Index Insights

Sustainable Investment | Climate Risks

Anticipating the climate change risks for sovereign bonds

Part 1: Insights on the macroeconomic impacts

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Overview

The deep economic changes necessary to achieve the Paris Agreement objectives require a consistent reallocation of resources. This gives the financial sector a key role in tackling climate change. Risk analysis is important in that perspective.

Due to the nature of climate change, with unprecedented and non-linear, dynamics, relying on historical data is not sufficient to anticipate climate change risks. This paper proposes a methodology for a forward-looking assessment of climate risks as recommended by regulating international institutions.

It is the first of a two-part study whose objective is to explore how sovereign bonds could be affected by climate change risks. This first part focuses on assessing the macroeconomic impacts related to climate change. Two “worst case” scenarios (similar to current trends, though) are explored, leading to the following conclusions:

- The magnitude of the estimated impacts is very high, with tens of GDP percentage points at risk in 2050 in the most vulnerable countries, from both transition and physical risks.
- Economically significant impacts could appear from 2030 onward.
- Accordingly, investors should take climate change consequences very seriously in their investment decisions.
- Overall, the results underline clear benefits of an orderly transition that would enable the development of sustainable economic activities.

Contents

1. Executive summary

- Among the necessary actions to implement the Paris Agreement, the assessment and disclosure of financial climate-related risks is critical. This would be a major step toward "making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development" (article 2.1.c of the Agreement).
- Climate change implies two main categories of risk for financial stakeholders through (i) its physical impacts and (ii) the transition to a carbon-neutral economy required to mitigate it. While a clear understanding of these risks could catalyze the reallocation of financial resources, a growing number of studies show that financial markets tend to undervalue climate change risks.
- Due to the nature of climate change, with underlying unprecedented, non-linear and likely irreversible dynamics, relying on historical data is not sufficient to anticipate climate change risks. As recommended by regulating international institutions, this paper proposes a methodology for a forward-looking assessment of climate-related risks. Providing a risk assessment at country level is another interesting outcome of this work.
- Two "worst-case" scenarios are independently explored in our analytical framework. It supposes pessimistic evolutions, with a continuation of past trends of greenhouse gas (GHG) emissions assumed in the assessment of the physical risks, and "last moment" mitigation efforts by the countries assumed in the assessment of the transition risk. When assessing risk, it is generally a reasonable approach to consider the more pessimistic scenarios. Furthermore, these hypotheses are not so far from current trends.
- The analysis shows that the higher current average temperature in equatorial regions makes them more vulnerable to global warming, where physical risks are very high. For example, the projected loss in GDP per capita in Malaysia reaches 31% in 2050 in the context of an unmitigated climate change.
- Despite a partial coverage of physical risks in this study, most countries would suffer significant negative impacts. Developed economies such as the US would be expected to lose 20% in GDP per capita by 2050.
- Countries with the most carbon intensive economies are, not surprisingly, the most exposed to transition risks; South Africa, Mexico, Poland, the United States, Australia and Canada are particularly exposed. The situation is all the more worrying in the United States, Australia and Canada where the depletion year of their carbon budget (consistent with a 2°C target) is very close.
- Countries that have already implemented significative carbon price measures such as market of GHG emissions quotas and fuel tax show better performances in this analysis, even if the transition risk is still significant.

2. Introduction

Regulators have sent clear warnings that financial assets are put at risk by the impacts of climate change, and that this risk could be mispriced by markets. The Network for Greening the Financial System (NGFS)[1] assumes a "strong risk that climate-related financial risks are not fully reflected in asset valuations," and therefore considers the better assessment of the transition and physical risks as a high priority for the financial sector (see Appendix for more details on the general context). Undervaluation by investors can be related to the lack of well-established and easily applicable framework.

The methodology proposed in this paper is *forward-looking* and scenario based. There is a broad consensus among regulating international institutions on the specific nature of the climate change risks and the need to make projections in the framework of climate and economic scenarios to estimate these risks. Relying only on past data would be inconsistent with unprecedented, non-linear and complex (irreversibility, correlations[2], etc.) dynamics of climate change. The recent positions by the main financial regulators[3] in favor of using a *forward-looking approach* to assess climate risks, can be interpreted as a shift of paradigm in a sector used to rely on empirical studies.

This paper is the first of a two-part study whose objective is to explore how the sovereign bond asset class could be affected by climate change risks. In the first part, the focus will be on the macroeconomic impacts. The next part will focus on the financial risk assessment that can result from this first macroeconomic analysis.

The choice of the macro level for our assessment is relevant *a priori* in the perspective of the sovereign risks' analysis. It could also be useful in the case of corporate risks (by proxy) by providing estimated impacts for the country in which a given corporate operates. Moreover, the micro risks (such as the market or liquidity risks) would be highly correlated to the macro risk given the order of magnitude of the expected shocks. As a first approximation, the impacts from climate change are measured in GDP percentage points.

Overview of the scenarios

Climate change risks are generally divided in two main types:

- *Physical risks*: risk of damages to human capital (mortality, productivity degradation, *etc*.), physical capital (destruction of infrastructures) and natural capital (decrease in crops yield, biodiversity losses, etc.). The damages can result from (i) extreme weather events such as hurricanes or floods (acute risk), or (ii) continual changes such as rise in temperatures or sea level (chronic risk);

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[1] NGFS, (2019), *First comprehensive report - A call for action Climate change as a source of financial risk.*
The Network for Greening the Financial System (NGFS) is a network of central banks and supervisors, launched at the One Planet Summit in 2017 in Paris, aiming at strengthening the global response required to meet the goals of the Paris agreement and to enhance the role of the financial system to manage climate change-related risks.

[2] Virtually all sectors and regions are exposed to these risks, with trade and financial relations spreading the local shocks

[3] See for instance:
- TCFD (2017b) *Technical Supplement: The Use of Scenario Analysis in Disclosure of Climate-related Risks and Opportunities* and TCFD (2019), 2019 Status Report.
- NGFS, (2019), *First comprehensive report - A call for action Climate change as a source of financial risk.*
- Grippa et al. (2019), *Climate Change and Financial Risk, Finance & Development.* [IMF journal]
- European Commission (2019), *Guidelines on non-financial reporting: Supplement on reporting climate-related information*, 2019/C 209/01.
- Bank of England (2019), *Enhancing banks' and insurers' approaches to managing the financial risks from climate change*, Bank of England Prudential Regulation Authority, Supervisory Statement SS3/19.
- Bank for International Settlements (2020), *Green Swan 2 – Climate change and Covid-19: reflections on efficiency versus resilience*, BIS Speech by Luiz A Pereira da Silva, May 13.

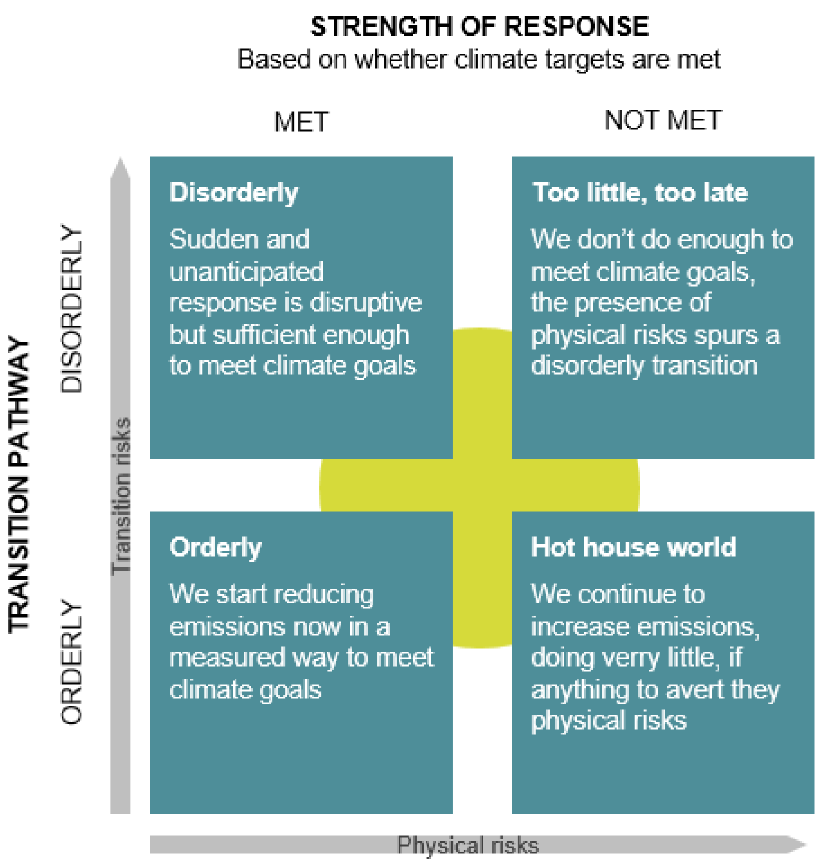
- *Transition risk*: "financial risks which could result from the process of adjustment towards a lower-carbon economy" (Carney, 2015)[4].

For the physical risks, this paper relies on Burke *et al*. (2015[5]) and Burke and Tanutama (2019[6]), and provides estimates of economic damages caused by productivity loss after a temperature increase. The climate scenario associated to these estimations is the RCP 8.5 scenario, corresponding to a global warming of about 4°C (2100 horizon). This scenario belongs to the "hot house world"[7] category of scenario in the framework developed by the NGFS (see chart 1 and Appendix for further details). It is important to note that the choice of this methodology implies that the impacts of the extreme weather events (acute risks) and the sea level rise are not captured in the estimations.

Regarding the transition risk, a specific methodology is developed in this paper to estimate the potential economic shock of a very abrupt transition, corresponding to the "disorderly transition" category of scenario in the NGFS framework (see again chart 1 and Appendix). The methodology assumes that the countries would make no further effort until the depletion of their "carbon budget" (consistent with a 2° target). Rather, they would use—in the final year—last resort technologies to respect their commitment to achieve the mitigation goal of the Paris Agreement.

Chart 1. The climate scenarios framework designed by the NGFS [a] and key elements of this study's framework [b]

[a]



Source: NGFS (2019a).

[4] Carney, M. (2015), *Breaking the Tragedy of the Horizon – climate change and financial stability*, speech delivered at Lloyd's of London, September 29
[5] Burke, M., Hsiang, S. M. & Miguel, E., 2015. Global non-linear effect of temperature on economic production. *Nature.*
[6] Burke, M., & Tanutama, V. (2019). Climatic constraints on aggregate economic output (No. w25779). National Bureau of Economic Research.
[7] The expression "hot house" used to qualify the NGFS worst case scenario, comes from the scientific term "Hothouse earth," which refers to a climatic state whose warming conditions are extreme and lead outside any climate equilibrium as seen for 100,000 years.

[b]

Scenario	Risk assessed	Main assumption	Main result
Disorderly transition	Transition	200$/tCO2 of abatement cost from carbon budget exhaustion	5% decrease in GDP/capita on average in WGBI countries
Hot house world	Physical	RCP8.5 trajectory (corresponding to a global warming of about $4^{0}C$)	16% decrease in GDP/capita on average in WGBI countries by 2050
Orderly transition	Not covered		
Too little, too late	Not covered		

The impacts of the “disorderly transition” and “hot house world” situations and their associated risks (respectively transition and physical risks) are assessed independently. Despite its disorderly nature in terms of public policies, the “disorderly transition” scenario supposes limited physical risks as climate targets are supposed to be met. Conversely, the “hot house world” scenario supposes unmitigated climate change, and therefore limited transition risks.

Overall, the analytic framework supposes pessimistic policy reaction. The impacts presented in this paper should be considered as belonging to the “upper limit” of the estimates. When assessing a risk, paying particular attention to the pessimistic scenario is a reasonable approach. It is especially important in the case of climate change in view of its non-linear impacts. Moreover, on one hand, the RCP 8.5 is the closest scenario from the current trends and still represents a plausible evolution[8]. On the other hand, the strategies for the vast majority of governments are not on track for an orderly transition. They are more akin to a “wait and see” strategy. In the end, although pessimistic, the analytic framework of this study is relevant in the current context.

The most significant contribution of this paper is to provide estimations of climate change risks at the country level. In general, the results of these estimates are presented for a list of 26 countries, which are constituents of the FTSE World Government Bond Index (WGBI). This has the advantage, in the perspective of the second part of the study, to give the results for a representative group of the sovereign bond market.

[8] See Schwalm *et al*., 2020. RCP8.5 tracks cumulative CO2 emissions. *PNAS*

3. Physical risks: a “hot house world” scenario

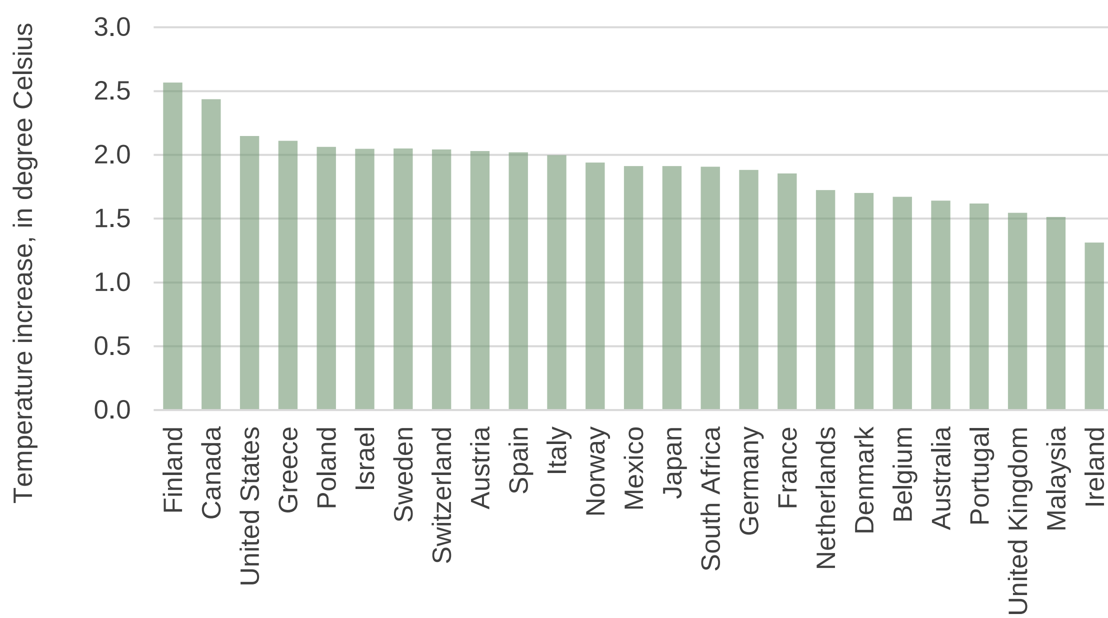
The first part of this section highlights the heterogeneity in the geographic impact of the global warming scenario. The second part presents the economic impact of the rising temperature by country. The final part shows the exposure to physical risks at the index level, using WGBI as the benchmark.

3.1 Global warming scenario

The usual scenario framework for climate researches is the *Representative Concentration Pathway* (RCP) scenarios developed in the framework of the 5th assessment report of the *Intergovernmental Panel on Climate change*—IPCC (AR5). Each RCP scenario (RCP 2.6, 4.5, 6.0 or 8.5) corresponds to a different level of GHG concentration in the atmosphere. Following the works of Burke *et al.* (2015), as in many other studies, the RCP 8.5 is considered in this paper as a “business as usual” scenario, and therefore as relevant to underpin the estimation of potential damages without proactive mitigation policies. This is close to the definition given by the NGFS for the hot house world scenario[9].

The geographical heterogeneity of temperature projections is an important point. Broadly, countries close to the equator should expect a lower increase than countries closer to the poles (see Chart 2). Among countries component of the WGBI[10], Canada and Finland would experience the highest temperature increase by 2050 (up to 2.5 Celsius degrees increase) compared to their historical (1980-2010) average. At the opposite end, Malaysia’s annual average temperature would rise by less than 1.5 degrees in the RCP 8.5 scenario.

Chart 2. Temperature increase by country up to 2050, scenario RCP 8.5



Source: Beyond Ratings, based on Burke et al. (2015) data.

[9] The NGFS climate-related scenarios regarding global temperature increase are given by a carbon-cycle and climate model (MAGICC), simulating the change in global mean temperature given a specified evolution of climate-relevant emissions. These evolutions are taken from Integrated Assessments Models (IAMs) simulated with different scenarios assumptions (further discussed in the transition risks part). As mentioned previously, in orderly and disorderly scenarios, climate goals are met by deep reductions in emissions, limiting the rise in global mean temperatures below 2°C with a 67% likelihood by the end of the century. In the hot house world scenario, transition does not occur, leading to a temperature rise exceeding 3°C and severe and irreversible impacts.

[10] Singapore is part of the WGBI but is not included in this physical risk analysis since Burke et al. did not include the country in their analysis.

3.2 Economic shocks resulting from the physical impacts from climate change

Damage functions, linking increase in temperature and GDP loss, are instruments widely used in climate change economics. They have been criticized, especially for their lack of empirical foundations (see for instance Pindyck, 2013[11]), but progress has been made in this regard over the last few years.

Following the IMF[12], this study builds on the works from Burke et al. (2015) to assess the countries' exposure to climate change physical risks. To estimate the economic damage of climate change, these authors rely on an econometric regression establishing a quadratic empirical relationship between the growth in GDP per capita and mean annual temperature[13]. They find an "optimal temperature," below and beyond where productivity[14] decreases. However, Burke and Tanutama (2019) found that this previous work overestimated the optimal temperature by underestimating the intra-country heterogeneity.

Contrary to the 2015 study estimates relying on country level data, the 2019 work is based on data at the local level (named as "districts" in the study, corresponding to counties in the United States, and local administrative units in the other countries). Therefore, the 2019 approach accounts for the intra-country heterogeneity in the approximated relation between productivity growth and temperature, in addition to the inter-countries heterogeneity already captured in the estimations of the 2015 paper.

Therefore, in this analysis, the economic damage at country level is estimated in the same modelling framework than in Burke *et al.* (2015) and Burke and Tanutama (2019), relying on the estimated coefficients from Burke and Tanutama (2019) for calibration (see Annex for the formalisation and illustration of the damage function).

Finally, the resulting damages take into account the strong heterogeneity of the countries' vulnerability to temperature increase. They depend on: (i) historical annual average temperature and (ii) increase in the annual average temperature. However, it is important to note that the econometric estimations used to calibrate the damage function do not capture the effect of extreme weather events and sea level rise[15], likely leading to underestimated results.

Current climate matters

The current climate, approximated by the average annual temperature during the period 1980-2010, has a strong influence on the damages by country presented in the next section. When an average temperature is much higher than the optimal temperature from Burke and Tanutama (2019), even a slight increase in temperature results in a significant negative impact on productivity. This explains why countries near the equator are particularly vulnerable to temperature increase, despite the lower increases described in the previous part.

For instance, among countries in the WGBI, Malaysia's historical average temperature is more than 25°C. At the other extreme, Finland experienced the lowest average temperature among WGBI components (around 3°C), which would be lower than the optimal temperature. This means that an increase in temperature could result in an increase in productivity, according to the Burke and Tanutama (2019) estimates.

[11] Pindyck (2013), *Climate Change Policy: What Do the Models Tell us?* NBER Working Paper N° 19244

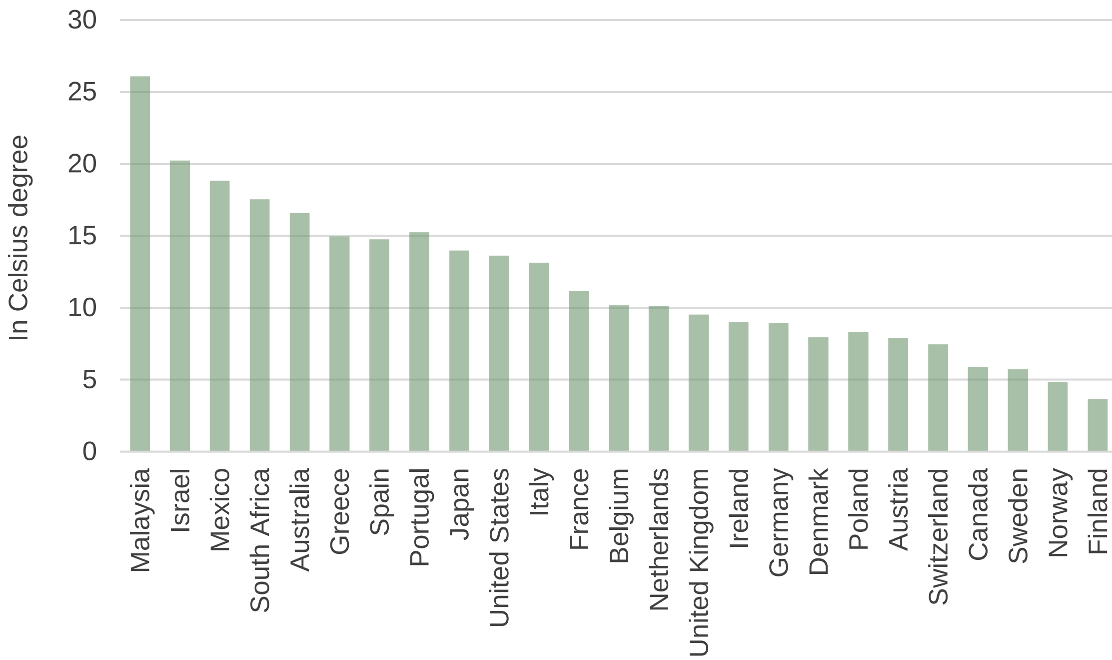
[12] Acevedo Mejia et al. (2019), *Weather Shocks and Output in Low-Income Countries: Adaptation and the Role of Policies,* IMF Working Paper WP/19/178.

[13] The mean annual precipitation is also used as control variable. However, it is not used in the projections.

[14]The evolution in productivity is approximated by the evolution of GDP per capita.

[15] If some effects are captured indirectly by the regression, it would only be very imperfectly.

Chart 3. Average historical (1980-2010) temperature by country



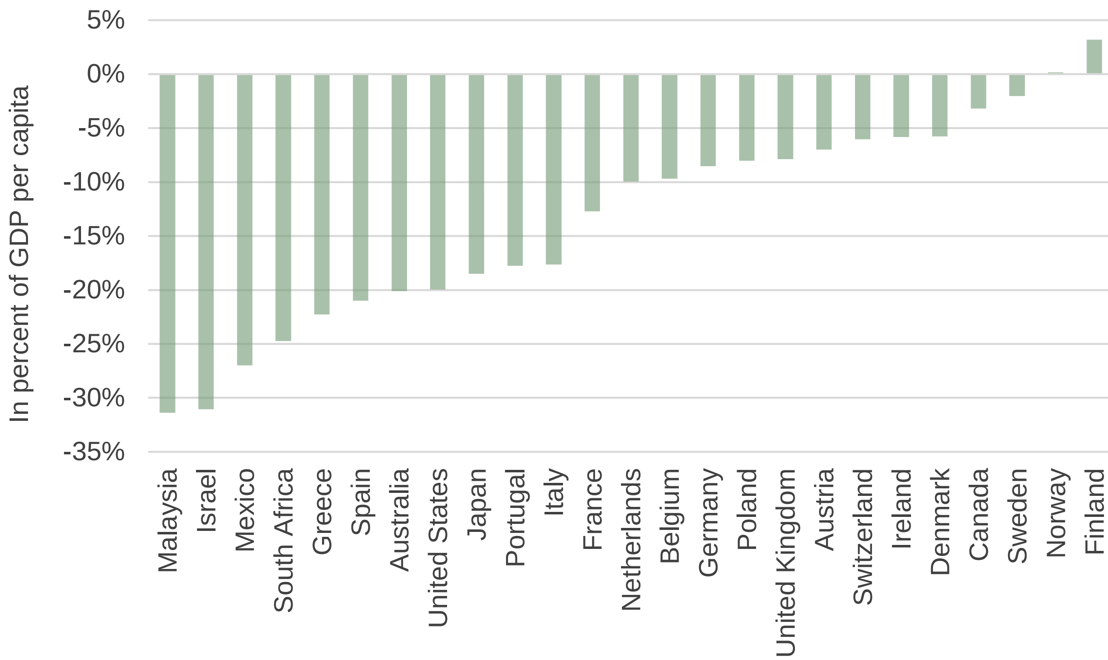
Source: Burke et al (2015) data.

Vulnerability to temperature increase

The projections of impact on GDP per capita resulting from a temperature increase corresponding to the RCP 8.5 scenario (using the econometric estimations mentioned *supra*), lead to very contrasted results among countries. The heterogeneity in the initial climate conditions is the main driver of the large differential of the countries' vulnerability to temperature increase (Chart 4).

Even if the expected temperature increase is lower nearer to the equator, the higher current average temperature in that area leads to greater estimated damages caused by global warming in the future. In 2050, the loss in GDP per capita in Malaysia reaches 31% (highest impact among the WGBI countries). Overall, most of the WGBI countries would suffer a negative impact from unmitigated global warming. Only Norway and Finland would slightly benefit from a temperature increase according to the damage function based on Burke and Tanutama (2019) coefficients.

Chart 4. Change in GDP per capita by 2050 compared to a world without climate change, scenario RCP 8.5



Source: Beyond Ratings, based on Burke and Tanutama (2019) calibration and Burke et al. (2015) data for temperature at country level.

The interpretation of these results should be made very cautiously as the damages function captures the impacts of temperature increase only on productivity, ignoring other direct or indirect losses already mentioned. The positive impacts are particularly uncertain. This is a simplified “all other things being equal” approach and the very high damages that most countries are likely to suffer in such a scenario would have negative repercussions on foreign trade or the spread of political instability as examples.

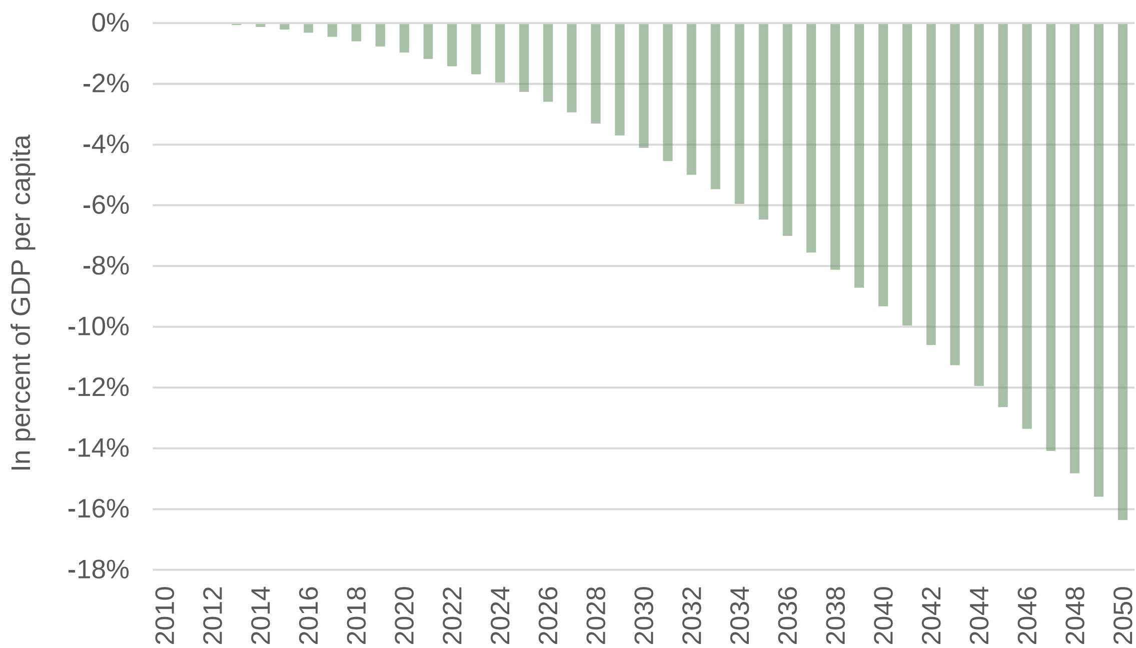
Besides approximating the level of impacts, this forward-looking analysis is useful to identify the most vulnerable regions to the physical impacts of climate change. Moreover, the order of magnitude of such impacts is a strong argument for a serious consideration of the physical risks by economic and financial actors.

3.3 Exposure to physical risks at the government bond index level

Building on the estimated impacts on GDP per capita already discussed, this section assesses the exposure of WGBI to physical risks. To do so, the impact on GDP per capita caused by the temperature increase is computed at the index level, using the weighting of the WGBI.

Chart 5 illustrates the exposure to macroeconomic impacts from physical risks in a “hot house world” scenario. Compared to a baseline scenario without climate change, GDP per capita would be lower by more than 4% in 2030 and 16% in 2050.

Chart 5. Loss in GDP per capita (scenario RCP 8.5): World Government Bond Index (WGBI)



Source: Beyond Ratings; Note: Damages are estimated at the index level applying a weighted average of constituent countries damages, using the weighting set of WGBI index, as of September 2020.

4. Transition risks: the worst-case scenario of a disorderly transition

To mitigate the physical risks of climate change, all the UN member states agreed to limit global warming well below 2°C during the COP21 in Paris. To achieve this goal, the GHG emissions will need to decrease dramatically to reach net zero emissions in the second half of the century. This requires a profound transformation of the economic system. The countries most dependent on fossil fuels and fossil fuels technologies will be particularly at risk during the transition. In this section, the risk of a transition towards a carbon neutral economy is assessed assuming that countries address mitigation at the very last moment by using technologies of last resort.

4.1 Scenario's narrative

According to the NGFS typology, the transition can be, in broad outline, orderly or disorderly. The strategy of postponing mitigation efforts would eventually require the use of expensive backstop technology leading to a disorderly transition.

To estimate the cost of this strategy, the methodology relies first on the calculation of the countries' carbon budgets, in line with the Paris Agreement objective. The budgets are determined *via* the *Climate Liabilities Assessment Integrated Methodology* (CLAIM) model developed by Giraud et al. (2017)[16]. Then the depletion rates are calculated using the last known emissions level to determine the year the budget was depleted.

[16] Giraud, G., Lantremange, H., Nicolas, E., & Rech, O. (2017). National carbon reduction commitments: Identifying the most consensual burden sharing.

Once their carbon budget is exhausted, countries wait for 'the very last moment' to make use of carbon removal solutions to absorb their residual emissions to meet their commitment[17], assuming they are the only available options in that context (see discussion on that assumption in 5.3 below). The direct air carbon dioxide capture and storage (DACCS) technologies are used as proxy for the removal solutions. The marginal abatement cost associated with these technologies is therefore applied to the volume of GHGs that countries continue to emit, giving an overall abatement cost.

Indirect economic effects of investments are usually estimated to get a full assessment of an orderly transition. Considering investments in DACCS technology as losses for society is, however, a reasonable simplification in the case of a disorderly transition[18]. The global abatement cost seems therefore to be a satisfactory proxy for the economic shock that such a scenario would imply.

4.2 Carbon budget

The methodological approach to compute the countries' carbon budgets and their depletion path is described in the following two sub-sections.

Definition of national carbon budgets

According to the IPCC (2018) [19], the remaining global carbon budget that would limit global warming to 2°C relative to pre-industrial level is 1500 GtCO2eq. for a 50% chance, or 1170 GtCO2eq.[20] for a 67% chance.

This study relies on the CLAIM methodology to define the countries' carbon budget. It enables the computation of national GHG budgets compliant with any average temperature target and time horizon (2°C compliant scenario here). This method does not assign a national budget following a unique criterion – such as "capacity" or "responsibility." It offers a statistical, and non-normative, approach, which avoids choosing between egalitarian or grandfathering sharing[21] that would be seen as non-consensual (see Giraud *et al.* 2017 for further details). Other burden-sharing methodologies exist, like the one developed by the ETH Zurich[22].

Chart 6 shows the cumulative carbon budget up to 2050 per country constituents of the WGBI index.

[17] This hypothesis supposes the sufficient capacity of all these solutions to meet the global needs of absorption. Such hypothesis could be questioned (see Fuss *et al.* (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environ. Res. Lett.*).

[18] These technologies would represent unproductive capital, see the Stern review (2007) which develops the same kind of argument with the concept of "balanced growth equivalent".

[19] Rogelj, J. et al. (2018). Mitigation pathways compatible with 1.5 C in the context of sustainable development In: Global Warming of 1.5°C. An IPCC Special Report.

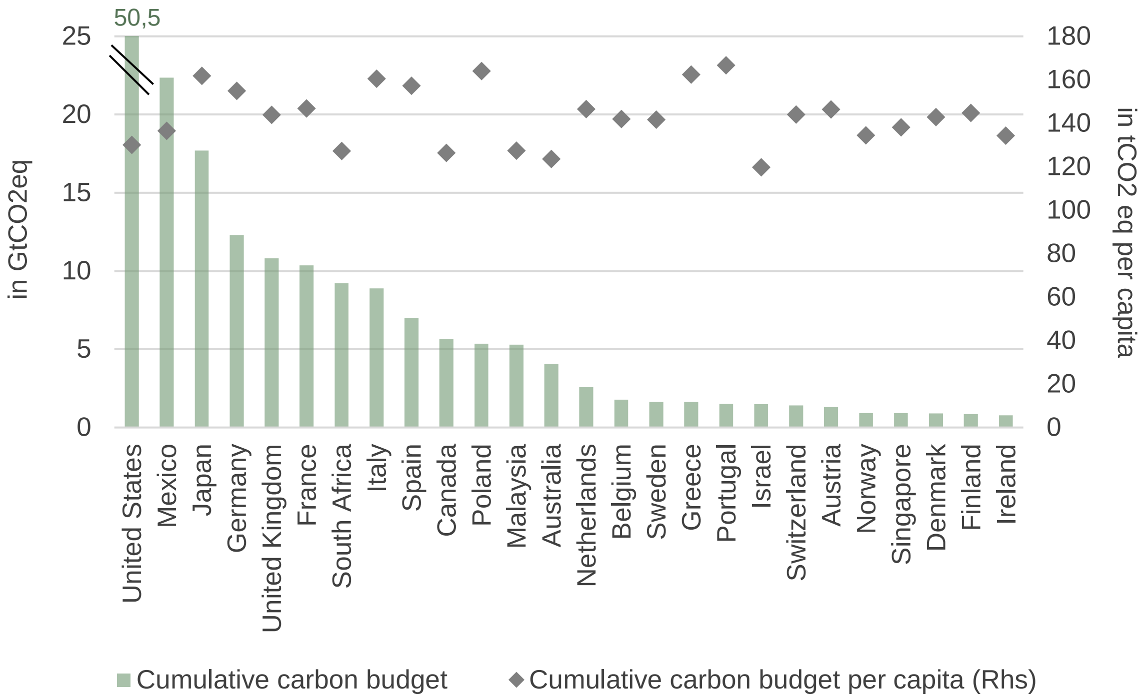
[20] The potential CO2 release from melting permafrost could lead to an overestimation of this carbon budget.

[21] The global budget sharing among countries is a source of scientific and diplomatic controversy. There are two main methodologies: (i) the egalitarian approach and (ii) the grandfathering approach. Hybrid approaches are also possible (see Giraud et al. 2017 for further details).

The *egalitarian* approach consists in allocating to each and every human being the same right to emit carbon dioxide, while the *grandfathering* approach relies on the idea that the global carbon budget should be divided along the criterion of current carbon emissions, meaning that the weight of each country in global emissions remains stable over time.

[22] http://www.ccalc.ethz.ch/calculator.php#instructions.

Chart 6. Carbon budget by 2050 per country*



Source: Beyond Ratings, based on CLAIM methodology

* Note: cumulative GHG emissions allowance up to 2050 in a 2°C scenario, per capita computed relative to 2050 UN population projection.

Depletion of the budget

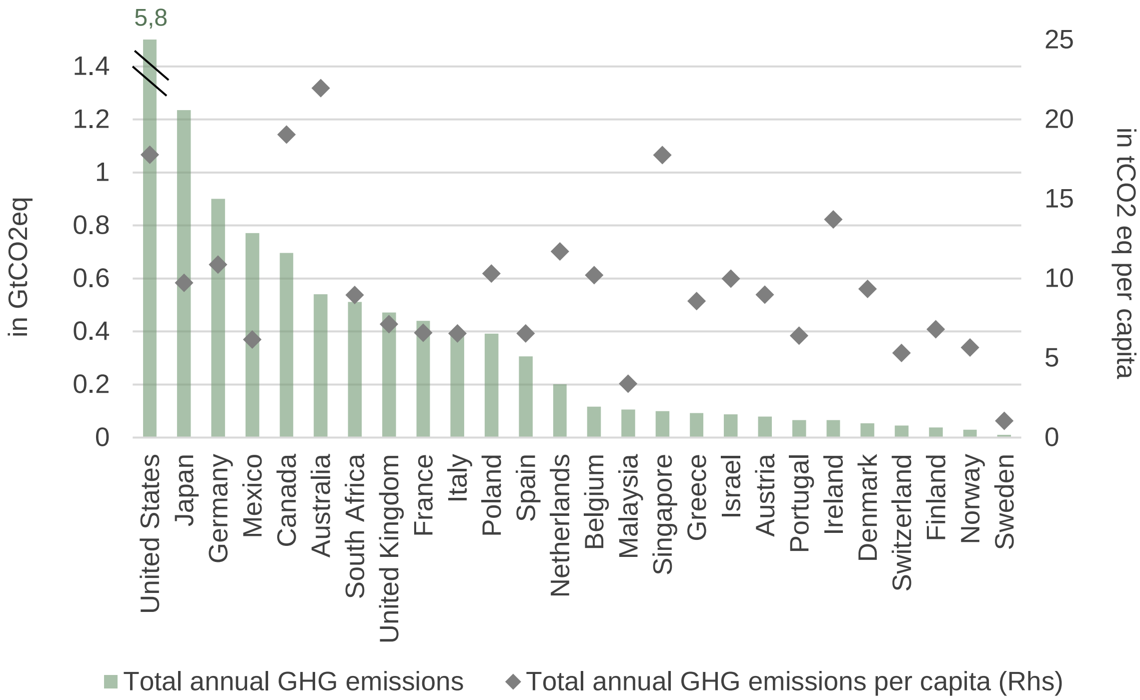
The national carbon budgets (consistent with the 2° objective) are consumed every year by annual GHG emissions. In order to determine the rate of depletion of the carbon budget, assumptions have to be made regarding the future evolution of emissions.

For simplicity, the GHG emissions are supposed to be constant at their current level (2017 being the last available data). The hypothesis on the constant level of emissions should be interpreted as a way to get a “snapshot view” of the current performance of the countries (see conclusions for alternatives that could be considered).

Chart 7 shows the annual emitted[23] GHG emissions per country.

[23] Please note that our study proposes to measure exposure to transition risks based on territorial GHG emissions rather than “consumed” GHG emissions. This would result in important differences in terms of estimates, as countries like France for instance have rather low territorial GHG emissions but high level of imported emissions.

Chart 7. Level of GHG emissions (including LULUCF*) per country in 2017

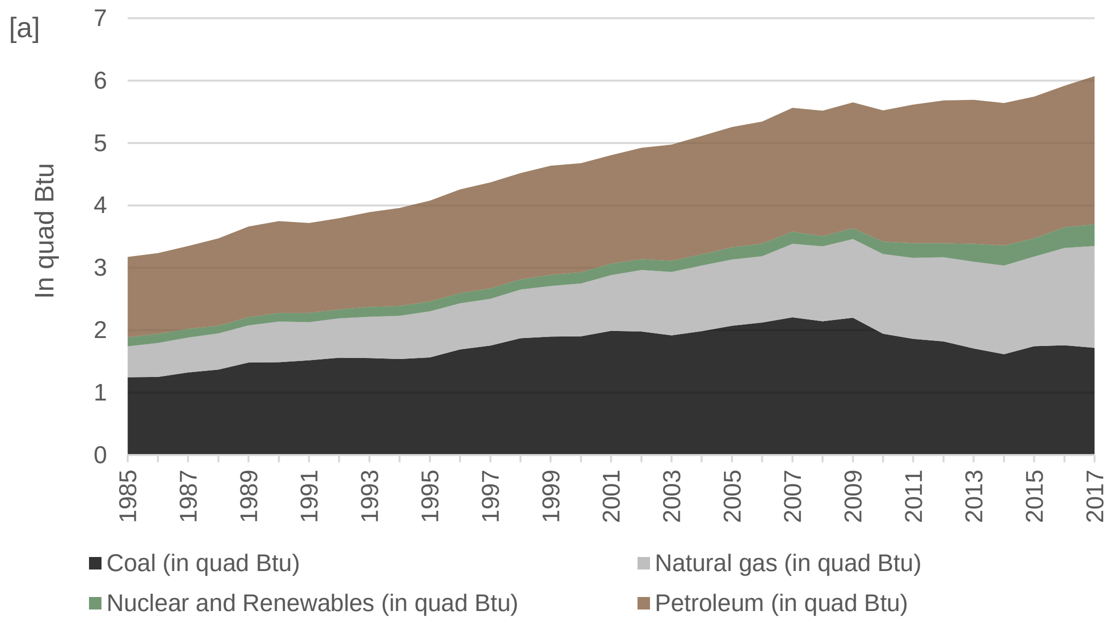


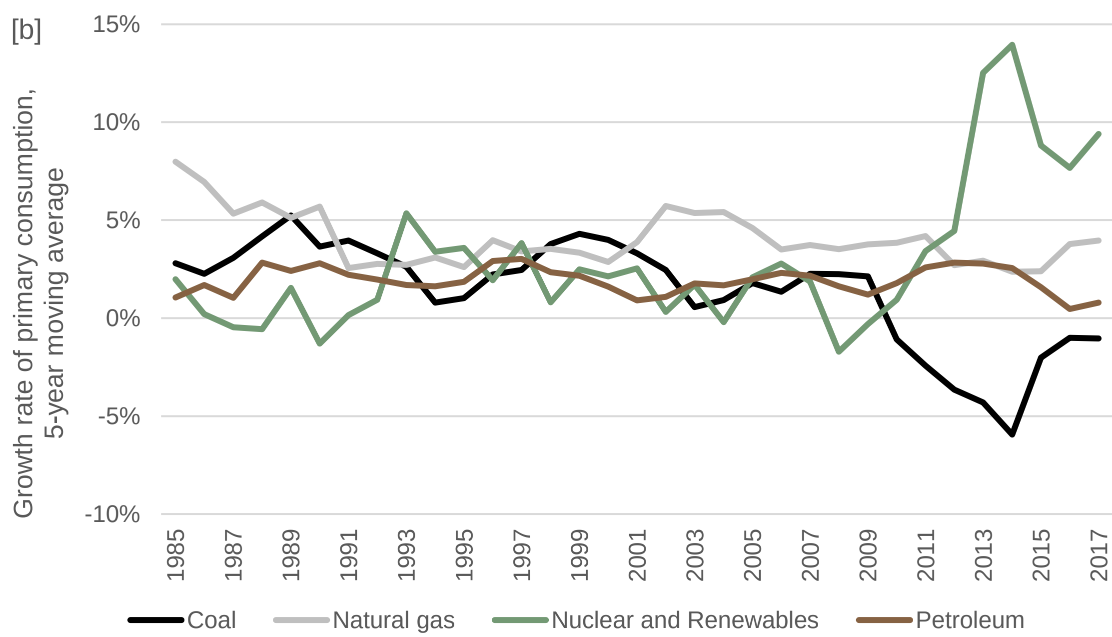
Source: Beyond Ratings

* Land Use and Land Use Change & Forestry.

The heterogeneity in emissions levels across countries comes from differences in terms of GDP per capita, energy intensity of GDP and carbon intensity of energy mix. Carbon intensity of energy mix is driven by the use of fossil fuels energy. Chart 8 [a] highlights the energy mix of Australia skewed towards non-renewable resources, resulting in a very high level of carbon intensity, despite some recent efforts especially on solar energy (Chart 8 [b]) This example shows how the transition risk could become high for countries delaying their efforts and relying overwhelmingly on fossil fuels.

Chart 8 Primary energy consumption by source, Australia (in quad Btu) [a] and growth rate of primary energy consumption by source, 5-year moving average, Australia [b]

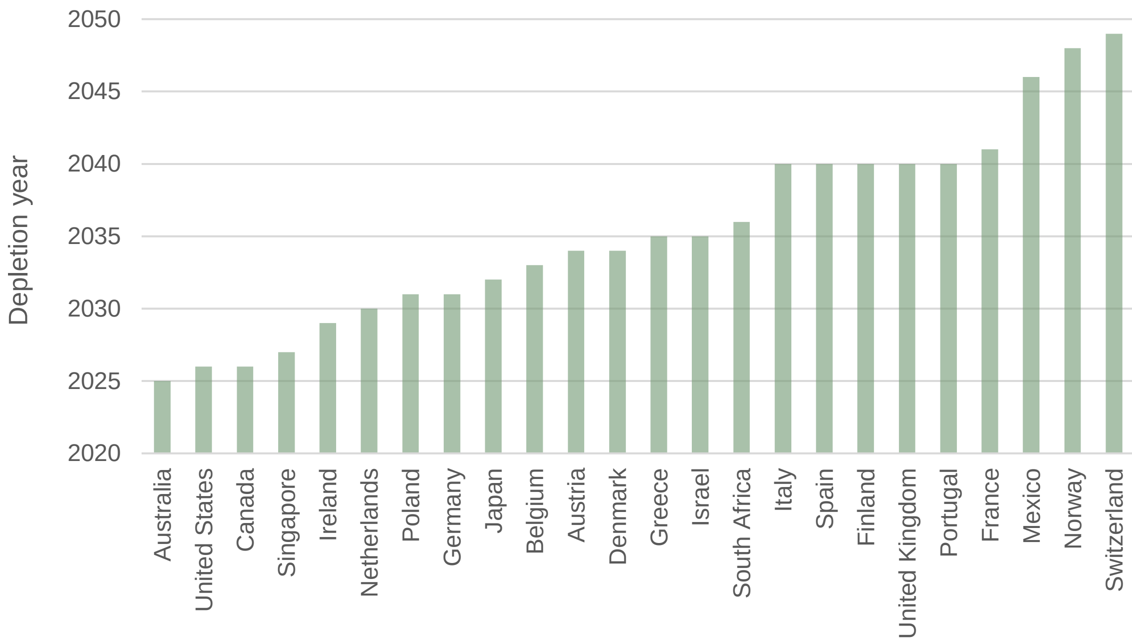




Source: US Energy Information Administration.

With the projected GHG emissions (kept constant up to 2050, based on the latest available data), the year at which carbon budget would be depleted can be determined. Chart 9 shows the results for countries in the WGBI. Australia, according to these estimates, would have depleted its carbon budget from 2025. This underlines the urgency regarding the transition. Sweden and Malaysia do not appear in the graph since their budgets are not depleted before 2050 (their depletion rate is very low thanks mainly to carbon sinks, accounted in their LULUCF (Land Use and Land Use Change & Forestry) sector.

Chart 9. Depletion year of carbon budget



Source: Beyond Ratings.

One could consider the depletion year as an indicator of limited operational outcome when seeing very close depletion years, like 2025 in the case of Australia. However, one should not interpret these deadlines as hard deadlines since they could actually be exceeded in a manner consistent with the global objective. Indeed, the mechanisms provided by the article 6 of the Paris Agreement allow transfers of mitigation outcomes between countries. For instance, the Netherlands recently paid Denmark €100 million to declare at least 8 TWh of Danish surplus renewable power on its own power accounts, in order to meet its EU renewables target[24]. With such mechanisms, the countries ahead of schedule can provide more time for the transition of countries late in their schedule, by selling them emissions reductions in the form of “credits.”

4.3 Economic impacts of a disorderly transition

Building on the methodology developed by Gueret *et al.* (2018)[25], an indicator on the country’s exposure to the transition risk is constructed in this sub-section (in the specific framework of a very abrupt transition). The total abatement costs for a country translate in monetary terms the amount of remaining emissions to be abated after depletion of that country’s carbon budget. The price of the backstop technology used to abate the remaining emissions is the last element needed to compute the total abatement cost.

Technology cost

The carbon dioxide removal (CDR) technology refers to “direct removal of carbon dioxide from the atmosphere, for example by combining bioenergy with carbon capture and storage (BECCS) or through land-related sequestration (e.g. afforestation)” (NGFS, 2020). The CDR technologies are mostly used in decarbonization scenarios in the end of the process to reach the net zero

[24] https://www.euractiv.com/section/energy/news/dutch-do-danish-deal-to-hit-clean-power-target/.
[25] Gueret, A., Malliet, P., Saussay, A., & Timbeau, X. (2018). An explorative evaluation of the climate debt. OFCE Policy paper.

emissions targets[26]. In this study, it is supposed that the CDR technologies are the only available option for countries waiting until the “last moment” to reduce their emissions. The broad idea is that usual main decarbonation technologies often require dense networks and/or several years for implementation (housing renovation, recharging stations for electric vehicles, electricity networks, etc.), and therefore would not be available.

Thus, the scenario framework implies that countries use the CDR solutions at a much larger scale than in the usual decarbonisation scenarios. This strategy is far from being a first best scenario. Beyond the high cost of the technologies, there is no assurance on the availability and the sustainability of the CDR options at this scale of implementation. In order to reflect on the non-optimality of the strategy, the cost of the DACCS technologies (one of the most expensive CDR solutions) is chosen as proxy for the price of the backstop technology. The cost for the DACCS technologies ranges from 100 to 300 USD[27] according to the IPCC. Here, the median cost of 200 USD is finally selected as the baseline price of the technology.

Total abatement costs

The total abatement costs are computed at the country level. Chart 10 shows the estimations of these costs expressed in terms of GDP[28] per country constituents of the WGBI index. With the highest abatement costs-to-GDP ratio, South Africa, Mexico, Poland, United States, Australia and Canada are the countries of the WGBI index the most exposed to transition risks. The situation is all the more worrying for countries where the depletion year of their carbon budget is very close, especially the United States, Australia and Canada.

The reorientation of such a significative fraction of national resources towards unproductive activities in a short period would likely come with high subsidies, and therefore would have an impact on debt sustainability.

Some countries have already begun, especially in the EU, to implement carbon price measures such as carbon allowances markets and fuel taxes, and have better performances in this assessment, even if the transition risk is still significant for these countries.

The total abatement costs of a country are incurred from the depletion year of that country’s carbon budget. These costs would continue to be incurred every year as long as residual emissions remain at the same level. These results clearly highlight the benefits of an orderly transition that would enable the development of (new low emissions) productive sectors. Regarding the economic impacts of an orderly transition, results in the literature are much less important (some studies even anticipate positive impacts on GDP of an orderly transition[29]).

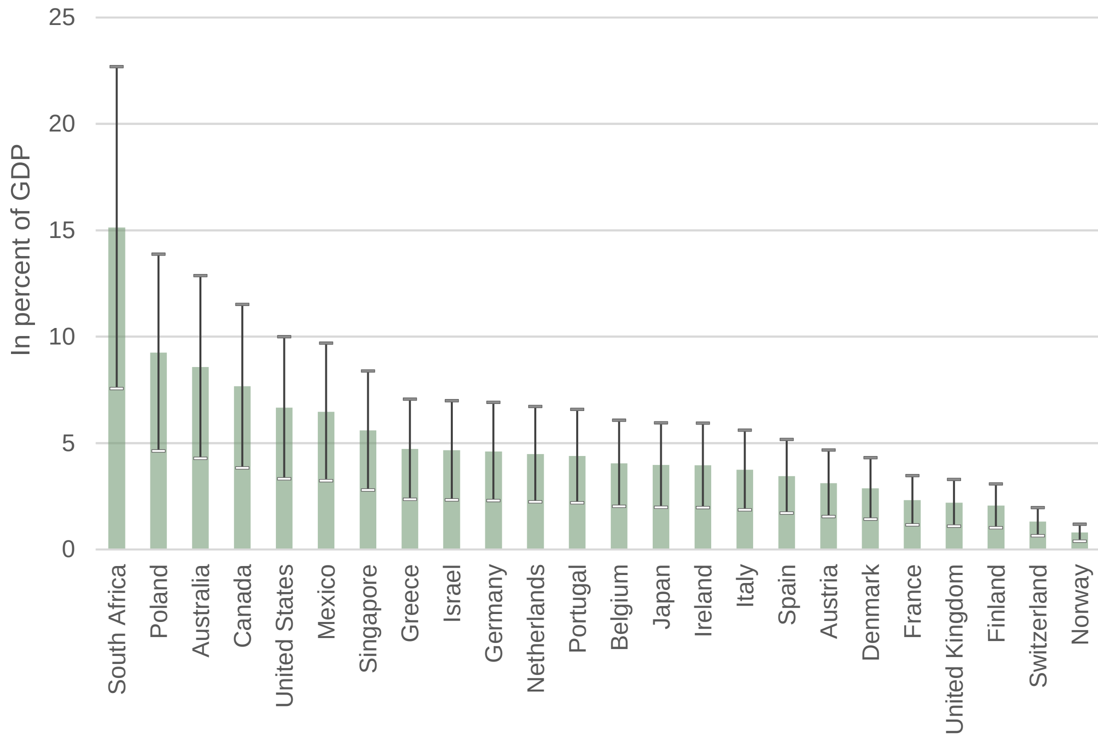
[26] See for instance de Coninck, H. *et al.* (2018). Strengthening and implementing the global response; in: Global Warming of 1.5°C. An IPCC Special Report.

[27] de Coninck, H. *et al.* (2018). *Ibid*

[28] GDP projections for SSP2 scenario from MaGE model (CEPII) are used here.

[29] *e.g.* OECD (2017), Investing in climate, investing in growth.

Chart 10. Total abatement costs (in percentage of GDP)* incurred from the depletion year



Source: Beyond Ratings.

*Note: the level of the impact represented by each histogram bar is calculated with a technology cost of 200$/tCO2 (reference) although the lower and the upper ends of the sensitivity bar are calculated respectively with a cost of 100$/tCO2 and 300$/tCO2 (range estimated by the IPCC for the DACCS technology).

Exposure to transitions risks at government bonds index level

Since there are different depletion years for every country, estimating the total abatement costs at the index level, as in section 3.3 for physical risk, is less relevant. It would require calculating the aggregated cost in 2050 when all the countries would have exhausted their carbon budget. Therefore, this would also require making weak assumptions for each country on the evolution of the residual GHG emissions level between its depletion year and 2050.

For countries like Australia, which has a very close depletion year (namely 2025), it would not be very realistic to suppose the same level of residual emissions for 25 years (continuing paying negative emissions at 200€/tCO_2eq. although there are much cheaper abatement solutions when there is sufficient time to implement them).

Building on the total abatement costs estimated by country in the previous section, the average cost at depletion year for WGBI countries can, however, be provided for illustrative purpose. This average cost is around 5% of GDP (WGBI index weightings).

5. Conclusion

Financial regulators are pushing for scenario-based projections when assessing climate risks. Given the nature of climate change risks (irreversible, nonlinear and correlated underlying dynamics), relying only on historical data is not sufficient to anticipate the risks. This study is therefore a first step in the broader project of investigating forward-looking analyses.

The methodologies developed in the study explore worst case scenarios for both transition and physical risks assessment. The chosen methodologies do not allow for the coverage of all possible futures and call for further developments and refinements. Despite the needs for improvements (see below), the report provides some interesting results. There is a strong geographic heterogeneity in the vulnerability to climate change-related risks:

- higher transition risks in countries lagging in the decarbonization process and strongly dependent on fossil fuels like Poland, Australia, Canada or the United States
- higher physical risks exposure in tropical areas due mainly to the higher current annual average temperature

In general, the magnitude of the impacts is very high. Tens of GDP points are at risk in 2050 in the most vulnerable countries, for both transition and physical risks. Economically significant impacts could even appear from 2030 onwards. Both risks could affect medium to long-term debt sustainability for sovereign issuers and reduce corporate profitability. These results confirm that investors should take into account climate change consequences very seriously in their investment decisions.

The second part of the study will be dedicated to the financial side of the risk assessment. The macroeconomic results of this first part will be used to explore the impacts of climate change on sovereign bonds asset pricing returns.

Regarding the future methodological developments, several areas for improvement should be considered.

a) Transition risks:
   - the emissions projections underpinning the determination of the budget's depletion should be refined, ideally with "current policies" projections;
   - the risks associated to an orderly transition scenario should also be assessed. This would require (i) a macroeconomic modelling to capture feedbacks of the transition investments and (ii) a sectoral breakdown to identify the most vulnerable actors of the economy. Besides, the sectoral breakdown would potentially enable an assessment of both sovereign and corporate risks within a consistent framework.

b) Physical risks:
   - in addition to the temperature increase (chronic hazard) addressed in this report, the risks associated with acute hazards, such as hurricanes, floods, heatwaves, wildfires, etc., should also be assessed.

Finally, the assessment of the risk exposures at country level, through the approximation of the impact on GDP, is a first step towards a more precise evaluation, especially with further work needed to explore the differentiated impacts of the transition at the sectoral level and among economic actors (government, firms or financial institutions).

Appendix:

Context of the study

In addition to the objectives of limiting global warming well below 2°C and increasing our societies' ability to adapt to the adverse impacts of climate change, the Paris Agreement aims to "make finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development" (article 2.1.c). The profound economic mutations necessary to achieve the Paris Agreement objectives requires a consistent reallocation of resources. This gives a key role to financial sector in tackling climate change. The assessment and disclosure of financial climate-related risks are critical in that context.

As described by the Task force on Climate-related Financial Disclosures (TCFD)[30] or the Network for Greening the Financial System (NGFS)[31], climate change implies two main categories of risk for financial stakeholders through (i) its physical impacts and (ii) the transition to a carbon-neutral economy required to mitigate it (see also Carney 2015[32]). As a complement to the public policy tools (tax and standards on GHG emissions, subsidies to low carbon technologies, etc.), a clear understanding of these climate risks could catalyze the reallocation of financial resources. This would limit the risks of investments becoming useless[33] after transition measures (coal mines, oil rigs, etc.) and capital destroyed by climate damages.

However, in its latest Global Financial Stability Report (2020)[34], the IMF warns about the undervaluation of climate change risks by financial markets. In particular, it examines the impact of physical risk from climate change on financial stability, and finds that equity investors might not be pricing these risks adequately. This confirms earlier research on sovereign bonds (Capelle-Blancard *et al.* 2019[35]), which found that environmental risks are uncorrelated with sovereign spreads. Beyond Ratings also studied this topic, leading to similar conclusions (Reznick *et al.* 2019[36] and 2020[37]). The NGFS (2019) recognizes the "strong risk that climate-related financial risks are not fully reflected in asset valuations", and thus considers a better assessment of the transition and physical risks as a high priority for the financial sector.

In general, since 2015 and Bank of England's Governor Mark Carney speech introducing the notion of "stranded assets" to a wider audience, more and more regulators have been sending increasingly clear warnings that investors' assets might become at risk from the impacts of climate change.

[30] TCFD (2017a), *Final report - Recommendations of the Task Force on Climate related Financial Disclosures*. The Task force on Climate-related Financial Disclosures (TCFD) was created in 2015 after the Financial Stability Board was requested by the G20 to "review how the financial sector can take account of climate-related issues".

[31] NGFS, (2019), *First comprehensive report - A call for action Climate change as a source of financial risk*.

The Network for Greening the Financial System (NGFS) is a network of central banks and supervisors, launched at the One Planet Summit in 2017 in Paris, aiming at strengthening the global response required to meet the goals of the Paris agreement and to enhance the role of the financial system to manage climate change-related risks.

[32] Carney, M. (2015), *Breaking the Tragedy of the Horizon – climate change and financial stability*, speech delivered at Lloyd's of London, September 29.

[33] Usually characterized as "stranded assets"

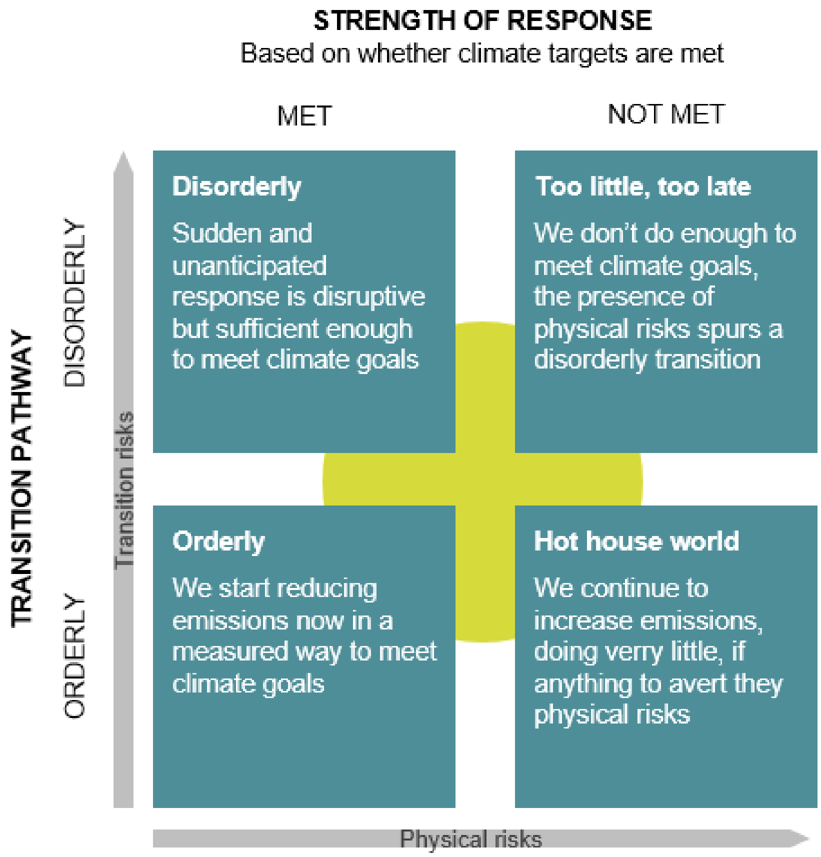
[34] IMF (2020), *Global financial stability report - Chapter 5: Climate Change: Physical Risk and Equity Prices*.

[35] Capelle-Blancard, G. *et al.* (2019), *Sovereign bond yield spreads and sustainability: An empirical analysis of OECD countries.* Journal of Banking & Finance, 98, 156-169.

[36] Reznick et al. (2019), *Pricing ESG risk in sovereign credit*, Research paper by Hermes Investment Management and Beyond Ratings.

[37] Reznick et al. (2020), *Pricing ESG risk in sovereign credit - Part II: Developed and emerging-market spreads split the difference*, Research paper by Hermes Investment Management and Beyond Ratings.

A forward-looking approach built on the NGFS scenario framework



Based on this matrix defined by the NGFS, the "too little, too late" scenario seems to be the most costly scenario. "Disorderly" scenario and "hot house world" are intermediary scenarios, where costs arise, in the first case, due to sudden transition pathway and, in the second case, due to large physical risks impacts. The orderly scenario is the most favorable one, as transition pathway is orderly and sufficient to avoid higher physical risks costs.

In the orderly scenario, the NGFS assume that net zero CO_2 emissions are achieved before 2070, giving a 67% chance of limiting global warming to below 2°C. In the disorderly scenario, it is assumed that climate policies are not introduced until 2030, leading to sharper emissions reductions than in the orderly scenario, aiming to limit global warming to the same target.

Finally, in the hot house world scenario, only currently implemented policies are kept and Nationally Determined Contributions (NDCs) are not met, leading to emissions growth up to 2080 and a +3°C global warming.

Regarding socioeconomic evolutions, the assumptions made by the NGFS are based on one of Shared Socioeconomic Pathways[38] (SSP), corresponding to a "middle of the road" scenario. In this scenario, global population growth is moderate and GDP continues to grow in line with historical trends. For the energy use part, the NGFS assumes in the hot house world scenario that energy use continues to grow, but still at a declining rate. This reduction in energy use has

[38] Towards modelling transition pathways in such a long-term timeframe, assumptions have to be made regarding socioeconomic evolutions. These assumptions have been standardized by the academic community as the Shared Socioeconomic Pathways (SSPs), giving insights about GDP, population and other structural changes such as technological advancements and resources use.

implications for growth in CO_2 emissions, as for a given energy mix, declining energy use leads to lower CO_2 emissions.

Building on the NGFS typology, this paper presents some impacts estimated in the “worst-case” scenarios: a “hot house world” and a “disorderly transition.”

Damage function

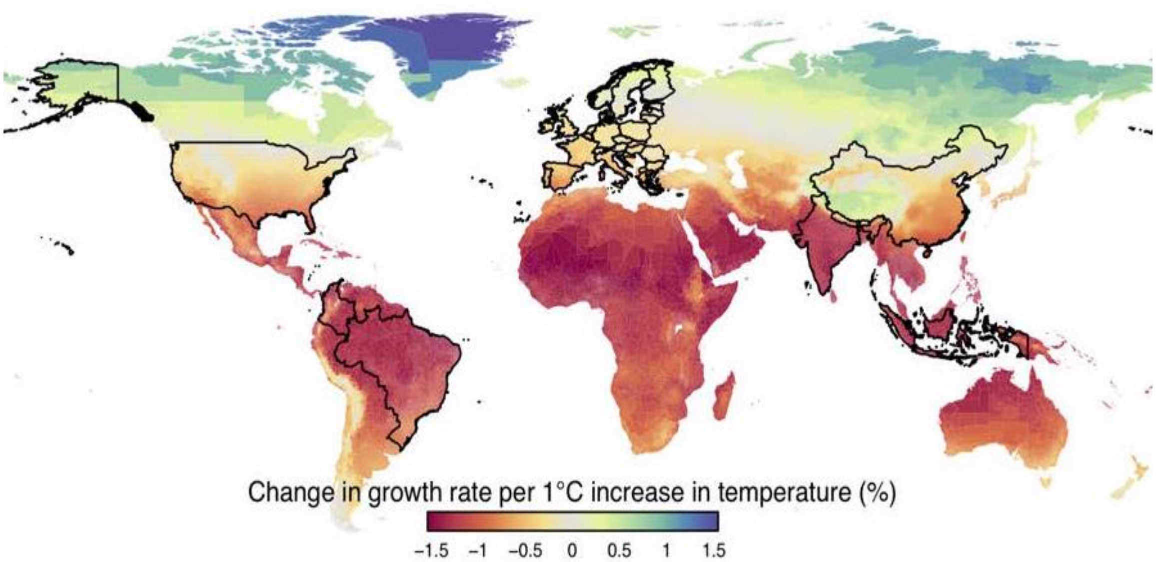
The damage function used in this study is computed according to the following formula from Burke *et al.* (2015):

$$D_T = (\varphi_1 T_t + \varphi_2 T_t^2) - (\varphi_1 \bar{T} + \varphi_2 \overline{T^2})$$

Where φ_1 and φ_2 are parameters estimated through econometric specifications by Burke and Tanutama (2019), T_t is the projected temperature at any year and $\bar{T}$ is the average historical temperature. D_T corresponds to the damages in terms of GDP per capita growth rate.

The effects of the damage function are illustrated in the following chart.

Chart 1. Impact of a 1°C increase in temperature on GDP per capita growth rate, resulting from Burke and Tanumata (2019) estimations that have been used in this study



Source: Burke and Tanutama (2019)

Abatement costs

In our framework, each year, emissions deplete the carbon budget CB (the amount of emissions that can be emitted in order to limit the atmospheric temperature increase by 2°C at the end of the century, compared to pre-industrial level).

$$CB = CB_{-1} - EMIS$$

Once the carbon budget is depleted, remaining emissions must be abated $EMIS_{\boldsymbol{AB}}$ with a technology of last resort (backstop technology).

$$EMIS_{\boldsymbol{AB}} = \begin{cases} 0 \; if \; CB > 0 \\ EMISif \; CB \leq 0 \end{cases}$$

Abatement costs Ω translate in monetary terms as the amount of emissions to be abated (remaining emissions after depletion of carbon budget):

$$\Omega_T = EMIS_{AB} * pbs$$

These abatement costs materialize from the date of carbon budget depletion.

In order to estimate this exposure to transition risk, we need:

- The amount of remaining emissions to be abated $EMIS_{AB}$;
- The date of carbon budget depletion T;
- The price for backstop technology pbs;

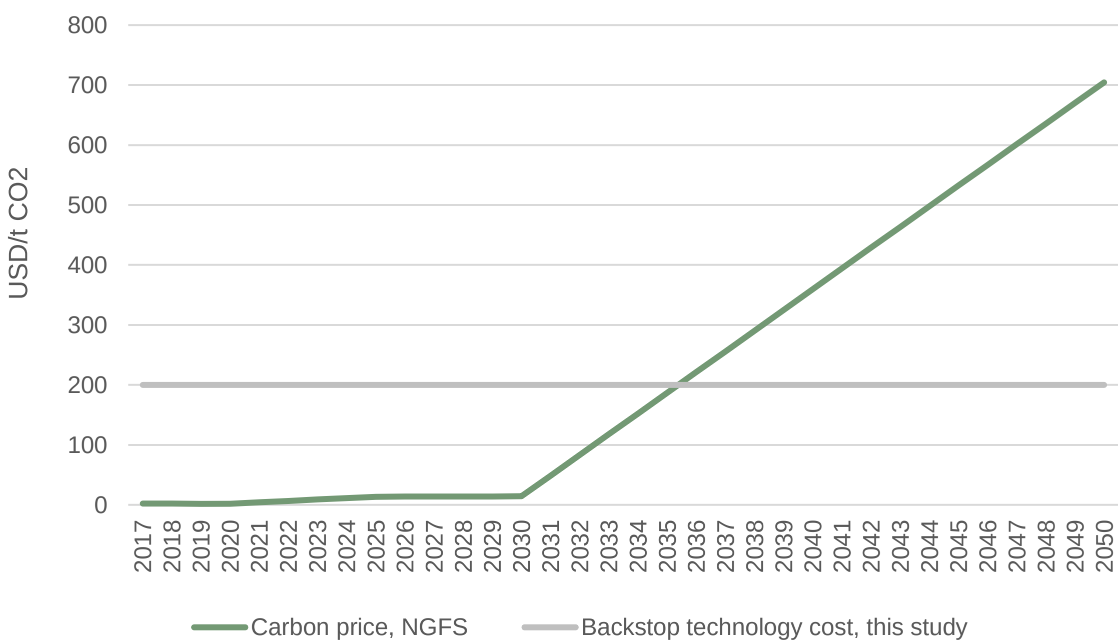
In order to estimate the date of carbon budget depletion, we need:

- An estimate of country's carbon budget;
- A projection for future emissions.

Estimates are sensitive to the main assumption regarding the price for backstop technology. For a given amount of emissions to be abated per year, translation in monetary terms (abatement costs) would increase linearly as the price for backstop technology increase.

Chart 2 compares our hypothesis on a fixed backstop technology cost at 200 USD to the evolution of carbon price in the disorderly scenario used in the NGFS modelling framework.

Chart 2. Carbon price evolution in the NGFS works versus the cost of the backstop technology in this study



Source: Beyond Ratings and NGFS Climate Scenario Database.

The approach developed in this study is very different from the one chosen in the NGFS works on the disorderly transition depiction. The price of the backstop technology (assumed constant) applied to the residual emissions is used as a proxy for the economic shock arising at the carbon budget exhaustion, thus allowing national assessment of the impact.

The NGFS framework rather focuses on the global dynamics of the economic shock. The shock is less abrupt with a lower carbon price signal in the beginning of the period but, in compensation, much higher in the end.

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