented – and when these thresholds could be crossed at the earliest.

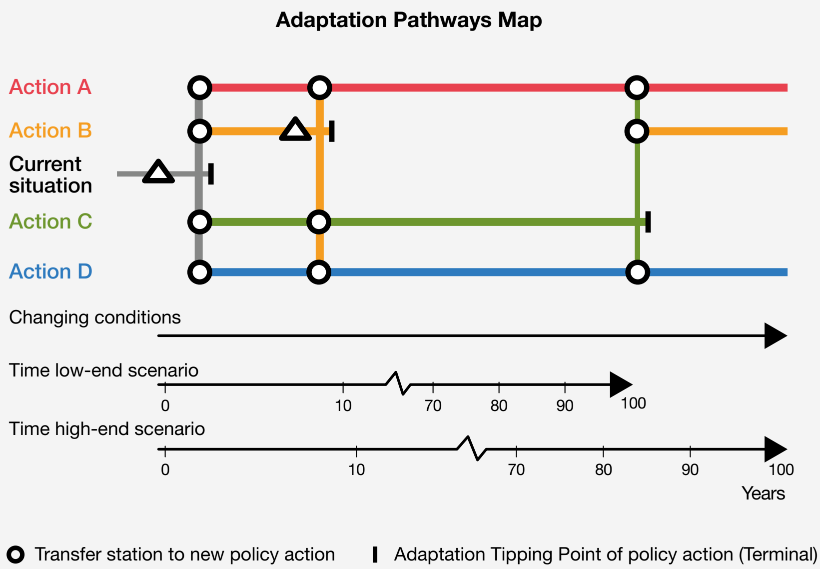
3. List all possible responses to reduce these thresholds, their implementation conditions (cost, deadlines, etc.) and to what extent they would be satisfactory.

4. Design the sequences of possible actions that make it possible to achieve the objective initially set. A sequence consists of a series of decisions, where a new management action is activated as soon as the previous one is no longer able to meet the definition of success.

5. Compare the possible sequences by taking into account the different parameters of interest: total cost of actions in the end, times when the choice must be made.

The analysis is often combined with graphical representations making it possible to identify one of the possible pathways:

FIGURE 3. EXAMPLE OF REPRESENTATION OF ADAPTATION PATHWAYS OVER TIME



Costs and benefits of pathways

Time horizon 20 years
Time horizon 50 years
Time horizon 100 years

Pathway	Costs	Benefits	Co-benefits
1	+++	0	0
2	+++++	0	0
3	+++	0	0
4	+++	0	0
5	0	0	-
6	++++	0	-
7	+++	0	-
8	+	+	---
9	++	+	---

Pathway that are not necessary in low-end scenario

Source: (Haasnoot et al. 2013)

9 NPV = Projected net present value + ("Value of options created - Value of options destroyed").

This exercise makes it possible to very quickly identify options without regrets, to sequence the decision over time and to keep options open for as long as possible, thus minimising the risks of lock-in and optimising the timing of the decision. Management is then combined with a monitoring and evaluation system that enables the monitoring of relevant indicators of changes in risk factors and the iterative adjustment of the management choices.

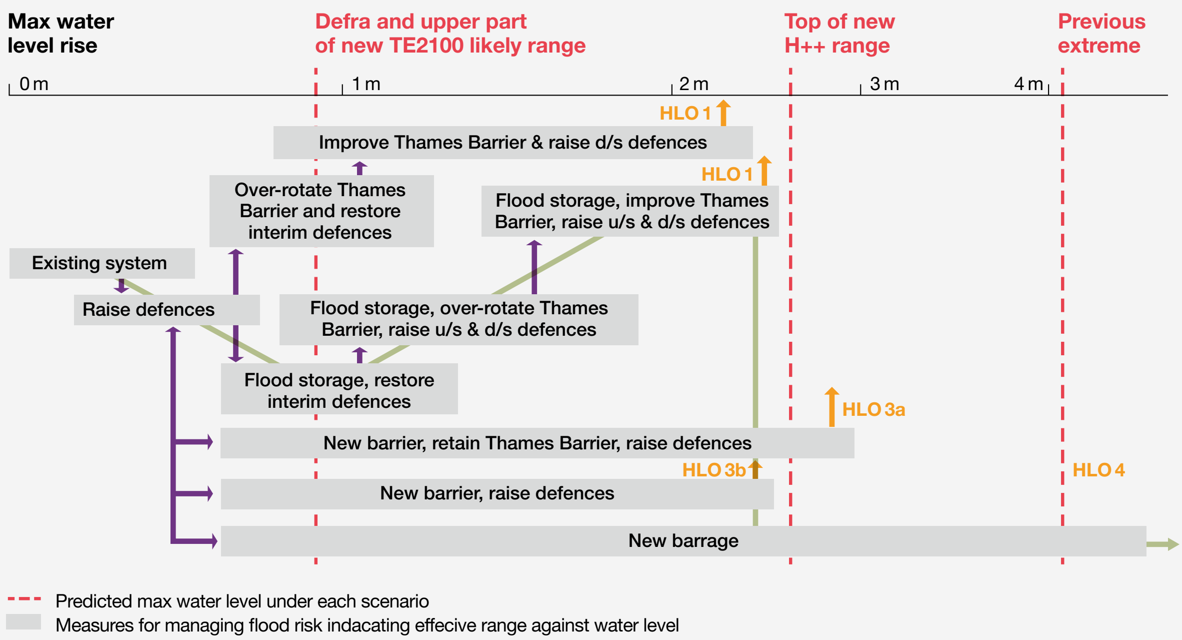
Real option analyses and Dynamic adaptation pathways can be used together as shown in the example below:

THE THAMES BARRIER EXAMPLE

Since 1982, London has had a system of locks that protects the city from flooding (river floods and high tides), sized according to the millennial flood. This system was increasingly used in the early 2000s. A project was launched in 2002 to propose a flood risk management plan for 2100 and answer the question: should we consider the construction of new infrastructure to replace the Thames barrier? The assessment took into account climate change, wear and tear of existing equipment, changes in the physical environment, socio-economic transformations and the level of awareness of populations and institutions. It was conducted with the MET office on the basis of climate projections incorporating uncertainty. This work made it possible to identify and analyse options (cost-benefit analysis and analysis of option values) and to propose a plan in three successive time horizons based on the robustness, adaptability, sequencing and monitoring of actions:

- **2010-2035:** Level of protection maintained and risk taken into account in new developments (£1.5 bn);
- **2035-2049:** renewal and strengthening of existing defences (+1m); redevelopment of the riverside areas (£1.8bn);
- **From 2070:** considering the construction of a new barrier (£7bn).

This proposal gave rise to the adoption of a strategy in 2012 identifying sequences and decision points based on critical thresholds monitored constituting adaptation pathways (**figure**). The interest of the analysis was that it was possible to postpone the most costly decisions (new infrastructure) while preparing for them and following developments as closely as possible to adapt the response as closely as possible.



Sources: (UK Environment Agency 2012, 2016a, 2016b; Penning-Rowsell et al. 2013; Ranger, Reeder, and Lowe 2013)

2. Robustness

A second type of response in situations of uncertainty is to favour robust strategies, *i.e.* favouring satisfactory results in a wide range of conditions and optimal results in very specific conditions. In other words, the aim is to find among the available management options one that minimises regrets regardless of the possible futures[10].

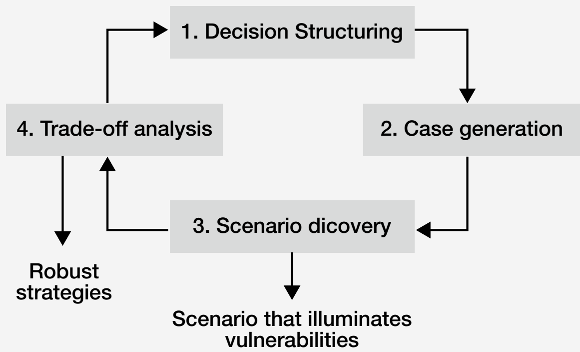
Approaches to identifying and qualifying these options are for example used for the dimensioning of critical infrastructure such as water capture and distribution systems or hydroelectric dams. Such infrastructure is built to operate over long periods of time and will therefore be subject to changing weather conditions. They cannot be allowed to be maladjusted at any time, where they can no longer perform the functions for which they were designed.

The Robust Decision Making (RDM) method is one of the analytical frameworks[11] developed to carry out such analyses (Dittrich, Wreford, and Moran 2016; R. J. Lempert *et al.* 2006, 2004; R. J. Lempert and Collins 2007). It is based on the use of digital simulations to create a broad set of plausible scenarios for the future. Each scenario represents an assumption about the functioning of the economy and/or the climate. The general principle is to confront each planned decision with this wide range of possible futures in order to (i) assess its robustness, *i.e.* to what extent the option remains satisfactory regardless of the characteristics of the future and (ii) identify the types of situations (families of futures) under which the envisaged decision would be non-efficient and highlight its weak points and vulnerabilities. Several criteria can be used to select the option to be retained based on the objective pursued, for example a MinMax Regret[12] criterion (Savage 1951; Rosenhead *et al.* 2016; Hall *et al.* 2012).

Robust decision analysis is an iterative process, often schematised in four steps (**Figure 4**). The steps can be repeated until a robust and satisfactory strategy emerges.

1. Determination of the framework of the analysis: the option(s) to be tested (candidate strategies), how to define their performance and the main risk factors with their uncertainty. This stage is generally conducted with the decision-making stakeholders.

FIGURE 4. DIAGRAM OF THE MAIN STEPS OF A ROBUST DECISION ANALYSIS



Source: (R. J. Lempert et al. 2013)

2. Generation of a (very) large number of possible futures exploring the entire field of uncertainty and assessment of the performance of the options to be tested in each case.

3. Characterisation of the performance of each candidate strategy in all plausible future states[13].

4. Analysis (graphical representation) of trade-offs comparing the performance of the different options and their robustness (or regret).

This method combines the use of digital tools to address a very large number of possibilities (generating these possibilities and identifying those that pose problems) and consulting experts or stakeholders to assess the extent of the relevant possibilities to be considered. It does not make it possible to identify the best strategy, but to discuss the trade-offs to be made. Assessment of the performance of different options in a wide variety of possible futures and use of new decision criteria (such as Minimax regret) are two distinct steps in the analysis.

Other approaches based on the same principles also exist (Decision scaling, many-objective robust decision making) and differ only in the way they generate and deal with the different possible states of the world.

Implementing this type of process can be long and costly in terms of resources and introduces a form of subjectivity in the interpretation of the proposed trade-offs. However, the analysis can be carried out in a light manner and used as a tool to launch a discussion.

10 It should be noted that the first robust solutions to be identified are decisions with no regrets, *i.e.* with a positive benefit regardless of future developments.
11 Originally developed and used by researchers at Rand Corporation.
12 Criterion consisting in minimising maximum loss (or regret) taking into account all possible scenarios.
13 At this stage, a scenario discovery algorithm can be used to identify possible families of futures in which the options envisaged are not very efficient and therefore at risk.

EXAMPLE OF APPLICATION TO THE CASE OF FRENCH NUCLEAR POLICY

For example, this approach was used by (Perrier 2018) to assess different options for the future of French nuclear power plants. France is currently at a crossroads in terms of energy policy: the 58 reactors built after the first oil shock are reaching the end of their initially planned lifetime. Should they be closed or should investments be made to extend their life – at an estimated cost of around €1.7 billion per reactor? This decision depends on several uncertain factors, in particular the evolution of the cost of renewables, the real cost of refurbishing power plants, the evolution of electricity demand and the carbon price.

To deal with these uncertainties, Perrier (2018) applies the Robust decision-making framework to determine which reactors should be modernised. It is based on a model for optimising French power plants, and uses it to study 27 strategies for renovating the nuclear facilities, according to all combinations of uncertain parameters – *i.e.* nearly 8,000 simulations. With this approach, he concludes that robust strategies involve the closure of 10 to 20 reactors, and the extension of all the other reactors. These strategies differ from official French scenarios, and offer better protection against the risks of unforeseen increases in refurbishment costs, low demand and low carbon prices.

Other application cases have been documented, for example for water resource management in Colorado and California (R.J. Lempert and Groves 2010), flood risk management in Vietnam (R.J. Lempert and Groves 2010), the dimensioning of a dam in Greece (Nassopoulos, Dumas, and Hallegatte 2012) and coastal development in Louisiana (Groves and Sharon 2013).

Conclusion: Towards an adaptation to finance?

The complexity and interactions between climate and socio-economic systems create many uncertainties about climate change. While some of these uncertainties may be reduced, most are inherent in natural climate variability and the complexity of the socio-economic system. There is, accordingly, a need to develop decision-making processes suited to this persistently uncertain environment.

Risk management has two characteristics in finance and particularly in the banking sector. First, the models are based on a probabilistic approach, the parameters being for the most part estimated from historical data. Second, banking risk management is intimately linked to a regulatory framework, which itself is constantly evolving. In order to factor in climate uncertainties, it therefore seems necessary to jointly develop decision-making tools (including models) as well as the associated regulations.

To this end, our proposal is to draw on exploratory approaches, which have mainly been developed to manage uncertainty in large-scale infrastructure projects. In the face of uncertainty, exploratory approaches study the adaptability and robustness of decision-making based on a multitude of scenarios to which no probability has been assigned.

Due to the precision of the data to be used and the scale of the analyses to be deployed for each specific case, these approaches are not suited to all decision-making processes related to risk management in the banking sector. In particular, they seem difficult to use directly for day-to-day asset management or standard lending. These practices require processes that can be used quickly and sometimes on a large scale (which can correspond to hundreds or even thousands of daily decisions). Projects that have so far used exploratory approaches have in common long durations, substantial investments, and structural or strategic roles for the economy. This is also why significant resources have been dedicated to the risk analysis process.

However, we believe there are possible variants that can be applied by a banking institution, at several levels (**Table 4**).

TABLE 4. APPLICABILITY OF EXPLORATORY APPROACHES TO BANKING MANAGEMENT PROCESSES

	Adaptability		Robustness
Process / decision	**Real option analysis**	**Dynamic adaptation pathways**	**Robust decision making**
Lending / investing for a specific asset (e.g. infrastructure, industrial, real estate projects)	++	++	++
Changing the composition of a bank loan portfolio	+	+	++
Modifying the composition of a market portfolio (long-term investment)	+	+	++
Defining the optimal allocation between major asset classes	++	++	++
Defining the optimal financing of the institution	+	+	+
Checking the institution’s solvency	+	+	++
Checking the institution’s liquidity	+	+	++
Checking compliance with stress tests (internal and regulatory)			++

Source: authors

Note: The “+”; “++” reflect the authors’ subjective estimate of the relevance and feasibility of further exploring possible uses of these tools in these decision-making processes.

1. Financing of specific assets: the only direct use

The most natural adaptation of exploratory approaches such as real option analyses, adaptation pathways or robust decision analyses concerns specific investment or asset financing decisions: infrastructure[14], large industrial or real estate projects. The scale of such projects, their relatively small number, the long time horizons involved and the low liquidity of these assets justify analyses specific to each asset undertaken by investors and financiers. This would make all the more sense as these projects are often very significant. Conducting them without taking climate issues into account creates a high lock-in risk in carbon intense trajectories (generating stranded assets). On the contrary, taking into account adaptability and robustness issues into their development can help shape a low-carbon and resilient economic model. International donors, particularly among development banks, are already experimenting with the use of robust decision-making analyses in the conduct

14 Investment needs in infrastructure development worldwide amount to $90,000 billion by 2030.(The new climate economy 2016).

of some of their projects. This is particularly the case of the World Bank and the EBRD[15]. Also, investors have a role to play in disseminating these risk management approaches to their counterparts.

2. Management of securities or loan portfolios

Exploratory approaches and in particular analyses of robust decisions could also make it possible to optimise the management of portfolios whose assets are intended to be kept over the long term (investment and loan portfolios). Decision-making criteria such as Minimax regret[16] (Kunreuther Geoffrey Heal Myles Allen Ottmar Edenhofer Christopher Field Gary Yohe *et al.* 2012; Battiston 2019) could, for example, make it possible to optimise not daily management, but the broad lines of sector segmentation within a portfolio of financial assets. This would involve testing the performance and risk exposure of several strategies for defining its investment universe in a wide variety of possible futures characterised, for example, by different carbon price values and/or by different probabilities of occurrence of climatic events to which the portfolio is exposed (in terms of frequency, geography, etc.).

3. Asset-liability management

Lastly, we believe it is relevant and possible to extend the recommendations of the TCFD (2017) by applying exploratory approaches in asset-liability management, in strategic decision-making processes and in conducting stress tests[17]. Defining the asset-liability management strategy is a long-term, structuring process for the banking institution. Applying robust decision analyses and identifying options to ensure the institution's long-term adaptability to various exogenous scenarios is therefore crucial. In addition to assessing the current robustness of the institutions to different change scenarios, the aim would also be to identify among possible development spectra which trajectories or events would be particularly problematic and to understand where the vulnerabilities are and how the risks spread. However, the decisions associated with asset-liability management are currently particularly regulated by banking regulations. Although exploratory studies can already be carried out, changes in practices over the medium term must be accompanied by an adaptation of the regulatory framework.

Transposing the exploratory approaches presented above into financial risk management corresponds to a radical change in risk assessment to adapt to the specific characteristics of climate risk. This note helps remove certain theoretical obstacles to such an approach. But the operational limits will also have to be discussed. Operational implementation challenges would depend on how these exploratory approaches would be transposed. In any case, such a change would nevertheless require financial and human resources, as well as a reorganisation of the risk management processes that would have to take into account the regulatory constraints that already exist. At this stage, such work could be envisaged as part of market initiatives, whether conducted by banking institutions or by the regulator (such as the working groups of UNEP FI or the Network for Greening the Financial System (NGFS 2019)).

In practice, the next step could be to conduct a case study on one of the situations proposed in Table 4, involving players from financial institutions (front office and financial risk management), the regulator as well as academic researchers.

15 https://www.ebrd.com/news/2014/climate-resilience-and-hydropower-in-tajikistan.html
16 Similar to the proposed examples of robust decision analysis
17 It should be noted here that considering situations of information to which no probability can be assigned is not a novelty in itself in financial analysis. Consideration of the geopolitical context in the assessment of credit risk or in the evaluation of companies' capacity to innovate in rapidly changing markets such as those of digital technologies are common challenges. Financial analysts then have a qualitative assessment based on expert opinions (Raynaud *et al.* 2018). This consists of issuing an ex-post assessment, downstream of the quantitative assessment of conventional risks to qualify or strengthen the modelling result with regard to non-quantitative assessment factors.

References

Battiston, Stefano. 2019. "Face Au Risque Climatique, Il Faut Adopter Une Attitude Prospective Pour Préserver La Stabilité Financière." *Revue de La Stabilité Financière : Verdir Le Système Financier : La Nouvelle Frontière*, no. 23: 21–52.

Bree, Leendert Van, and Jeroen P Van der Sluijs. 2014. "Background on Uncertainty Assessment Supporting Climate Adaptation Decision-Making." In *Adapting to an Uncertain Climate: Lessons from Practice*, edited by Capela Lourenço T. *et al.*, 17–40. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-04876-5_2.

Bruggen, Anne van, Igor Nikolic, and Jan Kwakkel. 2019. "Modeling with Stakeholders for Transformative Change." *Sustainability* 11 (3): 825. https://doi.org/10.3390/su11030825.

Bryant, Benjamin P, and Robert J Lempert. 2010. "Thinking inside the Box: A Participatory, Computer-Assisted Approach to Scenario Discovery." *Technological Forecasting and Social Change* 77 (1): 34–49. https://doi.org/10.1016/j.techfore.2009.08.002.

Buurman, Joost, and Vladan Babovic. 2016. "Adaptation Pathways and Real Options Analysis: An Approach to Deep Uncertainty in Climate Change Adaptation Policies." *Policy and Society* 35 (2): 137–50. https://doi.org/10.1016/j.polsoc.2016.05.002.

Carney, Mark. 2015. "Breaking the Tragedy of the Horizon–climate change and financial stability". Speech given at Lloyd's of London 29th September 2015.

CICERO. 2017. "Shades of Climate Risk, Categorizing Climate Risk for Investors."

CRED-UNISDR. 2017. "Economic Losses, Poverty & Disasters (1998-2017)." https://doi.org/10.1111/j.1469-7610.2010.02280.x.

Dessai, Suraje, Ajay Bhave, Cathryn Birch, Declan Conway, Luis Garcia-Carreras, John Paul Gosling, Neha Mittal, and David Stainforth. 2018. "Building Narratives to Characterise Uncertainty in Regional Climate Change through Expert Elicitation." *Environ. Res. Lett.* in press (7): 0–48. https://doi.org/10.1088/1748-9326/aabcdd.

Dessai, Suraje, and Jeroen P Van der Sluijs. 2007. *Uncertainty and Climate Change Adaptation - a Scoping Study*. *Sustainable Development*.

Dittrich, Ruth, Anita Wreford, and Dominic Moran. 2016. "A Survey of Decision-Making Approaches for Climate Change Adaptation: Are Robust Methods the Way Forward?" *Ecological Economics*. https://doi.org/10.1016/j.ecolecon.2015.12.006.

Gros, D., Lane, P. R., Langfield, S., Matikainen, S., Pagano, M., Schoenmaker, D., & Suarez, J. 2016. "Too late, too sudden: Transition to a low-carbon economy and systemic risk" (No. 6). Reports of the Advisory Scientific Committee.

European Commission. 2018. "Plan d'action de La Commission Pour Une Économie plus Verte et plus Propre."

Groves, David G., and Christopher Sharon. 2013. "Planning Tool to Support Planning the Future of Coastal Louisiana." *Journal of Coastal Research*. https://doi.org/10.2112/si_67_10.

Haan, Fjalar J. de, Briony C. Rogers, Rebekah R. Brown, and Ana Deletic. 2016. "Many Roads to Rome: The Emergence of Pathways from Patterns of Change through Exploratory Modelling of Sustainability Transitions." *Environmental Modelling and Software* 85: 279–92. https://doi.org/10.1016/j.envsoft.2016.05.019.

Haasnoot, Marjolijn, Jan H Kwakkel, Warren E. Walker, and Judith ter Maat. 2013. "Dynamic Adaptive Policy Pathways: A Method for Crafting Robust Decisions for a Deeply Uncertain World." *Global Environmental Change* 23 (2): 485–98. https://doi.org/10.1016/j.gloenvcha.2012.12.006.

Hall, J W, Robert J Lempert, K Keller, A Hackbarth, C Mijere, and D J McInerney. 2012. "Robust Climate Policies Under Uncertainty: A Comparison of Robust Decision Making and Info- Gap Methods" 32 (10): 1657–72.

Hallegatte, Stéphane, Ankur Shah, Casey Brown, Robert J Lempert, and Stuart Gill. 2012. "Investment Decision Making Under Deep Uncertainty: Application to Climate Change." *Policy Research Working Paper*, no. 6193 (September): 41. https://doi.org/doi:10.1596/1813-9450-6193.

Hawkins, Ed, and Rowan Sutton. 2009. "The Potential to Narrow Uncertainty in Regional Climate Predictions."

Henry, Claude. 2013. "Incertitude Scientifique et Incertitude Fabriquée" 64 (4): 589–98.

Hubert, Romain, Julie Evain, and Morgane Nicol. 2018. "Getting Started on Physical Climate Risk Analysis in Finance (Projet ClimINVEST)." Paris.

IPCC. 2014. "Working Group II Contribution to the IPCC Fifth Assessment Report, Climate Change 2014: Impacts, Adaptation and Vulnerability." Ipcc AR5 (2014).

———. 2018. "IPCC Special Report on the Impacts of Global Warming of 1.5 °C - Summary for Policy Makers," no. October 2018. http://www.ipcc.ch/report/sr15/.

Knight, Frank. 1921. *Risk, Uncertainty and Profit. Risk, Uncertainty and Profit, Houghton Mifflin Company, Boston, MA*. https://doi.org/10.1017/CBO9780511817410.005.

Kunreuther Geoffrey Heal Myles Allen Ottmar Edenhofer Christopher Field Gary Yohe, Howard B, Simon Dietz, Kristie Ebi, Christian Gollier, Robin Gregory, Benjamin Horton, Elmar Kriegler, *et al.* 2012. "Nber Working Paper Series Risk Management and Climate Change."

Kwakkel, Jan H, Marjolijn Haasnoot, and Warren E Walker. 2016. "Comparing Robust Decision-Making and Dynamic Adaptive Policy Pathways for Model-Based Decision Support under Deep Uncertainty." *Environmental Modelling and Software* 86: 168–83. https://doi.org/10.1016/j.envsoft.2016.09.017.

Lempert, Robert. 2013. "Scenarios That Illuminate Vulnerabilities and Robust Responses." *Climatic Change* 117 (4): 627–46. https://doi.org/10.1007/s10584-012-0574-6.

Lempert, Robert J., and David G. Groves. 2010. "Identifying and Evaluating Robust Adaptive Policy Responses to Climate Change for Water Management Agencies in the American West." *Technological Forecasting and Social Change*. https://doi.org/10.1016/j.techfore.2010.04.007.

Lempert, Robert J, and Myles T Collins. 2007. "Managing the Risk of Uncertain Threshold Responses: Comparison of Robust, Optimum and Precautionary Approaches." *Risk Analysis* 27 (4): 1009–26.

Lempert, Robert J, David G Groves, Steven W Popper, and Steve C Bankes. 2006. "A General, Analytic Method for Generating Robust Strategies and Narrative Scenarios." *Management Science* 52 (4): 514–28. https://doi.org/10.1287/mnsc.1050.0472.

Lempert, Robert J, K Kalra, S Peyraud, Z Mao, S B Tan, D Cira, and A Lotsch. 2013. "Ensuring Robust Flood Risk Management in Ho Chi Minh City."

Lempert, Robert J, N Nakicenovic, Daniel Sarewitz, and M Schesinger. 2004. "Characterizing Climate-Change Uncertainties for Decision-Makers" 65 (1): 1–9.

Maier, H. R., J. H.A. Guillaume, H. van Delden, G. A. Riddell, M. Haasnoot, and Jan H Kwakkel. 2016. "An Uncertain Future, Deep Uncertainty, Scenarios, Robustness and Adaptation: How Do They Fit Together?" *Environmental Modelling and Software* 81: 154–64. https://doi.org/10.1016/j.envsoft.2016.03.014.

Malekpour, Shirin, Rebekah R. Brown, Fjalar J. de Haan, and Tony H.F. Wong. 2017. "Preparing for Disruptions: A Diagnostic Strategic Planning Intervention for Sustainable Development." *Cities* 63: 58–69. https://doi.org/10.1016/j.cities.2016.12.016.

Malekpour, Shirin, Fjalar J. de Haan, and Rebekah R. Brown. 2016. “A Methodology to Enable Exploratory Thinking in Strategic Planning.” *Technological Forecasting and Social Change* 105: 192–202. https://doi.org/10.1016/j.techfore.2016.01.012.

Marchau, Vincent A. W. J., Warren E. Walker, Pieter J. T. M. Bloemen, and Steven W. Popper. 2019. *Decision Making under Deep Uncertainty: From Theory to Practice. Decision Making under Deep Uncertainty*. : Springer International Publishing. https://doi.org/10.1007/978-3-030-05252-2_1.

Métivier, Clément, Clément Bultheel, and Sébastien Postic. 2020. “Les comptes mondiaux du carbone en 2018», I4CE.

Monnin, Pierre. 2018. “Integrating Climate Risks into Credit Risk Assessment. Current Methodologies and the Case of Central Banks Corporate Bond Purchases.”

Nassopoulos, Hypatia, Patrice Dumas, and Stéphane Hallegatte. 2012. “Adaptation to an Uncertain Climate Change: Cost Benefit Analysis and Robust Decision Making for Dam Dimensioning.” *Climatic Change* 114 (3–4): 497–508. https://doi.org/10.1007/s10584-012-0423-7.

NGFS. 2019. “A call for action Climate change as a source of financial risk”.

Nicol, Morgane, Romain Hubert, Ian Cochran, and Benoît Leguet. 2017. “Gérer Les Risques de Transition de Son Portefeuille : De La Théorie à La Pratique.”

Penning-Rowsell, Edmund C., Nick Haigh, Sarah Lavery, and Loraine McFadden. 2013. “A Threatened World City: The Benefits of Protecting London from the Sea.” *Natural Hazards* 66 (3): 1383–1404. https://doi.org/10.1007/s11069-011-0075-3.

Perrier, Quentin. 2018. “The Second French Nuclear Bet.” *Energy Economics* 74 (2018): 858–77. https://doi.org/10.1016/j.eneco.2018.07.014.

Ranger, N, T Reeder, and J Lowe. 2013. “Addressing ‘Deep’Uncertainty over Long-Term Climate in Major Infrastructure Projects: Four Innovations of the Thames Estuary 2100 Project.” *EURO Journal on Decision Processes* 1 (3): 233–62.

Raynaud, Julie, Nicole Röttmer, Samuel Mary, Jean-Christian Brunke, and David Knewitz. 2018. “Climate Scenario Compass: Climate Change & Natural Capital (E.T Risk Project).”

Rosenhead, Jonathan, Martin Elton, Shiv K Gupta, and Jonathan Rosenhead. 2016. “Robustness and Optimality as Criteria for Strategic Decisions” 23 (4): 413–31.

Röttmer, Nicole, Jana Mintenig, and Luke Sussams. 2018. “Climate Change Scenarios: Risks and Opportunities (E.T Risk Project).”

Savage, L. J. 1951. “The Theory of Statistical Decision.” *Journal of the American Statistical Association* 46 (253): 55–67.

Sluijs, Jeroen P Van der. 1997. “Anchoring Amid Uncertainty: On the Management of Uncertainties in Risk Assessment of Antropogenic Climate Change.” Universiteit Utrecht.

———. 2010. “Uncertainty and Complexity: The Need for New Ways of Interfacing Climate Science and Climate Policy.” In *From Climate Change to Social Change*, edited by D Driessen, P Leroy, and W Van Vierssen, 31–49. Utrecht International Books.

Swiss Re Institute. 2017. “Catastrophes Naturelles et Techniques En 2016 : Une Année de Dommages Tous Azimuts.”

TCFD. 2017. “Recommendations of the Task Force on Climate-Related Financial Disclosures.” *Launch at the Tate Modern*. https://doi.org/10.1007/s00028-003-0117-8.

The New climate Economy. 2016. “The Sustainable Infrastructure Imperative: Financing for Better Growth and Development.”

Trutnevyte, Evelina, Céline Guivarch, Robert J Lempert, and Neil Strachan. 2016. “Reinvigorating the Scenario Technique to Expand Uncertainty Consideration.” Climatic Change 135 (3–4): 373–79. https://doi.org/10.1007/s10584-015-1585-x.

UK Environment Agency. 2012. “Thames Estuary 2100: Managing Flood Risk through London and the Thames Estuary.”

———. 2016a. “TE2100 5 Year Monitoring Review.”

———. 2016b. “TE2100 5 Year Review Non-Technical Summary.”

UNEP FI, and Acclimatise. 2018. “Navigating a New Climate. Assessing Credit Risk and Opportunity in a Changing Climate: Outputs of a Working Group of 16 Banks Piloting the TCFD Recommendations PART 2: Physical Risks and Opportunities.” *Finance: UNEP Initiative*. Vol. 2.

UNEP FI, and Carbon Delta. 2019. “Changin Course: A Comprehensive Investor Guide to Scenario-Based Methods for Climate Risk Assessment , in Response to the TCFD.”

Vailles, Charlotte, and Clément Métivier. 2019. “Very Few Companies Make Good Use of Scenarios to Anticipate Their Climate-Constrained Future.” *Climate Brief* - I4CE. Vol. 61.

Walker, Warren E., M Haasnoot, and Jan H Kwakkel. 2013. “Adapt or Perish: A Review of Planning Approaches for Adaptation under Deep Uncertainty.” Sustainability 5 (3): 955–79.

Walker, Warren E., S. Adnan Rahman, Jonathan Cave, M Haasnoot, and Jan H Kwakkel. 2001. “Adaptive Policies, Policy Analysis, and Policy-Making.” *European Journal of Operational Research* 128 (2): 282–89. https://doi.org/10.1016/S0377-2217(00)00071-0.

Wardekker, J. Arjan, Arie de Jong, Joost M. Knoop, and Jeroen P van der Sluijs. 2010. “Operationalising a Resilience Approach to Adapting an Urban Delta to Uncertain Climate Changes.” *Technological Forecasting and Social Change* 77 (6): 987–98. https://doi.org/10.1016/j.techfore.2009.11.005.

Watkiss, Paul, Alistair Hunt, William Blyth, and Jillian Dyszynski. 2015. “The Use of New Economic Decision Support Tools for Adaptation Assessment: A Review of Methods and Applications, towards Guidance on Applicability.” *Climatic Change* 132 (3): 401–16. https://doi.org/10.1007/s10584-014-1250-9.

Werners, Saskia E, Stefan Pfenninger, Erik van Slobbe, Marjolijn Haasnoot, Jan H Kwakkel, and Rob J Swart. 2013. “Thresholds, Tipping and Turning Points for Sustainability under Climate Change.” *Current Opinion in Environmental Sustainability* 5 (3–4): 334–40. https://doi.org/10.1016/j.cosust.2013.06.005.

Woodward, Michelle, Zoran Kapelan, Ben Gouldby, Z Kundzewicz, and Ben Gouldby. 2014. “Adaptive Flood Risk Management under Climate Change Uncertainty Using Real Options and Optimization.” *Risk Analysi* 34 (1): 74–92. https://doi.org/10.1111/risa.12088.

Word Bank Group. 2018. “State and Trends of Carbon Pricing 2018 by Word Bank Group.” Washington, DC: World Bank. https://openknowledge.worldbank.org/bitstream/handle/10986/29687/9781464812927.pdf.

World Economic Forum. 2019. “The Global Risks Report 2019.”

World Health Organization. 2018. “COP24 Special Report: Health and Climate Change.”

Wyman, Oliver. 2018. “Extending Our Horizons: Assessing Credit Risk and Opportunity in a Changing Climate: Outputs of a Working Group of 16 Banks Piloting the TCFD Recommendations.”

Yiou, Pascal, and Jean Jouzel. 2015. *Le Temps s’est-Il Détraqué ? : Comprendre Les Catastrophes Climatiques*. Edited by Buchet-Chastel. Paris.

Appendix

OVERVIEW OF BANK REGULATIONS

Following the various bank failures and financial crises, the regulator has been heavily involved in the management of banking sector risks since the late 1980s. The objective of the regulations is to ensure that banks are sufficiently capitalised with regard to the risks taken, in particular to guarantee depositor security and financial stability. The international standards of these regulations are derived from the recommendations of the Basel Committee: *"The Basel Committee standards are not directly legally binding. Nevertheless, the members of the Committee have a moral commitment to implement them in their legislative and regulatory framework".*

In 1988, the first Basel Agreement marked the beginning of the implementation of international standards for banking regulation (derived from the G10) and dealt only with credit risk. Basel I required banks to hold capital equal to at least 8% of their risk-weighted assets (Cooke ratio). A Basel I reform was introduced in 1996 to take market risk into account. Basel II, which has been in place since the end of 2007, aims to refine capital requirements according to the quality of issuers within companies. However, the 2007/2008 crisis called for a more comprehensive overhaul of the Basel agreements. The Basel III agreements, finalised in December 2017 and applicable from 2022, aim first of all to strengthen the level and quality of capital. An important component is dedicated to liquidity risk[19], particularly during the 2007/2008 crisis.

The Basel agreements are broken down into three pillars:

- **Pillar 1:** minimum capital requirements for banks (quality and level of capital);
- **Pillar 2:** risk management and monitoring process (governance);
- **Pillar 3:** market discipline (transparency and communication of financial information).

The Basel Committee standards are incorporated into European legislation (directives or regulations[20]). Faced with the sovereign debt crisis at the start of this decade, European leaders decided to create a European banking union, the first pillar of which is the implementation of a single supervisory mechanism (SSM) for Eurozone banks. The SSM is implemented by the European Central Bank (ECB) with the support of national supervisory authorities (in France, the French Prudential Supervision and Resolution Authority[21] - ACPR).

In addition to prudential regulation, IFRS 9 is an accounting standard for financial instruments and replaced IAS 39 in 2018. IFRS 9 introduces as a general principle the measurement at fair value of financial assets and liabilities. The cornerstone of this standard concerns the impairment of assets. At each reporting date, the financial institution must estimate the *expected losses* for a financial instrument and use the incurred losses model of IAS 39. These expected losses must be estimated on *the entire life of the product*, which represents a significant change in terms of time horizon and methodology.

18. Source: https://acpr.banque-france.fr/europe-et-international/banques/instances/comite-de-bale, consulted on 5 June 2019
19. The LCR (Liquidity Coverage Ratio) should enable banks to weather a liquidity crisis for one month. Also, Basel III introduces the NSFR (Net Stable Funding Ratio), which corresponds to the ratio between available stable funding and stable funding requirements over a one-year period.
20. Directive 2013/36/EU (the «CRD4») and Regulation (EU) No. 575/2013 (the «CRR») transpose Basel III into the European Union.
21. Since November 2014, the ECB has thus become the competent supervisory authority for so-called «significant» credit institutions.

INSTITUTE FOR CLIMATE ECONOMICS

Une initiative de la Caisse des Dépôts et de l'Agence Française de Développement

www.i4ce.org

Réalisation : SophieBerlioz.fr

The original document has been published in French. The authors would like to sincerely thank the Institut Louis Bachelier for the translation into English of this report.