Mobilisation des Marchés Financiers vers une Economie Bas Carbone

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THÈSE DE DOCTORAT DE L'UNIVERSITÉ PSL

Préparée à l'Université Paris-Dauphine

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Soutenue par
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Le 09 mars 2023

Ecole doctorale n° ED 543
Ecole doctorale SDOSE

Spécialité
Economie

Dauphine | PSL UNIVERSITÉ PARIS

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Remerciements

Cette thèse s'inscrit dans une démarche qui parcourt tout ma carrière. Tout au long de mes activités professionnelles, je me suis attaché à développer des innovations financières ayant des impacts sociétaux.

Très tôt, j'ai mis au point les premières offres d'actionnariat salariés à effet de levier à dimension mondiale. En se portant acquéreur d'une action, les salariés bénéficiaient d'une garantie en capital et d'un effet multiplicateur de la hausse de l'action. Ces offres ont permis à des centaines de milliers de personnes à travers le monde de devenir, pour la première fois, des actionnaires de leurs entreprises, et ce sans prendre de risque. Elles ont donc permis aux salariés aux revenus modestes de se constituer une épargne supplémentaire. Cette innovation financière a aussi souvent transformé la culture d'entreprise, en associant directement les salariés à la croissance de leurs entreprises.

Plus tard, étant présent aux Etats Unis lors de la crise financière de 2007-2008, j'ai pu observer au plus près les effets humains dévastateurs de la crise. Cela imposait de réfléchir à de nouvelles pistes, à sortir des sentiers battus. Dès lors, naturellement, je me suis intéressé à établir un dialogue sur ces sujets avec le monde académique. Dès 2009, j'ai eu la chance, sur une initiative personnelle, de développer une Initiative de Recherche, rattachée à Dauphine University et qui établira immédiatement un partenariat avec Columbia University afin travailler sur les Fonds Souverains et l'investissement de long-terme. Dès 2010, une première conférence prendra place réunissant fonds souverains, chercheurs, décideurs politiques, et praticiens. L'idée, simple, étant que les fonds souverains, ayant des horizons d'investissement longs, une absence de liability et des objectifs de transmettre de la richesse aux prochaines générations, étaient de bons candidats pour intégrer les « externalités négatives » et au premier plan de celles-ci, le climat. Se faisant, ces investisseurs de long terme pourraient d'une part bénéficier de rendements supplémentaires quand ces risques mal rémunérés (car mal appréciés) seraient analysés correctement, et d'autre part avoir un impact positif

sur la société en mobilisant des capitaux en complément des efforts des Etats. Bref, encore mobiliser les marchés financiers à des fins de bien public.

Je voudrais pour cela remercier chaleureusement Pierre-Louis Lions et Roger Guesnérie qui ont accepté d'être les premiers Présidents de cette Initiatrice de Recherche. Jean-Michel Beacco et Jean-Michel Lasry ont permis les premiers pas opérationnels. Un dialogue s'est aussi noué immédiatement avec Elyes Jouini, qui va devenir des années plus tard le Directeur de cette Thèse. Sans son ouverture d'esprit, et son soutien tout au long de ces années, je n'aurais pas entrepris cette démarche. Cela dit tout ce que je lui dois, et qu'il en soit très chaleureusement remercié. Que soient remerciés tous mes co-auteurs au cours des années, Mats Andersson, Rabah Arezki, Jean Boissinot, Morgan Despres, Haizhou Huang, Marcin Kacperczyk, Simon Levin, Luiz Awazu Pereira da Silva, Romain Svartzman et David Wood. Que soient aussi remerciés ceux qui par les soutiens financiers de leurs établissements, leurs visions de long terme ou leurs contributions personnelles ont permis ce travail, et donc Xavier Musca et Jerôme Grivet, grâce à qui tout a commencé. Une attention particulière pour Joseph Stiglitz qui a accepté de me recevoir dans son bureau de Columbia University et de soutenir ce projet, improbable à l'époque, avec un mélange d'exigence et de bienveillance. *Last but not least,* Patrick Bolton a été la rencontre déterminante qui a permis que ce aurait pu n'être qu'une idée devienne réalité, grâce à un dialogue ininterrompu, rigoureux et empreint d'amitié, tout au long de ces années. Qu'ils soient tous ici remerciés. Ces rencontres ont été la principale richesse issue de ces efforts.

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Introduction

La thèse « Mobilisation des marchés financiers vers une économie bas carbone » s'articule autour d'une même thématique, à savoir le climat et l'investissement responsable, et de deux axes : une contribution à l'analyse de la situation et des propositions de solutions concrètes en découlant.

1. Tableau général

La communauté scientifique nous alerte sur un danger mortel que nous générons nous-mêmes : l'émission de CO_2 en quantité telle qu'elle menace l'existence même des êtres humains et déstabilise le fonctionnement même du vivant sur la planète.

Alors que le phénomène scientifique est connu depuis le 19^{eme} siècle, et qu'il y a à peu près 25 ans les scientifiques nous ont alerté sur le phénomène, peu a été fait.
Par ailleurs, nous entrons désormais dans une zone dangereuse où la probabilité de dépasser les seuils posés comme limite par les scientifiques devient de plus en plus importante : il nous reste désormais moins de 6 ans de budget carbone et les probabilités sont très faibles de rester en deçà des seuils dictés par la science.
Les conséquences sont alors potentiellement dramatiques, avec la vie de milliards de personnes en jeu à la fin du siècle, dans le scénario le plus négatif du Giec (Groupe d'experts intergouvernemental sur l'évolution du climat). En effet, dans celui-ci, près de 4 à 5 milliards de personnes, situées essentiellement dans les pays en voie de développement font face à des risques mortels du fait de la combinaison de température et d'humidité élevées ; cela amène aussi la Banque Mondiale à estimer à 143 millions le nombre de migrants climatiques, dans trois régions seulement, d'ici 2050. Cela a déjà conduit, comme dans le cas de la Syrie, à des conflits meurtriers.

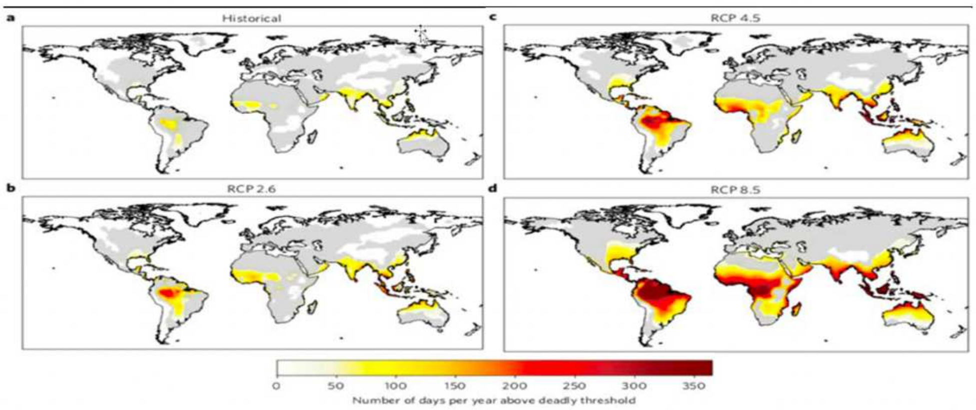
Il s'agit donc d'enjeux gigantesques : réinventer rapidement la manière de produite de l'énergie qui a engendré la révolution industrielle, éviter les ajustements trop brusques qui pourraient déstabiliser les marchés financiers, établir des règles distributives justes alors que le climat ne fait qu'augmenter les inégalités, inventer les cadres conceptuels pour aider les pouvoirs publics qui sont pris devant un risque de nature différente de tous ceux auxquels ils ont été confrontés jusque-là, développer la prise de décision robuste, inventer les structures de capital des entreprises qui permettent d'absorber les chocs, inventer les mécanismes financiers qui viendront canaliser l'épargne vers une économie bas-carbone, augmenter le financement de la R&D verte qui est actuellement inférieure aux subventions apportées aux sociétés polluantes, réinventer une coopération internationale nécessaire alors que l'on fait face à des montées de nationalisme à travers le monde, augmenter la résilience des marchés financiers, repenser une approche mécaniciste du fonctionnement de nos sociétés, repenser (la trop forte) confiance dans les modèles prédictifs en situation d'incertitude radicale, repenser la financiarisation des sociétés qui vient à modifier la valeur attribuée aux biens, repenser le principe de propriété moderne corolaire de la liberté individuelle, etc.

Bref, il s'agit certainement de « la plus grande défaillance des marchés que l'on ait jamais connue » (Stern 2006) et il serait illusoire de croire qu'un simple prix du carbone viendra répondre à ce défi de société; il s'agit donc de mobiliser toutes les ressources de nos sociétés.

Face à tous ces défis, une dynamique positive est née ; alors que le monde restait silencieux face aux alarmes émises, il s'est mis en mouvement autour de la COP21 et notamment dans le monde de la finance, tant via les investisseurs à travers de nouvelles allocations de capital, des coalitions et de l'innovation financière, que via les banques centrales.

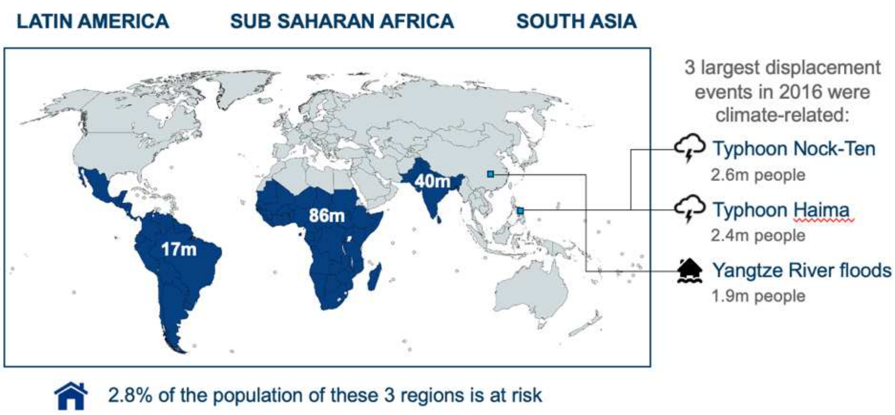
2. Littérature générale

Les scientifiques nous alertent depuis des années (Ripple *et al.*, 2017) sur l'aspect crucial du climat qui est un risque qui impacte la vie même des êtres humains (Mora, *et al.* 2017). Dans le scenario le plus négatif du Giec (Groupe d'experts intergouvernemental sur l'évolution du climat), près de 4 à 5 milliards de personnes, essentiellement dans les pays en voie de développement, sont dans des zones à risque mortel du fait de la combinaison de température et d'humidité élevées.



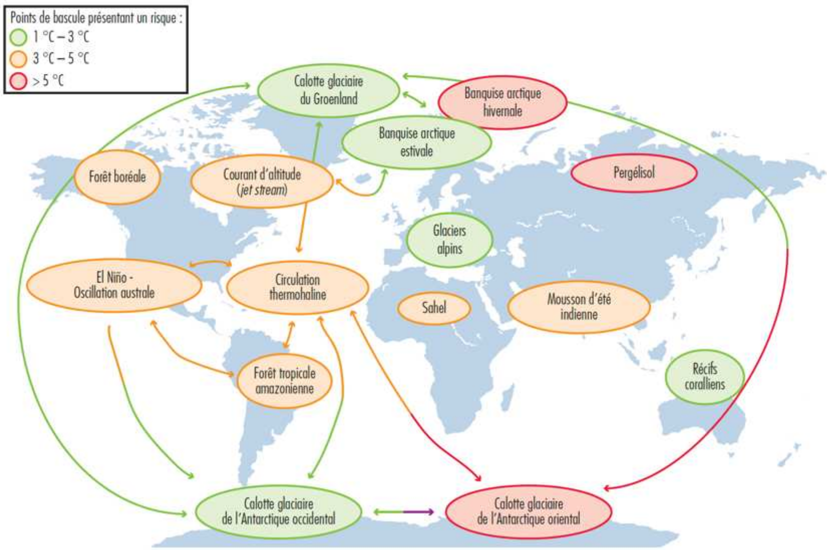
Source : Mora *et al*, 2017

Pareillement, 5 milliards de personnes pourraient souffrir d'un manque d'eau d'ici 2050 (UN Water Development Report). Et cela amène la Banque Mondiale (World Bank, 2018) à estimer à 143 millions le nombre de migrants climatiques, dans trois régions seulement, d'ici 2050). Et, en Syrie, les vagues de sécheresse ont conduit à des déplacements de population, menant au conflit et aux réfugiés en Europe (Abel, 2019).



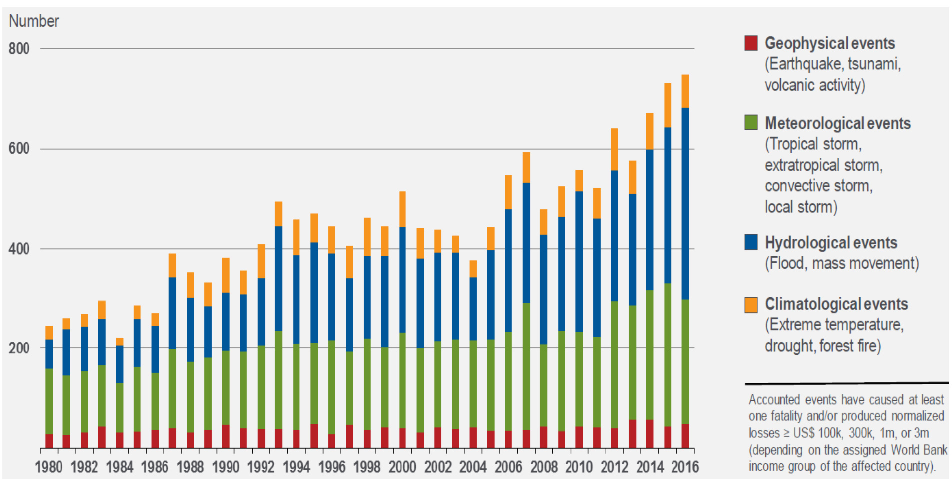
Source : adapté de la World Bank, 2018

On assiste déjà à une multiplication des années record de chaleur. 2020 a été l'une des 3 années les plus chaudes et la dernière décennie la plus élevée avec une augmentation par rapport à l'ère préindustrielle de 1.2° (American Meteorological Society, 2021). Et cela enclenche des risques forts d'effets de cascade (Steffen *et al.*, 2018) dont la fonte du permafrost, qui libèrerait alors aussi des virus (Legendre *et al.*, 2015).



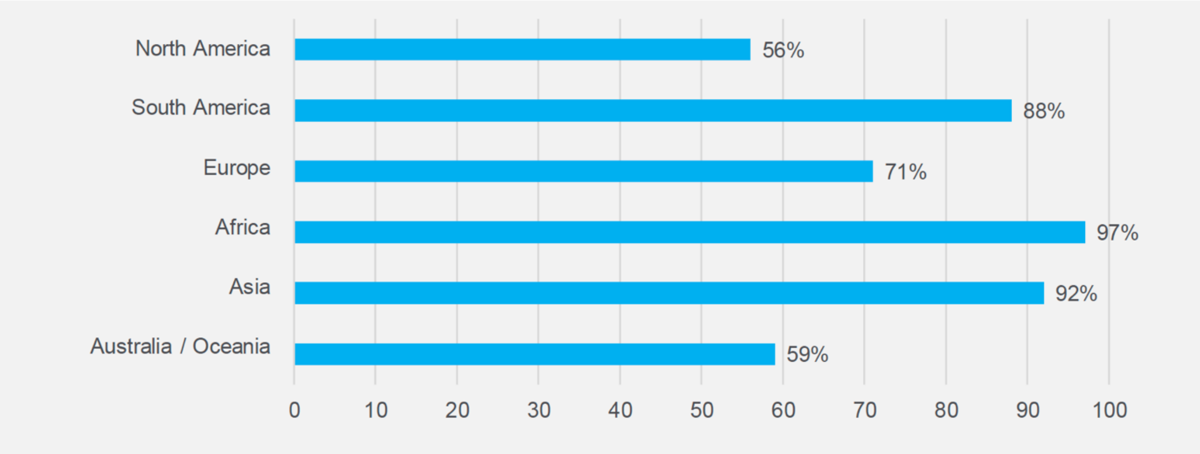
Source : Setffen *et al.*, 2018

En parallèle, on assiste à une forte progression des évènements climatiques extrêmes (multipliés par 4 sur les 40 derniers années)



Source : 2016 Munchener Ruckversicherungs-Gesellchaft Geo Risk Reseach NatCatSERVICE.

Et avec déficit de couverture des dommages par les compagnies d'assurance (insurance gap) très élevé : 92% en Asie, et 97% en Afrique, conduisant à des situations personnelles très délicates pour un nombre croissant de la population



Source : 2016 Munchener Ruckversicherungs-Gesellchaft Geo Risk Reseach NatCatSERVICE.

Et cela conduit, de façon générale, une augmentation des inégalités (Burke et Diffenbaugh, 2019), avec 90% de probabilité que, dans les pays les plus pauvres, le PIB par habitant ait été impacté par le climat, et non dans les pays riches.

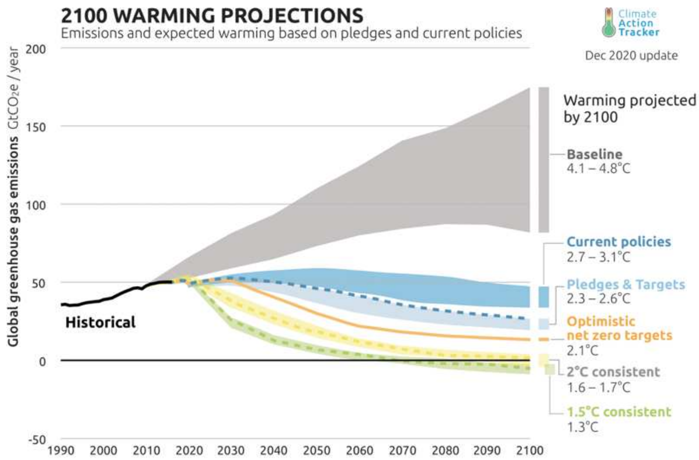
In fine, c'est tout l'équilibre de la planète tel que nous le connaissons depuis près de 10 000 ans, ce qui correspond à l'apparition de l'agriculture, l'augmentation de la sociabilisation, qui est en jeu (Steffen, 2015) et donc une sortie possible de l'holocène vers l'anthropocène.

L'objectif est connu : le Giec, met une limite à des nouveaux flux de carbone à 300GtCO_2 à partir de 2020 afin d'avoir 83% de probabilité de ne pas dépasser une hausse des températures de plus de 1.5° par rapport à l'âge préindustriel.

Or, compte tenu des tendances actuelles, il n'y a que 5% de probabilité de rester en deçà d'une augmentation de 2° (Liu et Raftery, 2021) et, même si tous les pays tiennent leurs engagements pris à la COP21 et maintiennent cette trajectoire, la probabilité n'augmente qu'à hauteur de 26%.

Une autre manière d'exprimer l'urgence de la situation est de remettre le budget de 300GtCO_2 (en date du 1er janvier 2020) en perspective des dépenses actuelles de près de 33Gt et des années écoulées : il ne resterait que de l'ordre de 6 ans de budget carbone

Bref, nous ne sommes pas, de loin, sur la bonne trajectoire, comme illustré par Carbone Tracker :



Alors que les sphères tant du public que du privé sont restées sourdes à ce message, la situation a changé avec la 21eme Conférence des Parties (ou COP 21) et l'accord de 196 pays, même si les émissions ont continué à croître depuis (Figueres *et al.*, 2018).

Tout d'abord, les Banques Centrales attirent alors l'attention sur la nature des risques, tant physiques que de transition (Carney, 2015), voire de risque existentiel (Yellen, 2021) ; rapidement, elles se regroupent lors du One Planet Summit de 2017 autour du Network for Greening the Financial System qui, rapidement, passe de 8 membres à sa création à près de 140 en 2023 et publient leurs premiers rapports (NGFS 2018, NGF 2019) mettant en avant la menace que pose le climat pour la stabilité financière ; ce faisant les banques centrales envoient un message fort à l'ensemble de la communauté financière : si le climat est un risque de premier ordre pour, par exemple, la Bundesbank, il devient difficile pour les investisseurs allemands de l'ignorer .

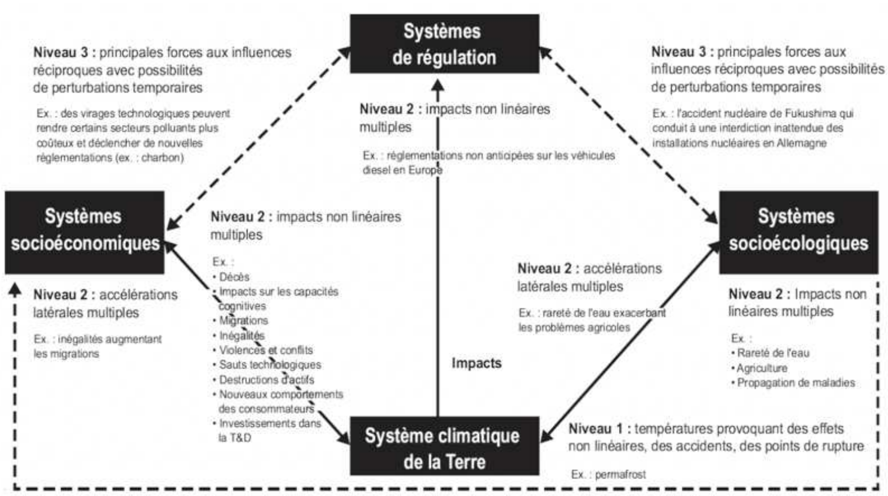
En parallèle, différentes innovations (Andersson *et al.*, 2016a, Eccles et Klimenko, 2019) et coalitions (Andersson *et al.,* 2016b, Boissinot et Samama, 2017), créent une dynamique positive au sein de la finance privée.

Mais, si l'amorçage a eu lieu, il reste encore beaucoup à faire, notamment dans la coopération entre les différents acteurs internationaux ou une plus grande intégration des risques climatiques par tous les acteurs, etc. (Bolton *et al.*, 2021).

3. Présentation des papiers

Dans "The Green Swan. Central Banking and Financial Stability in the Age of Climate Change" (Bolton *et al.*, 2020a), et en référence évidente au Black Swan (Taleb, 2007), le climat est décrit comme un risque d'une nature très particulière en ce qu'il combine (i) une forte probabilité d'occurrence (par opposition à des risques à faible probabilité d'occurence), (ii) des forces en jeu multiples, non-linéaires et se renforçant les unes les autres (notamment avec une forte augmentation de la réglementation tant directe qu'indirecte, la progression des évènements climatiques extrêmes et enfin des changements de préférence par la société ou des évolutions technologiques) menant à une difficulté fondamentale à modéliser le problème et (iii) un impact irrémédiable, voire qui menace la vie humaine.

Graphe d'interaction des différentes forces



Source : Bolton et al. 2020a

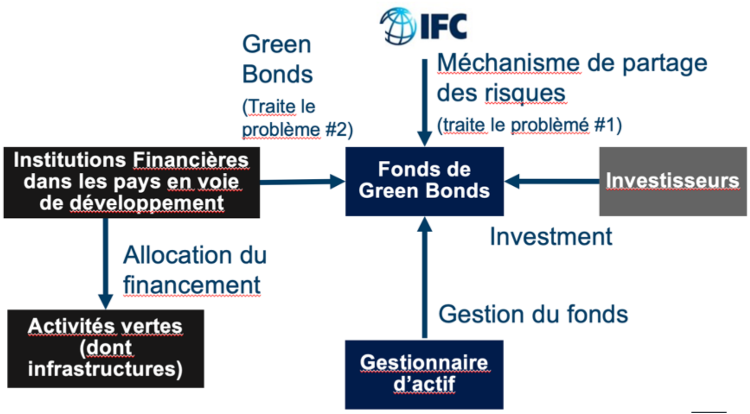
C'est donc un risque systémique, non assurable et existentiel. La Covid 19 ou encore la perte de biodiversité (IPBES 2019) sont d'autres exemple de *Green Swan.*

A partir de là, les modèles habituels, fondés sur des données passées et prenant difficilement en compte les interactions de forces non-linéaires et à impacts mortels, sont peu adaptés.

Cela amène à modifier l'approche avec le passage de la recherche de modèles conduisant à déterminer l'approche optimale, vers l'action, avec des ajustements progressifs.
Il devient donc nécessaire de repenser une coordination des différents acteurs, et notamment entre le secteur public et le secteur privé.

Le papier "From Global Savings Glut to Financing Infrastructures" (Arezki *et al.*, 2017) montre le déficit du financement des infrastructures vertes et notamment dans les pays en voie de développement (de 3% du GDP par an dans les pays développés à 9% dans les pays en voie de développement) avec une allocation sous-optimale de l'épargne : essentiellement localisée dans les pays développés faisant face à une croissance limitée et des taux bas et non dans les pays en voie de développement, où la croissance est importante. Ce manque de financement conduit à repenser le rôle et le fonctionnement des banques de développement et à rechercher des solutions pour développer un effet de levier dans leurs capacités d'intervention.

En forme de réponse, le papier "Global Public-Private Investment-Partnerships (GPPIPs): a Financial Innovation with a Positive Impact on Society" (Bolton *et al.*, 2020b) présente un partenariat innovant entre le secteur « public » (l'IFC, International Finance Corporation) et le secteur privé pour le financement des infrastructures dans les pays émergents. Généralement les partenariats public-privés sont une concession attribuée par un Etat à un opérateur privé, l'exemple classique étant le financement des routes, avec de nombreuses difficultés associées (Arezki *et al.*, 2017). Ce faisant, cette approche n'inclut pas les sources de financement des investisseurs institutionnels, ce qui conduit à une situation globale sous-optimale car ces dernières ne bénéficient pas des taux de croissance élevées des pays en voie de développement et sont confinés à des investissements dans des économie développées qui sont dans des environnements de taux bas ; et, à l'inverse, les pays en voie de développement n'ont pas accès à ces sources de financement dans les pays à forte croissance. On peut identifier deux raisons majeures au faible financement des infrastructures dans les pays émergents par les investisseurs institutionnels : tout d'abord, une appréciation élevée par les investisseurs institutionnels du risque souverain dans les pays en voie de développement et, ensuite, une asymétrie très élevée d'information sur les projets d'infrastructures entre les investisseurs et les développeurs de projets, localement et donc, *a fortiori,* à l'étranger. A partir de là, un prototype mis, au point avec l'IFC, traite les deux écueils : tout d'abord, la mise en place d'un fonds structuré avec différents niveaux de risques, l'IFC investissant dans la tranche la plus risquée et les investisseurs institutionnels dans celle portant le plus faible niveau ; ensuite, l'investissement par le fonds dans des obligations vertes (*green bonds)* émises par des banques dans les pays émergents ; ce faisant, le fonds prend le risque lié au bilan de la banque émettrice (et non le projet vert en lui-même), ayant ainsi accès à (i) la diversification de ce bilan, (ii) la conversion en dollars, (iii) la diligence raisonnable *(due-diligence)* mise en place par la banque sur le projet d'infrastructure, tout en ayant la garantie que son financement sera alloué au financements de projets verts (du fait de l'émission de *green bonds*).

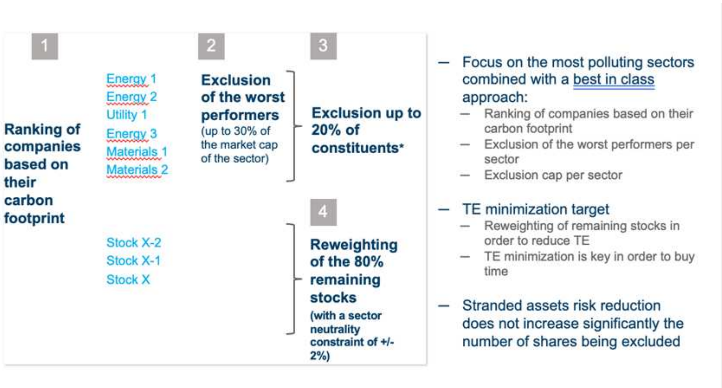


Source : à partir de Bolton *et al.*, 2020b

In fine, les investisseurs institutionnels, en apportant leurs investissements à ce fonds, s'alignent avec l'objectif de financement de l'IFC, qui ainsi multiplie, avec un investissement minimal dans ce fonds, son financement dans les projets verts. Cette approche a été reprise par la BEI (Banque Européenne d'Investissement) et l'AIIB (Asian Infrastructure Investment Bank) et a reçu 6 prix, dont le prestigieux prix du PRI (Principles for Responsible Investment) de *Real World Impact Initiative of the Year*[1].

Pareillement, une des caractéristiques forte du climat, mise en avant par Mark Carney, est « the tragedy of the horizon » (lors d'un discours à la Lloyd's, le 29 septembre 2015). Ici, le papier "Climate Change Hedging" (Andersson *et al.*, 2016a) présente une solution innovante, développée pour le fonds de pension Suédois AP4, puis le fonds de pension français FRR, et désormais reprise à travers le monde par des investisseurs institutionnels (Eccles et Klimenko, 2019), et qui permet de combiner investissement passif (en forte progression à travers le monde) avec une intégration du risque climatique. Cette technologie revient à réduire le poids dans des portefeuilles répliquant des indices des entreprises ayant une forte exposition au risque climatique à travers une empreinte carbone élevée (ramenée éventuellement au chiffre d'affaires), tout en réduisant de manière très faible la déviation par rapport aux indices standards.

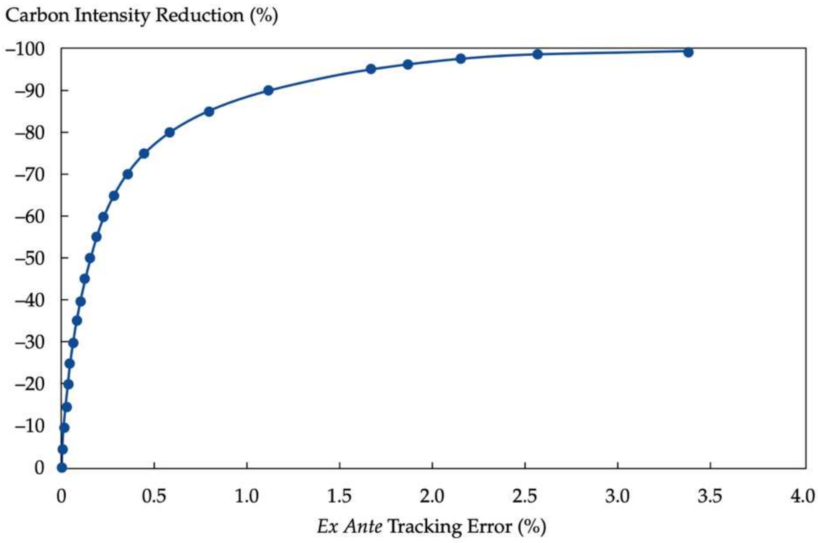
Méthodologie de réduction du poids des entreprises polluantes



Source : à partir de Andersson *et al.*, 2016a

Tracking-Error en fonction du niveau de réduction de l'empreinte carbone du portefeuille

[1] https://www.environmental-finance.com/content/awards/green-social-and-sustainability-bond-awards-2019/winners/green-bond-fund-of-the-year-initiative-of-the-year-amundi-and-ifcs-emerging-green-one.html



Source : Andersson *et al.*, 2016a

Cela revient à construire une d'option « gratuite » sur un risque mal rémunéré : autrement dit, soit le risque reste non rémunéré, et l'investisseur conserve une exposition standard aux marchés, soit le coût du risque se reflète dans les valorisations, et l'investisseur enregistre alors une surperformance ; Bref, cette solution, en permettant d'acheter du temps « gratuitement » permet de traiter « the tragedy of the horizon ». De plus, comme le montre le papier, en retenant une approche transparente sur les règles d'exclusion (par opposition au recours à un optimisateur), le mécanisme crée une compétition intra-sectorielle entre les entreprises les plus polluantes : celles qui ont été exclues peuvent être réintroduites ultérieurement en cas d'amélioration de leur empreinte carbone et ont donc des incitations pour accélérer leur transition vers une économie bas-carbone. Et à partir de là, c'est tout le secteur qui est tiré vers le haut en matière de réduction de ses émissions. C'est donc une forme d'engagement très actif (par flux de capitaux) et dynamique. *In fine*, cette stratégie a montré des surperformances, traduisant ainsi que l'investissement bas-carbone est générateur de rendements financiers, et non l'inverse.

Ces deux exemples d'innovation financières mettent en avant un nouveau rôle potentiel de l'investissement public : initier un prototype par un investissement tant en temps qu'en ressources financières, qui, ensuite, par réplication par d'autres investisseurs, démultiplie l'impact positif pour la société.

Conclusion

Une respiration entre le cadre conceptuel et les solutions pratiques semble d'une grande importance, compte tenu de la spécificité unique du risque climatique. Tant dans sa dimension de risque existentiel, que dans la remise en question des approches de modélisations qui ont été utilisées jusqu'à présent. Et comme l'horizon de temps est très court, il y a une nécessité absolue de limiter autant que de possible les errements et d'obtenir la mobilisation de toutes les forces possibles. Il est donc important d'inventer des mécanismes financiers qui répondent à ces nouveaux défis (comme celui de l'horizon de temps ou l'asymétrie d'information dans le financement des infrastructures) et d'alimenter le débat conceptuel avec des perspectives pragmatiques ; alors que le régulateur cherche à canaliser les flux d'investissement vers une économie bas-carbone, et met en priorité, en Europe, essentiellement le recours à des formes d'information *(reporting)* telles que la taxonomie mise au point par la Commission Européenne, il est nécessaire de mettre en avant qu'il est aussi, sinon surtout, nécessaire d'inventer des solutions qui correspondent aux vrais défis auxquels les investisseurs font face, afin d'accélérer la canalisation de l'investissement au bénéfice d'une économie bas-carbone.

Bref, deux défis sont devant nous : inventer une économie résiliente, et repenser les valeurs de notre société (Carney, 2021, Sandel, 2020). Défis *et* opportunité.

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BANQUE DE FRANCE

EUROSYSTÈME

The green swan

Central banking and financial stability in the age of climate change

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January 2020

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ISBN 978-92-9259-325-4 (print)
ISBN 978-92-9259-326-1 (online)

Abstract

Climate change poses new challenges to central banks, regulators and supervisors. This book reviews ways of addressing these new risks within central banks' financial stability mandate. However, integrating climate-related risk analysis into financial stability monitoring is particularly challenging because of the radical uncertainty associated with a physical, social and economic phenomenon that is constantly changing and involves complex dynamics and chain reactions. Traditional backward-looking risk assessments and existing climate-economic models cannot anticipate accurately enough the form that climate-related risks will take. These include what we call "green swan" risks: potentially extremely financially disruptive events that could be behind the next systemic financial crisis. Central banks have a role to play in avoiding such an outcome, including by seeking to improve their understanding of climate-related risks through the development of forward-looking scenario-based analysis. But central banks alone cannot mitigate climate change. This complex collective action problem requires coordinating actions among many players including governments, the private sector, civil society and the international community. Central banks can therefore have an additional role to play in helping coordinate the measures to fight climate change. Those include climate mitigation policies such as carbon pricing, the integration of sustainability into financial practices and accounting frameworks, the search for appropriate policy mixes, and the development of new financial mechanisms at the international level. All these actions will be complex to coordinate and could have significant redistributive consequences that should be adequately handled, yet they are essential to preserve long-term financial (and price) stability in the age of climate change.

Acknowledgements

We acknowledge suggestions, comments and contributions by: Michel Aglietta, Thomas Allen, Nathalie Aufauvre, Lisa Biermann, Jean Boissinot, Antoine Boirard, Clément Bourgey, Régis Breton, Ben Caldecott, Emanuele Campiglio, Adam Cap, Pierre Cardon, Michel Cardona, Hugues Chenet, Valérie Chouard, Laurent Clerc, Benoît Cœuré, Stéphane Dees, Simon Dikau, Torsten Ehlers, Frank Elderson, Ulrike Elsenhuber, Etienne Espagne, Gauthier Faure, Ingo Fender, Antoine Godin, Ian Goldin, Sylvie Goulard, Kevin Hoskin, Kumar Jegarasasingam, Joaquim Levy, David Lunsford, Sabine Mauderer, Jean-François Mercure, Juliette Mollo, Xavier Musca, William Oman, Adrian Orr, Alban Pyanet, Fernando Restoy, Guilllaume Richet-Bourbousse, Dilyara Salakhova, Edo Schets, Nicholas Stern, Josué Tanaka, Jakob Thomä, Charlotte Vailles, Pierre-François Weber and Jeffery Yong. All errors are exclusively our own.

We also thank the BIS communications team (Maria Canelli, Emma Claggett, Krista Hughes, Nathalie Savary, Fanny Sorgato and Victoria Torrano), and Giulio Cornelli, Alan Villegas and Adam Cap for excellent research assistance.

Contents

Foreword by Agustín Carstens

A growing body of research by academics, central banks and international institutions including the BIS focuses on climate-related risks. These studies show that physical risks related to climate change can severely damage our economies, for example through the large cost of repairing infrastructure and coping with uninsured losses. There are also transition risks related to potentially disorderly mitigation strategies. Both physical and transition risks, in turn, can increase systemic financial risk. Thus their potential consequences have implications for central banks' financial stability mandate. All these considerations prompted central banks to create the Central Banks and Supervisors Network for Greening the Financial System (NGFS), which the BIS has been part of since its inception.

This book helps to trace the links between the effects of climate change, or global warming, and the stability of our financial sectors. It includes a comprehensive survey of how climate change has been progressively integrated into macroeconomic models and how these have evolved to better assess financial stability risks stemming from climate change (eg stress testing models using global warming scenarios). But the book also recognises the limitations of our models, which may not be able to accurately predict the economic and financial impact of climate change because of the complexity of the links and the intrinsic non-linearity of the related phenomena. Nevertheless, despite the high level of uncertainty, the best scientific advice today suggests that action to mitigate and adapt to climate change is needed.

Naturally, the first-best solution to address climate change and reduce greenhouse gas emissions is Pigovian carbon taxation. This policy suggests that fundamental responsibility for addressing issues related to climate change lies with governments. But such an ambitious new tax policy requires consensus-building and is difficult to implement. Nor can central banks resolve this complex collective action problem by themselves. An effective response requires raising stakeholders' awareness and facilitating coordination among them. Central banks' financial stability mandate can contribute to this and should guide their appropriate involvement. For instance, central banks can coordinate their own actions with a broad set of measures to be implemented by other players (governments, the private sector, civil society and the international community). This is urgent since climate-related risks continue to build, and negative outcomes such as what this book calls "green swan" events could materialise.

Contributing to this coordinating role is not incompatible with central banks doing their share within their current mandates. In this sense there are many practical actions central banks can undertake (and, in some cases, are already undertaking). They include enhanced monitoring of climate-related risks through adequate stress tests; developing new methodologies to improve the assessment of climate-related risks; including environmental, social and governance (ESG) criteria in their pension funds; helping to develop and assess the proper taxonomy to define the carbon footprint of assets more precisely (eg "green" versus "brown" assets); working closely with the financial sector on disclosure of carbon-intensive exposure to assess potential financial stability risks; studying more precisely how prudential regulation could deal with risks to financial stability arising from climate change; and examining the adequate room to invest surplus FX reserves into green bonds.

The BIS has been collaborating with the central bank community on all these aspects. In addition, in September 2019 it launched its green bond BIS Investment Pool Fund, a new vehicle that facilitates central banks' investments in green bonds. And with this book it hopes to steer the debate and discussions further while recognising that all these actions will require more research and be challenging, but nevertheless essential to preserving long-term financial and price stability in the age of accelerated climate change.

Agustín Carstens
BIS General Manager

Foreword by François Villeroy de Galhau

In the speech he delivered when receiving the Nobel Prize in Literature in 1957, the French writer Albert Camus said: "Each generation doubtless feels called upon to reform the world. Mine knows that it will not reform it, but its task is perhaps even greater. It consists in preventing the world from destroying itself". Despite a different context, these inspiring words are definitely relevant today as mankind is facing a great threat: climate change.

Climate change poses unprecedented challenges to human societies, and our community of central banks and supervisors cannot consider itself immune to the risks ahead of us. The increase in the frequency and intensity of extreme weather events could trigger non-linear and irreversible financial losses. In turn, the immediate and system-wide transition required to fight climate change could have far-reaching effects potentially affecting every single agent in the economy and every single asset price. Climate-related risks could therefore threaten central banks' mandates of price and financial stability, but also our socio-economic systems at large. If I refer to our experience at the Banque de France and to the impressive success of the Network for Greening the Financial System (NGFS) we launched in December 2017, I would tend to affirm that our community is now moving in the right direction.

But despite this growing awareness, the stark reality is that we are all losing the fight against climate change. In such times, the role our community should play in this battle is questioned. It is then important to clearly state that we cannot be the only game in town, even if we should address climate-related risks within the remit of our mandates, which may include considering options relating to the way we conduct monetary policy. On monetary policy, I have two strong beliefs, and we will have the opportunity to discuss them against the backdrop of the ECB strategic review led by Christine Lagarde. First, we need to integrate climate change in all our economic and forecasting models; second we need, instead of opening a somewhat emotional debate on the merits of a green quantitative easing, which faces limitations, to do an overhaul of our collateral assessment framework to reflect climate-related risks.

In order to navigate these troubled waters, more holistic perspectives become essential to coordinate central banks', regulators' and supervisors' actions with those of other players, starting with governments. This is precisely what this book does. If central banks are to preserve financial and price stability in the age of climate change, it is in their interest to help mobilize all the forces needed to win this battle. This book is an ambitious, carefully thought-out and therefore necessary contribution toward this end.

François Villeroy de Galhau
Governor of the Banque de France

Scientific knowledge is as much an understanding of the diversity of situations for which a theory or its models are relevant as an understanding of its limits.

Elinor Ostrom (1990)

Executive Summary

This book reviews some of the main challenges that climate change poses to central banks, regulators and supervisors, and potential ways of addressing them. It begins with the growing realisation that climate change is a source of financial (and price) instability: it is likely to generate physical risks related to climate damages, and transition risks related to potentially disordered mitigation strategies. Climate change therefore falls under the remit of central banks, regulators and supervisors, who are responsible for monitoring and maintaining financial stability. Their desire to enhance the role of the financial system to manage risks and to mobilise capital for green and low-carbon investments in the broader context of environmentally sustainable development prompted them to create the Central Banks and Supervisors Network for Greening the Financial System (NGFS).

However, integrating climate-related risk analysis into financial stability monitoring and prudential supervision is particularly challenging because of the distinctive features of climate change impacts and mitigation strategies. These comprise physical and transition risks that interact with complex, far-reaching, nonlinear, chain reaction effects. Exceeding climate tipping points could lead to catastrophic and irreversible impacts that would make quantifying financial damages impossible. Avoiding this requires immediate and ambitious action towards a structural transformation of our economies, involving technological innovations that can be scaled but also major changes in regulations and social norms.

Climate change could therefore lead to "green swan" events (see Box A) and be the cause of the next systemic financial crisis. Climate-related physical and transition risks involve interacting, nonlinear and fundamentally unpredictable environmental, social, economic and geopolitical dynamics that are irreversibly transformed by the growing concentration of greenhouse gases in the atmosphere.

In this context of deep uncertainty, traditional backward-looking risk assessment models that merely extrapolate historical trends prevent full appreciation of the future systemic risk posed by climate change. An "epistemological break" (Bachelard (1938)) is beginning to take place in the financial community, with the development of forward-looking approaches grounded in scenario-based analyses. These new approaches have already begun to be included in the financial industry's risk framework agenda, and reflections on climate-related prudential regulation are also taking place in several jurisdictions.

While these developments are critical and should be pursued, this book presents two additional messages. First, scenario-based analysis is only a partial solution to apprehend the risks posed by climate change for financial stability. The deep uncertainties involved and the necessary structural transformation of our global socioeconomic system are such that no single model or scenario can provide a full picture of the potential macroeconomic, sectoral and firm-level impacts caused by climate change. Even more fundamentally, climate-related risks will remain largely unhedgeable as long as system-wide action is not undertaken.

Second, it follows from these limitations that central banks may inevitably be led into uncharted waters in the age of climate change. On the one hand, if they sit still and wait for other government agencies to jump into action, they could be exposed to the real risk of not being able to deliver on their mandates of financial and price stability. Green swan events may force central banks to intervene as "climate rescuers of last resort" and buy large sets of devalued assets, to save the financial system once more. However, the biophysical foundations of such a crisis and its potentially irreversible impacts would quickly show the limits of this "wait and see" strategy. On the other hand, central banks cannot (and should not) simply replace governments and private actors to make up for their insufficient action, despite growing social pressures to do so. Their goodwill could even create some moral hazard. In short, central banks, regulators and supervisors can only do so much (and many of them are already taking action within their mandates), and their action can only be seen as enhancing other climate change mitigation policies.

To overcome this deadlock, a second epistemological break is needed: central banks must also be more proactive in calling for broader and coordinated change, in order to continue fulfilling their own mandates of financial and price stability over longer time horizons than those traditionally considered. We believe that they can best contribute to this task in a role that we dub the five Cs: **c**ontribute to **c**oordination to **c**ombat **c**limate **c**hange. This coordinating role would require thinking concomitantly within three paradigmatic approaches to climate change and financial stability: the risk, time horizon and system resilience approaches (see Box B).

Contributing to this coordinating role is not incompatible with central banks, regulators and supervisors doing their own part within their current mandates. They can promote the integration of climate-related risks into prudential regulation and financial stability monitoring, including by relying on new modelling approaches and analytical tools that can better account for the uncertainty and complexity at stake. In addition, central banks can promote a longer-term view to help break the "tragedy of the horizon", by integrating sustainability criteria into their own portfolios and by exploring their integration in the conduct of financial stability policies, when deemed compatible with existing mandates.

But more importantly, central banks need to coordinate their own actions with a broad set of measures to be implemented by other players (ie governments, the private sector, civil society and the international community). This coordination task is urgent since climate-related risks continue to build up and negative outcomes could become irreversible. There is an array of actions to be consistently implemented. The most obvious ones are the need for carbon pricing and for systematic disclosure of climate-related risks by the private sector.

Taking a transdisciplinary approach, this book calls for additional actions that no doubt will be difficult to take, yet will also be essential to preserve long-term financial (and price) stability in the age of climate change. These include: exploring new policy mixes (fiscal-monetary-prudential) that can better address the climate imperatives ahead and that should ultimately lead to societal debates regarding their desirability; considering climate stability as a global public good to be supported through measures and reforms in the international monetary and financial system; and integrating sustainability into accounting frameworks at the corporate and national level.

Moreover, climate change has important distributional effects both between and within countries. Risks and adaptation costs fall disproportionately on poor countries and low-income households in rich countries. Without a clear indication of how the costs and benefits of climate change mitigation strategies will be distributed fairly and with compensatory transfers, sociopolitical backlashes will increase. Thus, the needed broad social acceptance for combating climate change depends on studying, understanding and addressing its distributional consequences.

Financial and climate stability could be considered as two interconnected public goods, and this consideration can be extend to other human-caused environmental degradation such as the loss of biodiversity. These, in turn, require other deep transformations in the governance of our complex adaptive socioeconomic and financial systems. In the light of these immense challenges, a central contribution of central banks is to adequately frame the debate and thereby help promote the mobilisation of all capabilities to combat climate change.

Box A: From black to green swans

The "green swan" concept used in this book finds its inspiration in the now famous concept of the "black swan" developed by Nassim Nicholas Taleb (2007). Black swan events have three characteristics: (i) they are unexpected and rare, thereby lying outside the realm of regular expectations; (ii) their impacts are wide-ranging or extreme; (iii) they can only be explained after the fact. Black swan events can take many shapes, from a terrorist attack to a disruptive technology or a natural catastrophe. These events typically fit fat tailed probability distributions, ie they exhibit a large skewness relative to that of normal distribution (but also relative to exponential distribution). As such, they cannot be predicted by relying on backward-looking probabilistic approaches assuming normal distributions (eg value-at-risk models).

The existence of black swans calls for alternative epistemologies of risk, grounded in the acknowledgment of uncertainty. For instance, relying on mathematician Benoît Mandelbrot (1924–2010), Taleb considers that fractals (mathematically precise patterns that can be found in complex systems, where small variations in exponent can cause large deviation) can provide more relevant statistical attributes of financial markets than both traditional rational expectations models and the standard framework of Gaussian-centred distributions (Taleb (2010)). The use of counterfactual reasoning is another avenue that can help hedge, at least partially, against black swan events. Counterfactuals are thoughts about alternatives to past events, "thoughts of what might have been" (Epstude and Roese (2008)). Such an epistemological position can provide some form of hedging against extreme risks (turning black swans into "grey" ones) but not make them disappear. From a systems perspective, fat tails in financial markets suggest a need for regulation in their operations (Bryan et al (2017), p 53).

Green swans, or "climate black swans", present many features of typical black swans. Climate-related risks typically fit fat-tailed distributions: both physical and transition risks are characterised by deep uncertainty and nonlinearity, their chances of occurrence are not reflected in past data, and the possibility of extreme values cannot be ruled out (Weitzman (2009, 2011)). In this context, traditional approaches to risk management consisting in extrapolating historical data and on assumptions of normal distributions are largely irrelevant to assess future climate-related risks. That is, assessing climate-related risks requires an "epistemological break" (Bachelard (1938)) with regard to risk management, as discussed in this book.

However, green swans are different from black swans in three regards. First, although the impacts of climate change are highly uncertain, "there is a high degree of certainty that some combination of physical and transition risks will materialize in the future" (NGFS (2019a), p 4). That is, there is certainty about the need for ambitious actions despite prevailing uncertainty regarding the timing and nature of impacts of climate change. Second, climate catastrophes are even more serious than most systemic financial crises: they could pose an existential threat to humanity, as increasingly emphasized by climate scientists (eg Ripple et al (2019)). Third, the complexity related to climate change is of a higher order than for black swans: the complex chain reactions and cascade effects associated with both physical and transition risks could generate fundamentally unpredictable environmental, geopolitical, social and economic dynamics, as explored in Chapter 3.

Box B: The five Cs – contribute to coordination to combat climate change: the risk, time horizon and system resilience approaches

<table>
<tr><th>Responsibilities / Paradigmatic approach to climate change</th><th>Measures to be considered[1] by central banks, regulators and supervisors</th><th>Measures to be implemented by other players[2] (government, private sector, civil society)</th></tr>
<tr><td>Identification and management of climate-related risks

>> Focus on risks</td><td>Integration of climate-related risks (given the availability of adequate forward-looking methodologies) into:
– Prudential regulation
– Financial stability monitoring</td><td>Voluntary disclosure of climate-related risks by the private sector (Task Force on Climate-related Financial Disclosures)
– Mandatory disclosure of climate-related risks and other relevant information (eg French Article 173, taxonomy of “green” and “brown” activities)</td></tr>
<tr><td colspan="3">Limitations:
– Epistemological and methodological obstacles to the development of consistent scenarios at the macroeconomic, sectoral and infra-sectoral levels
– Climate-related risks will remain unhedgeable as long as system-wide transformations are not undertaken</td></tr>
<tr><td>Internalisation of externalities

>> Focus on time horizon</td><td>Promotion of long-termism as a tool to break the tragedy of the horizon, including by:
– Integrating environmental, social and governance (ESG) considerations into central banks’ own portfolios
– Exploring the potential impacts of sustainable approaches in the conduct of financial stability policies, when deemed compatible with existing mandates</td><td>– Carbon pricing
– Systematisation of ESG practices in the private sector</td></tr>
<tr><td colspan="3">Limitations:
– Central banks’ isolated actions would be insufficient to reallocate capital at the speed and scale required, and could have unintended consequences
– Limits of carbon pricing and of internalisation of externalities in general: not sufficient to reverse existing inertia/generate the necessary structural transformation of the global socioeconomic system</td></tr>
<tr><td>Structural transformation towards an inclusive and low-carbon global economic system

>> Focus on resilience of complex adaptive systems in the face of uncertainty</td><td>Acknowledgment of deep uncertainty and need for structural change to preserve long-term climate and financial stability, including by exploring:
– Green monetary-fiscal-prudential coordination at the effective lower bound
– The role of non-equilibrium models and qualitative approaches to better capture the complex and uncertain interactions between climate and socioeconomic systems
– Potential reforms of the international monetary and financial system, grounded in the concept of climate and financial stability as interconnected public goods</td><td>– Green fiscal policy (enabled or facilitated by low interest rates)
– Societal debates on the potential need to revisit policy mixes (fiscal-monetary-prudential) given the climate and broader ecological imperatives ahead
– Integration of natural capital into national and corporate accounting systems
– Integration of climate stability as a public good to be supported by the international monetary and financial system</td></tr>
</table>

[1] Considering these measures does not imply full support to their immediate implementation. Nuances and potential limitations are discussed in the book. [2] Measures which are deemed essential to achieve climate and financial stability, yet which lie beyond the scope of what central banks, regulators and supervisors can do.

Source: Authors’ elaboration.

1. INTRODUCTION – "PLANET EARTH IS FACING A CLIMATE EMERGENCY"

Scientists have a moral obligation to clearly warn humanity of any catastrophic threat and to "tell it like it is." On the basis of this obligation [...] we declare, with more than 11,000 scientist signatories from around the world, clearly and unequivocally that planet Earth is facing a climate emergency.

Ripple et al (2019)

Climate change poses an unprecedented challenge to the governance of global socioeconomic and financial systems. Our current production and consumption patterns cause unsustainable emissions of greenhouse gases (GHGs), especially carbon dioxide (CO_2): their accumulated concentration in the atmosphere above critical thresholds is increasingly recognised as being beyond our ecosystem's absorptive and recycling capabilities. The continued increase in temperatures has already started affecting ecosystems and socioeconomic systems across the world (IPCC (2018), Mora et al (2018)) but, alarmingly, climate science indicates that the worst impacts are yet to come. These include sea level rise, increases in weather extremes, droughts and floods, and soil erosion. Associated impacts could include a massive extinction of wildlife, as well as sharp increases in human migration, conflicts, poverty and inequality (Human Rights Council (2019), IPCC (2018), Masson-Delmotte and Moufouma-Okia (2019), Ripple et al (2019)).

Scientists today recommend reducing GHG emissions, starting immediately (Lenton et al (2019), Ripple et al (2019)). In this regard, the 2015 United Nations Climate Change Conference (COP21) and resulting Paris Agreement among 196 countries to reduce GHG emissions on a global scale was a major political achievement. Under the Paris Agreement (UNFCCC (2015)) signatories agree to reduce greenhouse gas emissions "as soon as possible" and to do their best to keep global warming "to well below 2 degrees" Celsius (2°C), with the aim of limiting the increase to 1.5°C. Yet global emissions have kept rising since then (Figueres et al (2018)),[1] and nothing indicates that this trend is reverting.[2] Countries' already planned production of coal, oil and gas is inconsistent with limiting warming to 1.5°C or 2°C, thus creating a "production gap", a discrepancy between government plans and coherent decarbonisation pathways (SEI et al (2019)).

Changing our production and consumption patterns and our lifestyles to transition to a low-carbon economy is a tough collective action problem. There is still considerable uncertainty on the effects of climate change and on the most urgent priorities. There will be winners and losers from climate change mitigation, exacerbating free rider problems. And, perhaps even more problematically, there are large time lags before climate damages become apparent and irreversible (especially to climate change sceptics): the most damaging effects will be felt beyond the traditional time horizons of policymakers and other economic and financial decision-makers. This is what Mark Carney (2015) referred to as "the tragedy of the horizon": while the physical impacts of climate change will be felt over a long-term horizon, with massive costs and possible civilisational impacts on future generations, the time horizon in which financial, economic and political players plan and act is much shorter. For instance, the time horizon of rating

[1] Ominously, David Wallace-Wells recently observed in *The Uninhabitable Earth* (2019), "We have done as much damage to the fate of the planet and its ability to sustain human life and civilization since Al Gore published his first book on the climate than in all the centuries – all the millenniums – that came before."

[2] The Agreement itself is legally binding, but no enforcement mechanisms exist and the GHG reduction targets set by each country through their Nationally Determined Contributions (NDCs) are only voluntary.

agencies to assess credit risks, and of central banks to conduct stress tests, is typically around three to five years.

Our framing of the problem is that climate change represents a green swan (see Box A): it is a new type of systemic risk that involves interacting, nonlinear, fundamentally unpredictable, environmental, social, economic and geopolitical dynamics, which are irreversibly transformed by the growing concentration of greenhouse gases in the atmosphere. Climate-related risks are not simply black swans, ie tail risk events. With the complex chain reactions between degraded ecological conditions and unpredictable social, economic and political responses, with the risk of triggering tipping points,[3] climate change represents a colossal and potentially irreversible risk of staggering complexity.

Carbon pricing and beyond

Climate change is widely considered by economists as an externality that, as such, should be dealt with through publicly imposed Pigovian carbon taxes[4] in order to internalise the climate externalities. Indeed, according to basic welfare economics, a good policy to combat climate change requires such a "price" to act as an incentive to reduce GHG emissions. A carbon tax, for example, creates an incentive for economic agents to lower emissions by switching to more efficient production processes and consumption patterns. The amount of this tax needs to reflect what we already know about the medium- to long-term additional costs of climate change. From a mainstream economist's perspective, a carbon tax that reflects the social cost of carbon (SCC) would make explicit the "shadow cost" of carbon emissions and would be sufficient to induce economic actors to reduce emissions in a perfect Walrasian world.

By this analytical framing, central banks, regulators and supervisors have little to do in the process of decarbonising the economic system. Indeed, the needed transition would mostly be driven by non-financial firms and households, whose decentralised decisions would be geared towards low-carbon technologies thanks to carbon pricing. From a financial perspective, using a carbon tax to correctly price the negative externality would be sufficient to reallocate financial institutions' assets from carbon-intensive towards greener capital. At most, central banks and supervisors should carefully scrutinise financial market imperfections, in order to ensure financial stability along the transition towards a low-carbon economy.

Yet the view that carbon pricing is the sole answer to climate change, and its corollary in terms of monetary and prudential policies (ie that central banks, regulators and supervisors should not really be concerned by climate change) suffers from three significant limitations, which contribute to overlooking potential "green swan" events.

First, even though conceptually carbon pricing has been recognised as the first best option for decades, in practice it has not been implemented at a level sufficient to drive capital reallocation from "brown" (or carbon-intensive) to "green" (or low-carbon) assets. The reality is that governments have failed to act and will continue to do so unless much broader pressure from civil society and business induces significant policy change. Given the current deficiency in global policy responses, it only becomes more likely that the physical impacts of climate change will affect the socioeconomic system in a rapidly warming world. Given that rising temperatures will unleash complex dynamics with tipping points, the impact of

3 A tipping point in the climate system is a threshold that, when exceeded, can lead to large changes in the state of the system. Climate tipping points are of particular interest in reference to concerns about global warming in the modern era. Possible tipping point behaviour has been identified for the global mean surface temperature by studying self-reinforcing feedbacks and the past behaviour of Earth's climate system. Self-reinforcing feedbacks in the carbon cycle and planetary reflectivity could trigger a cascading set of tipping points that lead the world into a hothouse climate state (source: Wikipedia).

4 From Arthur C Pigou (1877–1959), who proposed the concept and the solution to externality problems by taxation, an idea that is key to modern welfare economics and to the economic analysis of environmental impacts. Other economic instruments aimed at pricing carbon exist, such as emission trading schemes (ETS), also known as cap-and-trade systems. Unlike a tax, where the price is determined ex ante, the price of CO_2 in a cap-and-trade mechanism is determined ex post, as a result of the supply and demand of quotas to emit CO_2.

global warming will affect our economies in a disorderly yet cumulative manner that, in turn, could trigger unforeseeable negative financial dynamics.

These so-called physical risks will have financial consequences that are naturally of concern to central bankers and supervisors. They can threaten financial stability by causing irreversible losses, as capital is affected by climate change and as financial agents may be unable to protect themselves from such climate shocks. These risks can also threaten price stability by triggering supply shocks on various commodities, which could in turn generate inflationary or even stagflationary effects (Villeroy de Galhau (2019a)). It should also be noted that traditional policy instruments may be less effective at smoothing these shocks, to the extent that these are more or less permanent biophysical shocks, rather than transitory economic shocks (Cœuré (2018)).

Second, climate change is not merely another market failure but presumably "the greatest market failure the world has ever seen", as leading climate economist Lord Nicholas Stern puts it (Stern (2007)). Given the size of the challenge ahead, carbon prices may need to skyrocket in a very short time span towards much higher levels than currently prevail. Moreover, taking climate-related risks and uncertainty seriously (eg by including the possibility of tipping points leading to catastrophic and irreversible events) should lead to even sharper increases in the SCC (Ackerman et al (2009), Cai and Lontzek (2019), Daniel et al (2019), Weitzman (2009)). With this in mind, the transition may trigger a broad range of unintended consequences. For example, it is increasingly evident that mitigation measures such as carbon price adjustments could have dramatic distributional consequences, both within and across countries.

More to the point of actions by central bankers and supervisors, newly enforced and more stringent environmental regulations could produce or reinforce financial failures in credit markets (Campiglio (2016)) or abrupt reallocations of assets from brown to green activities motivated by market repricing of risks and/or attempts to limit reputational risks and litigations. All this could result in a "climate Minsky moment" (Carney (2018)), a severe financial tightening of financial conditions for companies that rely on carbon-intensive activities (so-called "stranded assets"; see Box 1), be it directly or indirectly through their value chains. These risks are categorised as transition risks; as with physical risks, they are of concern to central bankers and supervisors. Here, the "paradox is that success is failure" (Carney (2016)): extremely rapid and ambitious measures may be the most desirable from the point of view of climate mitigation, but not necessarily from the perspective of financial stability over a short-term horizon. Addressing this tension requires a broad range of measures, as extensively discussed in this book.

Third, the climate change market failure is of such magnitude that it would be prudent to approach it as more than just a market failure. It is a subject that combines, among other things, uncertainty, risk, potentially deep transformations in our lifestyles, prioritising long-term ethical choices over short-term economic considerations, and international coordination for the common good. With this in mind, recent and growing transdisciplinary work suggests that our collective inability to reverse expected climate catastrophes originates in interlocked, complex institutional arrangements, which could be described as a socio-technical system: "a cluster of elements, including technology, regulations, user practices and markets, cultural meanings, infrastructure, maintenance networks and supply networks" (Geels et al (2004), p 3).

Given this institutional or sociotechnical inertia, higher carbon prices alone may not suffice to drive individual behaviours and firms' replacement of physical capital towards low-carbon alternatives, as economics textbooks suggest. For instance, proactive fiscal policy may be an essential first step to build adequate infrastructure (eg railroads), before carbon pricing can really lead agents to modify their behaviour (eg by switching from car to train). Tackling climate change may therefore require finding complex policy mixes combining monetary, prudential and fiscal instruments (Krogstrup and Oman (2019)) as well as many other societal innovations, as discussed in the last chapter. Going further, the fight against climate change is taking place at the same time when the post-World War II global institutional framework is under growing criticism. This means that the unprecedented level of international coordination required to address the difficult (international) political economy of climate change is seriously compromised.

Therefore, to guarantee a successful low-carbon transition, new technologies, new institutional arrangements and new cultural frameworks should emerge (Beddoe et al (2009)) towards a comprehensive reshaping of current productive structures and consumption patterns. The analogy one may use to envision the change ahead is that of engaging in a multidimensional combat against climate change (Stiglitz (2019)). Even for the sceptics who prefer a "wait and see" approach, a pure self-interested risk management strategy recommends buying the proper insurance of ambitious climate policies (Weitzman (2009)) as a kind of precautionary principle[5] (Aglietta and Espagne (2016)), "pari Pascalien"[6] or "enlightened doomsaying"[7] (Dupuy (2012)), ie as a hedging strategy against the possibility of green swan events.

For all these reasons, even if a significant increase in carbon pricing globally remains an essential step to fight climate change, other (second-, third- or fourth-best from a textbook perspective) options must be explored, including with regard to the financial system.

Revisiting financial stability in the age of climate change

The reflections on the relationship between climate change and the financial system are still in their early stages: despite rare warnings on the significant risks that climate change could pose to the financial system (Carbon Tracker (2013)), the subject was mostly seen as a fringe topic until a few years ago (Chenet (2019a)). But the situation has changed radically in recent times, as climate change's potentially disruptive impacts on the financial system have started to become more apparent, and the role of the financial system in mitigating climate change has been recognised.

This growing awareness of the financial risks posed by climate change can be related to three main developments. First, the Paris Agreement's (UNFCCC (2015)) Article 2.1(c) explicitly recognised the need to "mak[e] finance flows compatible with a pathway toward low greenhouse gas emissions and climate-resilient development", thereby paving the way to a radical reorientation of capital allocation. Second, as mentioned above, the Governor of the Bank of England, Mark Carney (2015), suggested the possibility of a systemic financial crisis caused by climate-related events. Third, in December 2017 the Central Banks and Supervisors Network for Greening the Financial System[8] (NGFS) was created by a group of central banks and supervisors willing to contribute to the development of environment and climate risk management in the financial sector, and to mobilise mainstream finance to support the transition toward a sustainable economy.

The NGFS quickly acknowledged that "climate-related risks are a source of financial risk. It is therefore within the mandates of central banks and supervisors to ensure the financial system is resilient to these risks" (NGFS (2018), p 3).[9] The NGFS also acknowledged that these risks are tied to complex layers of interactions between the macroeconomic, financial and climate systems (NGFS (2019b)). As this book

5 The precautionary principle is used to justify discretionary measures by policymakers in situations where there are plausible risks of harming the public through certain decisions, but extensive scientific knowledge on the matter is lacking.

6 The French philosopher, mathematician and physicist Blaise Pascal (1623–62) used a game theory argument to justify faith as a "hedge": rational people should believe in God as a "pari" or bet. They would incur small losses of pleasure (by accepting to live a life without excessive pleasures), which would be more than offset by infinite gains (eternity in heaven) if God existed. In the same way, accepting some small inconveniences (adjusting one's lifestyle to climate imperatives) is compensated by a more sustainable earth ecosystem, if indeed global warming exists (from the climate change sceptic's perspective).

7 The concept of "enlightened doomsaying" (catastrophisme éclairé) put forward by the French philosopher of science Jean-Pierre Dupuy (2012) involves imagining oneself in a catastrophic future to raise awareness and trigger immediate action so that this future does not take place.

8 As of 12 December 2019, the NGFS is composed of 54 members and 12 observers. For more information, see www.ngfs.net.

9 As acknowledged by the NGFS (2019a), the legal mandates of central banks and financial supervisors vary throughout the world, but they typically include responsibility for price stability, financial stability and the safety and soundness of financial institutions.

will extensively discuss, assessing climate-related risks involves dealing with multiple forces that interact with one another, causing dynamic, nonlinear and disruptive dynamics that can affect the solvency of financial and non-financial firms, as well as households' and sovereigns' creditworthiness.

In the worst case scenario, central banks may have to confront a situation where they are called upon by their local constituencies to intervene as climate rescuers of last resort For example, a new financial crisis caused by green swan events severely affecting the financial health of the banking and insurance sectors could force central banks to intervene and buy a large set of carbon-intensive assets and/or assets stricken by physical impacts.

But there is a key difference between green swan and black swan events: since the accumulation of atmospheric CO_2 beyond certain thresholds can lead to irreversible impacts, the biophysical causes of the crisis will be difficult, if not impossible, to undo at a later stage. Similarly, in the case of a crisis triggered by a rapid transition to a low-carbon economy, there would be little ground for central banks to rescue the holders of assets in carbon-intensive companies. While banks in financial distress in an ordinary crisis can be resolved, this will be far more difficult in the case of economies that are no longer viable because of climate change. Intervening as climate rescuers of last resort could therefore affect central bank's credibility and crudely expose the limited substitutability between financial and natural capital.

Given the severity of these risks, the uncertainty involved and the awareness of the interventions of central banks following the 2007–08 Great Financial Crisis, the sociopolitical pressure is already mounting to make central banks (perhaps again) the "only game in town" and to substitute for other if not all government interventions, this time to fight climate change. For instance, it has been suggested that central banks could engage in "green quantitative easing"[10] in order to solve the complex socioeconomic problems related to a low-carbon transition.

Relying too much on central banks would be misguided for many reasons (Villeroy de Galhau (2019a), Weidmann (2019)). First, it may distort markets further and create disincentives: the instruments that central banks and supervisors have at their disposal cannot substitute for the many areas of interventions that are needed to transition to a global low-carbon economy. That includes fiscal, regulatory and standard-setting authorities in the real and financial world whose actions should reinforce each other. Second, and perhaps most importantly, it risks overburdening central banks' existing mandates. True, mandates can evolve, but these changes and institutional arrangements are very complex issues because they require building new sociopolitical equilibria, reputation and credibility. Although central banks' mandates have evolved from time to time, these changes have taken place along with broader sociopolitical adjustments, not to replace them.

Outline

These considerations suggest that central banks may inevitably be led into uncharted waters in the age of climate change. Whereas they cannot and should not replace policymakers, they also cannot sit still, since this could place them in the untenable situation of climate rescuer of last resort discussed above. This book sets out from this analytical premise and asks the following question: what, then, should be the role of central banks, regulators and supervisors in preserving financial stability[11] in the age of climate change? It is organised as follows.

Chapter 2 provides an overview of how climate-related risks are threatening socioeconomic activities, thereby affecting the future ability of central banks and supervisors to fulfil their mandates of monetary and financial stability. Following the old adage "that which is measured can be managed" (Carney (2015)), the obvious task in terms of financial regulation and supervision is therefore to ensure

[10] See De Grawe (2019) and the current debate about green quantitative easing in the United States and Europe.

[11] The question of price stability is also touched upon, although less extensively than financial stability.

that climate-related risks become integrated into financial stability monitoring and prudential supervision. However, such a task presents a significant challenge: traditional approaches to risk management consisting in extrapolating historical data based on assumptions of normal distributions are largely irrelevant to assess future climate-related risks. Indeed, both physical and transition risks are characterised by deep uncertainty, nonlinearity and fat-tailed distributions. As such, assessing climate-related risks requires an "epistemological break" (Bachelard (1938)) with regard to risk management. In fact, such a break has started to take place in the financial community, with the development of forward-looking, scenario-based risk management methodologies.

Chapter 3 assesses the methodological strengths and limitations of these methodologies. While their use by financial institutions and supervisors will become critical, it should be kept in mind that scenario-based analysis will not suffice to preserve financial stability in the age of climate change: the deep uncertainty at stake and the need for a structural transformation of the global socioeconomic system mean that no single model or scenario can provide sufficient information to private and public decision-makers (although new modelling and analytical approaches will be critical to embrace the uncertain and non-equilibrium patterns involved). In particular, forward-looking approaches remain highly sensitive to a broad set of uncertain parameters involving: (i) the choice of a scenario regarding how technologies, policies, behaviours, macroeconomic variables and climate patterns will interact in the future; (ii) the translation of such scenarios into granular sector- and firm-level metrics in an evolving environment where all firms will be affected in unpredictable ways; and (iii) the task of matching the identification of a climate-related risk with the adequate mitigation action.

Chapter 4 therefore argues that the integration of climate-related risks into prudential regulation and (to the extent possible) into the relevant aspects of monetary policy will not suffice to shield the financial system against green swan events. In order to deal with this challenge, a second epistemological break is needed: there is an additional role for central banks to be more proactive in calling for broader changes. This needs not threaten existing mandates. On the contrary, calling for broader action by all players can only contribute to preserving existing mandates on price and financial stability. As such, and grounded in the transdisciplinary approach that is required to address climate change, this book makes four propositions (beyond the obvious need for carbon pricing) that are deemed essential to preserve financial stability in the age of climate change, related to: long-termism and sustainable finance; coordination between green fiscal policy, prudential regulation and monetary policy; international monetary and financial coordination and reforms; and integration of natural capital into national and corporate systems of accounting. Some potential obstacles related to each proposition are discussed.

Chapter 5 concludes by discussing how financial (and price) stability and climate stability can be considered as two public goods, the maintenance of which will increasingly depend on each other. Moreover, the need to ensure some form of long-term sustainability increasingly applies to prevent other human-caused environmental degradations such as biodiversity loss, and could require deep transformations in the governance of our socio-ecological systems. All this calls for new quantitative and qualitative approaches aimed at building system resilience (OECD (2019a), Schoon and van der Leeuw (2015)). At a time when policymakers are facing well known political economy challenges and when the private sector needs more incentives to transition to a low-carbon economy, an important contribution of central banks is to adequately frame the debate and thereby help promote the mobilisation of all efforts to combat climate change.

2. CLIMATE CHANGE IS A THREAT TO FINANCIAL AND PRICE STABILITY

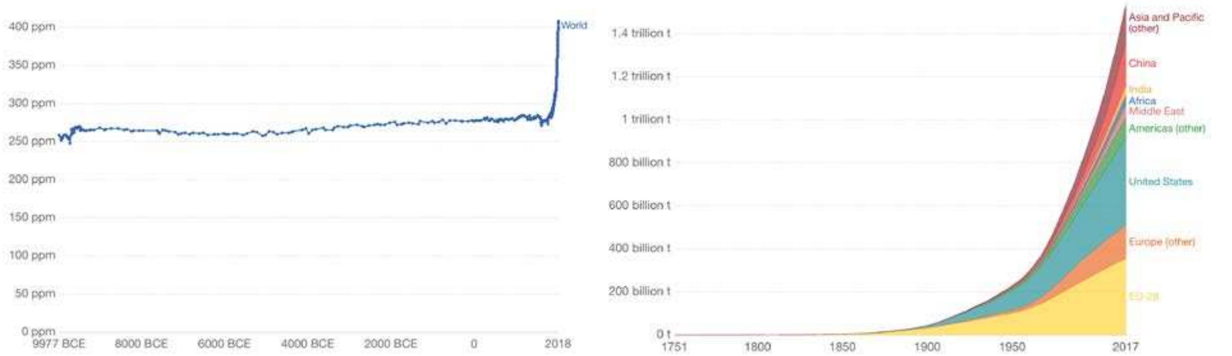
Climate change is the Tragedy of the Horizon. We don't need an army of actuaries to tell us that the catastrophic impacts of climate change will be felt beyond the traditional horizons of most actors – imposing a cost on future generations that the current generation has no direct incentive to fix.

Mark Carney (2015)

2.1 Climate change as a severe threat to ecosystems, societies and economies

At 415 parts per million (ppm),[12] Earth's concentration of CO_2 as of 11 May 2019 was higher than ever in human history, and far above the 270–280 ppm that had prevailed for millennia up to the Industrial Revolution (Graph 1, left-hand panel), guaranteeing stable climate conditions in which human societies were able to develop agriculture (Feynman and Ruzmaikin (2007)) and become more complex (Chaisson (2014)). The past decades, in particular, have shown a sharp increase in levels of atmospheric CO_2, from approximately 315 ppm in 1959 to 370 ppm in 1970 and 400 ppm in 2016 (right-hand panel).[12]

Evolution of atmospheric CO_2 concentration — Graph 1



Atmospheric CO_2 concentration over the past 12 millennia, measured in parts per million (left-hand panel); and annual total CO_2 emissions by world region since 1751 (right-hand panel).

Sources: Bereiter et al. (2015), NOAA, www.esrl.noaa.gov/gmd/ccgg/trends/data.html; Carbon Dioxide Information Analysis Center, http://cdiac.ornl.gov; and Global Carbon Project (2018). Published online at OurWorldInData.org. Retrieved from: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions.

These increasing levels of atmospheric CO_2 concentration, caused by human activity (IPCC (2018)), primarily the burning of fossil fuels (Hansen et al (2013)) but also deforestation and intensive agriculture (Ripple et al (2017)), prevent the Earth's natural cooling cycle from working and cause global warming. Global warming has already increased by close to 1.1°C since the mid-19th century. Temperatures are currently rising at 0.2°C per decade, and average yearly temperatures are increasingly

[12] Based on the daily record of global atmospheric carbon dioxide concentration measured at Mauna Loa Observatory in Hawaii, and reported by the Scripps Institution of Oceanography at UC San Diego. See https://scripps.ucsd.edu/programs/keelingcurve/.

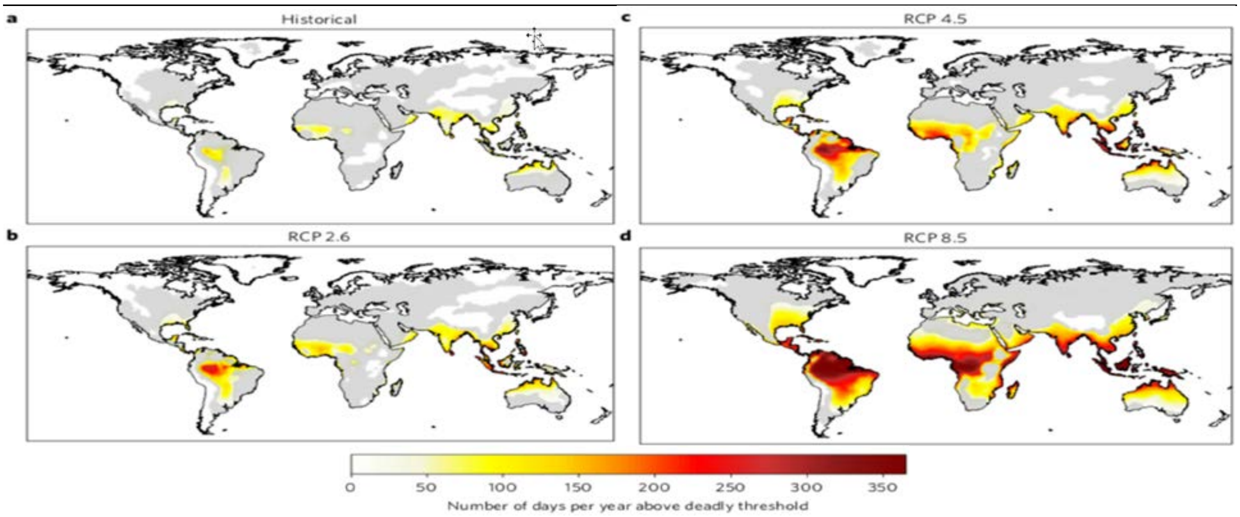
among the hottest ever recorded (IPCC (2018), Masson-Delmotte and Moufouma-Okia (2019), Millar et al (2017), Ripple et al (2017)).

Current trends are on track to lead to systemic disruptions to ecosystems, societies and economies (Steffen et al (2018)). The continued increase in temperatures will lead to multiple impacts (IPCC (2018)) such as rising sea levels, greater intensity and incidence of storms, more droughts and floods, and rapid changes in landscapes. For instance, mean sea levels rose 15 centimetres in the 20th century, and the rate of rising is increasing. The impacts on ecosystems will be significant, potentially leading to species loss or even a massive extinction of wildlife (Ripple et al (2017)). Soil erosion could also accelerate, thereby decreasing food security and biodiversity (IPCC (2019)). Marine biodiversity, marine ecosystems and their ecological functions are also threatened (Masson-Delmotte and Moufouma-Okia (2019)).

The effects of climate change may be catastrophic and irreversible for human populations, potentially leading to "untold suffering", according to more than 11,000 scientists (Ripple et al (2019)). Sea levels could rise by several metres with critical impacts for small islands, low-lying coastal areas, river deltas and many ecological systems on which human activity depends. For instance, increased saltwater intrusion could lead to major agricultural losses, and flooding could damage existing infrastructure (Masson-Delmotte and Moufouma-Okia (2019)). A two-metre sea level rise triggered by the potential melting of ice sheets could displace nearly 200 million people by 2100 (Bamber et al (2019)). Even more worrisome, past periods in the Earth's history indicate that even warming of between 1.5°C and 2°C could be sufficient to trigger long-term melting of ice in Greenland and Antarctica and a sea level rise of more than 6 metres (Fischer et al (2018)).

Humans may have to abandon many areas in which they currently manage to sustain a living, and entire regions in South America, Central America, Africa, India, southern Asia and Australia could become uninhabitable due to a mix of high temperatures and humidity levels (Im et al (2017), Mora et al (2018); see Graph 2). About 500 million people live in areas already affected by desertification, especially in southern and East Asia, the Middle East and sub-Saharan Africa, which will only be under greater socioeconomic pressure due to climate change (IPCC (2019)).

Average temperature changes Graph 2



Number of days per year above a deadly threshold by the end of the century in a business as usual scenario.

Source: Mora et al (2017).

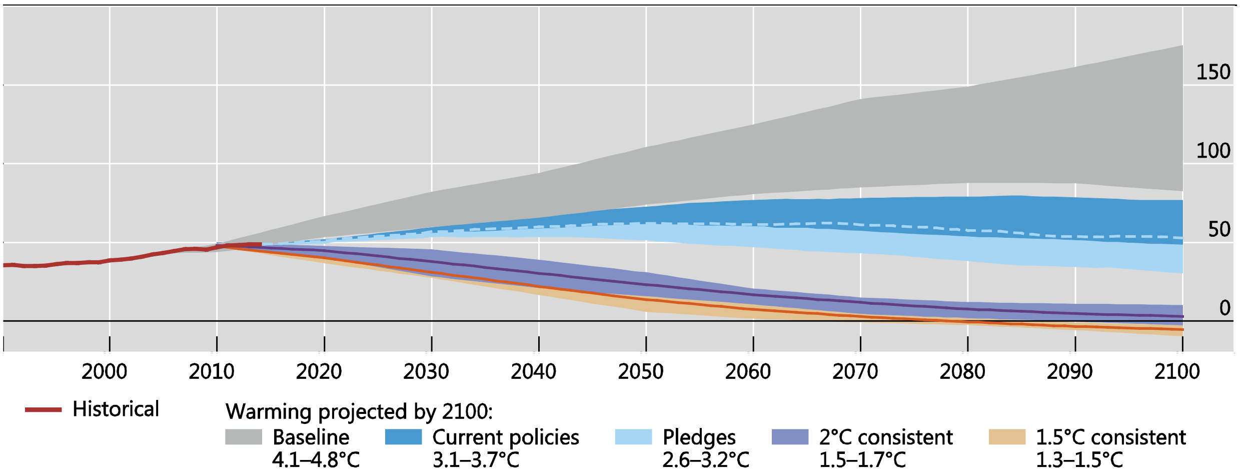
Climate change is not just a future risk: it has actually already started to transform human and non-human life on Earth,[13] although the worst impacts are yet to come. Crop yields and food supply are already affected by climate change in many places across the globe (Ray et al (2019)). Parts of India are undergoing chronic severe water crises (Subramanian (2019)). Heatwaves are becoming more frequent in most land regions, and marine heatwaves are increasing in both frequency and duration (Masson-Delmotte and Moufouma-Okia (2019)). Extreme weather events have increased significantly over the past 40 years (Stott (2016)). Large-scale losses of coral reefs have started to occur (Hughes et al (2018)). Even keeping global warming below 1.5°C could result in the destruction of 70–90% of reef-building corals (IPCC (2018)), on which 25% of all marine life depends (Gergis (2019)).

In turn, avoiding the worst impacts of climate change amounts to a massive, unprecedented, challenge for humanity. The planet is producing close to 40 gigatonnes (Gt) of CO_2 per year, and it is on track to double by 2050. We should reduce emissions to almost zero by then (Graph 3) in order to comply with the UN Paris Agreement of 2015 (UNFCCC (2015)), which set the goal of keeping global warming well below 2°C and as close as possible to 1.5°C above pre-industrial levels (defined as the climate conditions experienced during 1850–1900).

Nevertheless, the special report of the IPCC on the 1.5°C goal (IPCC (2018)) shows that the gap between current trends and emission reduction targets set by countries through their nationally determined contributions (NDCs) – which were already insufficient to limit global warming to 2°C – is widening and leading to somewhere between 3°C and 4°C of warming, which is consistent with a "Hothouse Earth" pathway (Steffen et al (2018)).

2100 warming projections: emissions and expected warming based on pledges and current policies

Global greenhouse gas emissions ($GtCO_2e$/year) Graph 3



Source: Climate Action Tracker.

The impacts on economic output could be significant if no action is taken to reduce carbon emissions. Some climate-economic models indicate that up to a quarter of global GDP could be lost (Burke et al (2015a)), with a particularly strong impact in Asia, although these predictions should be taken cautiously given the deep uncertainty involved (as discussed in Chapter 3). In any case, both the demand side and the supply side are affected (examples in Table 1).

[13] A list of observed impacts, with links to relevant studies, can be found at: impact.gocarbonneutral.org/.

Climate change-related shocks and their effects on… Table 1

	Type of shock	From gradual global warming	From extreme weather events
Demand	Investment	Uncertainty about future demand and climate risks	Uncertainty about climate risk
	Consumption	Changes in consumption patterns, eg more savings for hard times	Increased risk of flooding to residential property
	Trade	Changes in trade patterns due to changes in transport systems and economic activity	Disruption to import/export flows due to extreme weather events
Supply	Labour supply	Loss of hours due to extreme heat. Labour supply shock from migration	Loss of hours worked due to natural disasters, or mortality in extreme cases. Labour supply shock from migration
	Energy, food and other inputs	Decrease in agricultural productivity	Food and other input shortages
	Capital stock	Diversion of resources from productive investment to adaptation capital	Damage due to extreme weather
	Technology	Diversion of resources from innovation to adaptation capital	Diversion of resources from innovation to reconstruction and replacement

Sources: NGFS (2019b), adapted from Batten (2018).

Demand-side shocks are those that affect aggregate demand, such as private (household) or public (government) consumption demand and investment, business investment and international trade. Climate damages could dampen consumption, and business investments could be reduced due to uncertainty about future demand and growth prospects (Hallegatte (2009)). Climate change is also likely to disrupt trade flows (Gassebner et al (2010)) and reduce household wealth. Even less exposed economies can have extensive interactions with global markets and be affected by extreme climate shocks.

Supply-side shocks could affect the economy's productive capacity, acting through the components of potential supply: labour, physical capital and technology. For instance, higher temperatures tend to reduce the productivity of workers and agricultural crops (IPCC (2019)). Moreover, climate change can trigger massive population movements (Opitz Stapleton et al (2017)), with long-lasting effects on labour market dynamics and wage growth. Supply-side shocks can also lead to a diversion of resources form investment in productive capital and innovation to climate change adaptation (Batten (2018)). Damages to assets affect the longevity of physical capital through an increased speed of capital depreciation (Fankhauser and Tol (2005)). Even if the relevant capital stocks might survive, efficiency might be reduced and some areas might have to be abandoned (Batten (2018)).

These economic shocks can have major impacts on the price and financial instability, as respectively explored next.

2.2 The redistributive effects of climate change

Climate change has important distributional effects both between and within countries. The geographical distribution of potential physical risks triggered by rising temperatures (Graph 2) clearly shows that they primarily affect poor and middle-income countries. Moreover, transition risks might also disproportionately impact the natural endowments, traditional carbon-intensive industries and consumption habits of poor countries and low-income households. The cost of mitigation and adaptation might also be prohibitive for both groups.

The degree of awareness about the risks posed by climate change is also unevenly shared within societies, following – and sometimes reinforced by – inequalities of wealth and income. In some cases, denial has been a convenient demagogic response to these issues, compounded by accusations of intrusion into national sovereignty. Another popular political stance has been to dismiss the challenges posed by climate change as merely a concern of the wealthy and well protected. The debate with climate change sceptics is a legitimate and necessary step towards improving the analytics on these issues while creating the sociopolitical conditions to start implementing policies to mitigate risks. There is a relatively old and large literature calling for fairness and social justice when designing adaptation and mitigation policies (eg Adger et al (2006), Cohen et al (2013)). All this will require a better understanding of the redistributive effects of climate change, of the policies to adapt our economies and of the associated costs of mitigation. Without a clear map for how the costs and benefits of climate change mitigation strategies will be distributed, it is almost certain – as we have been observing in many recent cases – that political backlashes will increase against a lower-carbon society. Thus, the sociopolitical viability of combating climate change depends on addressing its distributional consequences.

Indeed, the enormous challenges described above mean that the policies to combat climate change will be quite invasive and are likely to have significant collateral effects on our societies and our production and consumption processes, with associated distributional effects. Zachmann et al (2018) conduct a study of the distributional consequences of mitigation policies and point out that the intensity of these effects depends on the choice of the policy instrument used, the targeted sector, the design of the intervention and the country's degree of development and socioeconomic conditions. They study the impact of climate policies on households of different income levels (low to high) and assess policies addressing climate change as regressive, proportionate or progressive. They take into account households' budget and wealth constraints (eg their inability to quickly shift to lower carbon consumption baskets as well as investment in lower-carbon houses and durable goods). They conclude that the regressive distributional effects of many climate policies requires compensating lower-income households for their negative income effects as well as being gradual and progressive in the introduction of such policies.

Dennig et al (2015) also study regional and distributional effects of climate change policies. They use a variant of the Regional Integrated model of Climate and the Economy (RICE) – a regionally disaggregated version of the Dynamic Integrated model of Climate and the Economy (DICE) – and introduce economic inequalities in the model's regions. Their study confirm that climate change impacts are not evenly distributed within regions and that poorer people are more vulnerable, suggesting that this must be taken into account when setting the social cost of carbon. However, improving the poverty and inequality modelling in climate research requires more efforts as the current approaches are limited as argued by Rao et al (2017) because current models do not capture well household heterogeneity and proper representation of poor and vulnerable societal segments.

Finally, there is an extensive literature and numerous studies pointing to the distributional impact of climate change on poor countries and the need to scale up international mechanisms to finance their transition and reduce their vulnerability to climate change-related events with well known implications for massive migration. This has been a significant part of the discussions of the UN Conference of the Parties (COP) since its inception. For example, the Adaptation Fund was established at the COP 7 in 2001 but only set up under the Kyoto Protocol of the United Nations Framework Convention on Climate Change

(UNFCCC) and officially launched in 2007. The mechanism has revolved around the need for rich countries to contribute to the adaptation cost by developing countries. At COP 2015 in 2009, this resulted in the pledge by advanced economies to mobilise $100 billion in aid by 2020. So far, the practical implementation has remained limited.

2.3 Climate change as source of monetary instability

Although this book focuses on financial stability, it should be noted that climate-related shocks are likely to affect monetary policy through supply-side and demand-side shocks, and thereby affect central banks' price stability mandate. Regarding supply-side shocks (McKibbin et al (2017)), pressures on the supply of agricultural products and energy are particularly prone to sharp price adjustments and increased volatility. The frequency and severity of such events might increase, and impact supply through more or less complex channels. There are still relatively few studies analysing the impact of climate-related shocks on inflation, but some studies indicate that food prices tend to increase in the short term following natural disasters and weather extremes (Parker (2018), Heinen et al (2018), Debelle (2019)).

In addition to these short-term pressures on prices, supply shocks can also reduce economies' productive capacity. For instance, climate change could have long-standing impacts on agricultural yields, lead to frequent resource shortages or to a loss in hours worked due to heat waves. These effects, in turn, can reduce the stock of physical and human capital, potentially resulting in reduced output (Batten (2018), McKibbin et al (2017)). But climate change can also translate into demand shocks, for instance by reducing household wealth and consumption (Batten (2018)). Climate mitigation policies could also affect investment in some sectors, with various indirect impacts further discussed in the next chapter.

In sum, the impacts of climate change on inflation are unclear partly because climate supply and demand shocks may pull inflation and output in opposite directions, and generate a trade-off for central banks between stabilising inflation and stabilising output fluctuations (Debelle (2019)). Moreover, if climate-related risks end up affecting productivity and growth, this may have implications for the long-run level of the real interest rate, a key consideration in monetary policy (Brainard (2019)).

Traditionally, monetary policy responses are determined by looking at their impact on prices and expectations. If there is a presumption that the impact is temporary, the response can be to wait and see or "look through" the shock as it does not affect prices and expectations on a permanent basis. However, if the shock has more lasting effects, there could be motives to consider a policy reaction to adjust aggregate demand conditions. In the case of climate-related risks, the irreversibility of certain climate patterns and impacts poses at least three new challenges for monetary policy (Olovsson (2018)):

(i) While the use of cyclical instruments aims to stimulate or subdue activity in the economy over relatively short periods, climate change is expected to maintain its trajectory for long periods of time (Cœuré (2018)). This situation can lead to stagflationary supply shocks that monetary policy may be unable to fully reverse (Villeroy de Galhau (2019a)).

(ii) Climate change is a global problem that demands a global solution, whereas monetary policy seems, currently, to be difficult to coordinate between countries (Pereira da Silva (2019a)). As such, the case for a single country or even a monetary zone to react to inflationary climate-related shocks could be irrelevant.

(iii) Even if central banks were able to re-establish price stability after a climate-related inflationary shock, the question remains whether they would be able to take pre-emptive measures to hedge ex ante against fat-tail climate risks, ie green swan events (Cœuré (2018)).

It should nevertheless be admitted that studies on the impact of climate change on monetary stability are still at an early stage, and that much more research is needed. Far more evidence has been collected on the potential financial impacts of climate change, as discussed in the rest of this book.

2.4 Climate change as a source of financial instability

Even though a growing number of stakeholders has recognised the socioeconomic risks posed by climate change over the past decades, much of the financial sector seemed to remain unconcerned until a few years ago. The situation has changed radically over the past few years, as the potentially disruptive impacts of climate change on the financial system started to become more apparent (Carney (2015)). As further detailed in Chapter 4, some central banks, regulators and supervisors are already taking steps towards integrating climate-related risks into supervisory practices, and more could follow in the near future. The NGFS, created in December 2017, quickly recognised that "climate-related risks are a source of financial risk. It is therefore within the mandates of central banks and supervisors to ensure the financial system is resilient to these risks" (NGFS (2018), p 3).

There are two main channels[14] through which climate change can affect financial stability:

Physical risks are "those risks that arise from the interaction of climate-related hazards [...] with the vulnerability of exposure to human and natural systems" (Batten et al (2016)). They represent the economic costs and financial losses due to increasing frequency and severity of climate-related weather events (eg storms, floods or heat waves) and the effects of long-term changes in climate patterns (eg ocean acidification, rising sea levels or changes in precipitation). The losses incurred by firms across different financial portfolios (eg loans, equities, bonds) can make them more fragile.

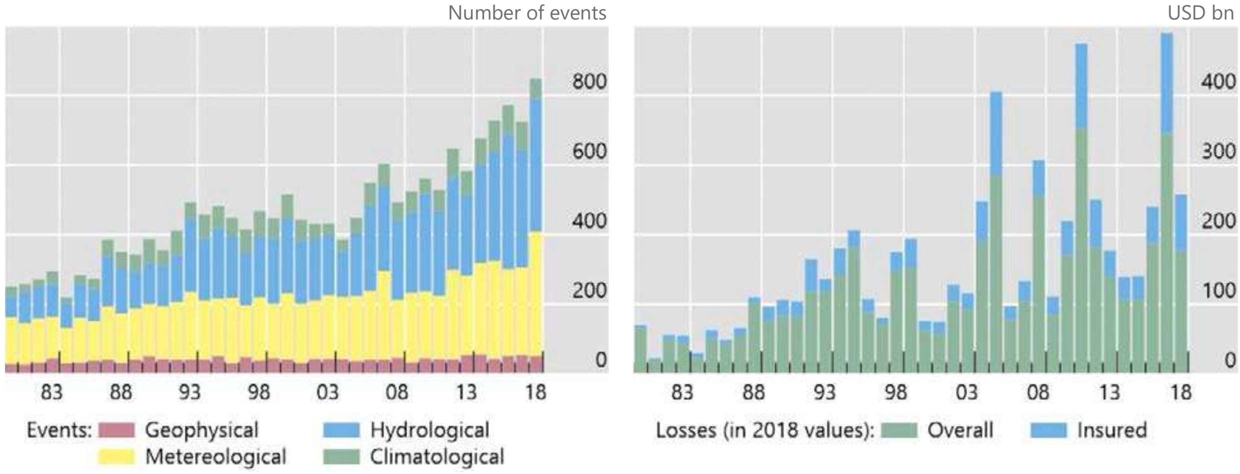
The destruction of capital and the decline in profitability of exposed firms could induce a reallocation of household financial wealth. For instance, rising sea levels could lead to abrupt repricing of real estate (Bunten and Kahn (2014)) in some exposed regions, causing large negative wealth effects that may weigh on demand and prices through second-round effects. Climate-related physical risks can also affect the expectation of future losses, which in turn may affect current risk preferences. For instance, homes exposed to sea level rise already sell at a discount relative to observationally equivalent unexposed properties equidistant from the beach (Bernstein et al (2019)).

As natural catastrophes increase worldwide (Graph 4), non-insured losses (which represent 70% of weather-related losses (IAIS (2018)) can threaten the solvency of households, businesses and governments, and therefore financial institutions. Insured losses, on their end, may place insurers and reinsurers in a situation of fragility as claims for damages keep increasing (Finansinspektionen (2016)). More broadly, damages to assets affect the longevity of physical capital through an increased speed of capital depreciation (Fankhauser and Tol (2005)).

[14] A third type of risk, liability risk, is sometimes mentioned. This refers to "the impacts that could arise tomorrow if parties who have suffered loss or damage from the effects of climate change seek compensation from those they hold responsible" (Carney (2015), p 6). However, such costs and losses are often considered to be part of either physical or transition risk.

Increase in the number of extreme weather events and their insurance,[15] 1980–2018 — Graph 4

Number of relevant natural loss events — Overall and insured losses



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Source: MunichRe (2018).

Moreover, the fat-tailed probability distributions of many climate parameters are such that the possibility of extreme values cannot be ruled out (Weitzman (2009, 2011)). This could place financial institutions in situations in which they might not have sufficient capital to absorb climate-related losses. In turn, the exposure of financial institutions to physical risks can trigger contagion and asset devaluations propagating throughout the financial system.

Transition risks are associated with the uncertain financial impacts that could result from a rapid low-carbon transition, including policy changes, reputational impacts, technological breakthroughs or limitations, and shifts in market preferences and social norms. In particular, a rapid and ambitious transition to lower emissions pathways means that a large fraction of proven reserves of fossil fuel cannot be extracted (McGlade and Elkins (2015)), becoming "stranded assets", with potentially systemic consequences for the financial system (see Box 1). For instance, an archetypal fire sale might result if these stranded assets suddenly lose value, "potentially triggering a financial crisis" (Pereira da Silva (2019a)). As Mark Carney puts it: "too rapid a movement towards a low-carbon economy could materially damage financial stability. A wholesale reassessment of prospects, as climate-related risks are re-evaluated, could destabilise markets, spark a pro-cyclical crystallisation of losses and lead to a persistent tightening of financial conditions: a climate Minsky moment" (Carney (2016), p 2).

Moreover, the value added of many other economic sectors dependent on fossil fuel companies will probably be impacted indirectly by transition risks (Cahen-Fourot et al (2019a,b)). For instance, the automobile industry may be strongly impacted as technologies, prices and individual preferences evolve. Assessing how the entire value chain of many sectors could be affected by shocks in the supply of fossil fuels is particularly challenging, as will be further discussed in the next chapter.

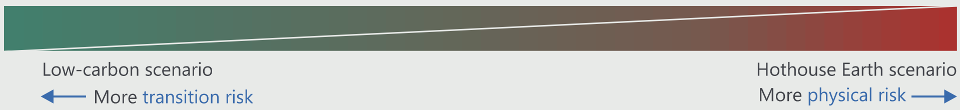
Physical and transition risks are usually assessed separately, given the complexity involved in each case (as discussed in the next chapter). However, they should be understood as part of the same framework and as being interconnected (Graph 5). A strong and immediate action to mitigate climate change would increase transition risks and limit physical risks, but those would remain existent (we are already

[15] This figure does not allow them to be extrapolated into the future, and they should be interpreted carefully. For instance, some natural catastrophes, such as typhoons, could become less frequent but more intense.

experiencing some of the first physical risks of climate change). In contrast, delayed and weak action to mitigate climate change would lead to higher and potentially catastrophic physical risks, without necessarily entirely eliminating transition risks (eg some climate policies are already in place and more could come). Delayed actions followed by strong actions in an attempt to catch up would probably lead to high both physical and transition risks (not represented in Graph 5).

Framework for physical and transition risks

Graph 5



Scenario	Rapid Transition	Two-degree	Business-as-intended	Business-as-usual
Corrective transition response	Very strong	Strong	Substantial	Limited
Change in temperature, 2100 vs pre-industrial era	1.5°C	2°C	3°C	4°C

Source: adapted from Oliver Wyman (2019); authors' elaboration.

Box 1: Introduction to stranded assets

Limiting global warming to less than 1.5°C or 2°C requires keeping a large proportion of existing fossil fuel reserves in the ground (Matikainen (2018)). These are referred to as stranded assets. For instance, a study (McGlade and Elkins (2015)) found that in order to have at least a 50% chance of keeping global warming below 2°C, over 80% of current coal reserves, half of gas reserves and a third of oil reserves should remain unused from 2010 to 2050. As the risk related to stranded assets is not reflected in the value of the companies that extract, distribute and rely on these fossil fuels, these assets may suffer from unanticipated and sudden writedowns, devaluations or conversion to liabilities.

Estimates of the current value and scope of stranded assets vary greatly from one study to another. For instance, Mercure et al (2018) estimate that the discounted loss in global wealth resulting from stranded fossil fuel assets may range from $1 trillion to $4 trillion. Carbon Tracker (2018)[16] approximates the amount at $1.6 trillion, far below the International Renewable Energy Agency's (IRENA) (2017) estimate of $18 trillion, but the scope and definitions used by each of them differ. Therefore, as discussed more extensively in Chapter 3, it is critical to understand the models used by each of these studies to fully appreciate their respective outcomes and potential limitations.

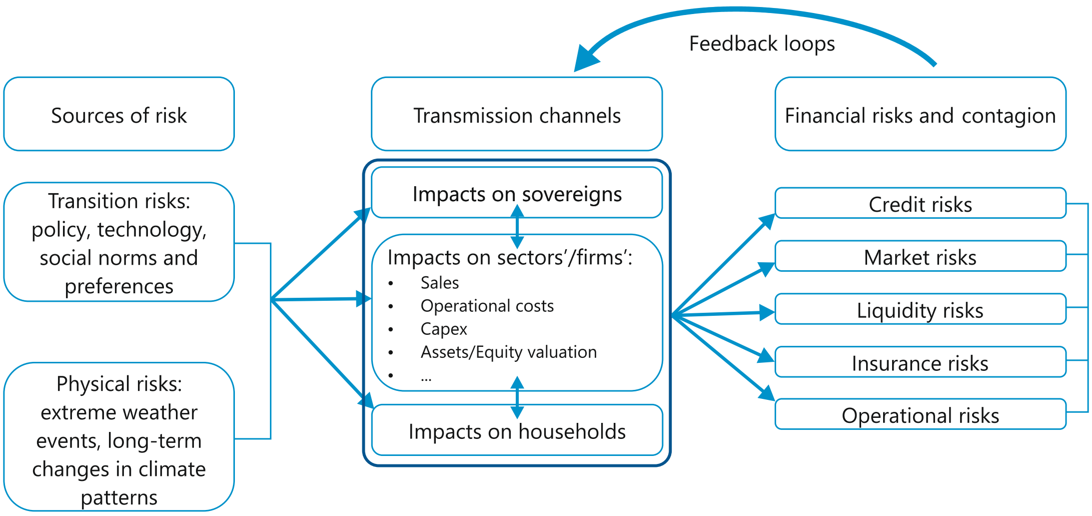
Physical and transition risks can materialise in terms of financial risk in five main ways (DG Treasury et al (2017)), with many second-round effects and spillover effects among them (Graph 6):

- ***Credit risk***: climate-related risks can induce, through direct or indirect exposure, a deterioration in borrowers' ability to repay their debts, thereby leading to higher probabilities of default (PD) and a higher loss-given-default (LGD). Moreover, the potential depreciation of assets used for collateral can also contribute to increasing credit risks.

[16] In a scenario with an increase in temperatures of 1.75°C.

- ***Market risk***: Under an abrupt transition scenario (eg with significant stranded assets), financial assets could be subject to a change in investors' perception of profitability. This loss in market value can potentially lead to fire sales, which could trigger a financial crisis. The concept of climate value-at-risk (VaR) captures this risk and will be further discussed in the next chapter.
- ***Liquidity risk***: although it is covered less in the literature, liquidity risk could also affect banks and non-bank financial institutions. For instance, banks whose balance sheet would be hit by credit and market risks could be unable to refinance themselves in the short term, potentially leading to tensions on the interbank lending market.
- ***Operational risk***: this risk seems less significant, but financial institutions can also be affected through their direct exposure to climate-related risks. For instance, a bank whose offices or data centres are impacted by physical risks could see its operational procedures affected, and affect other institutions across its value chain.
- ***Insurance risk***: for the insurance and reinsurance sectors, higher than expected insurance claim payouts could result from physical risks, and potential underpricing of new insurance products covering green technologies could result from transition risks (Cleary et al (2019)).

Channels and spillovers for materialisation of physical and transition risks — Graph 6



Sources: adapted from DG Treasury et al (2017); authors' elaboration.

2.5 The forward-looking nature of climate-related risks – towards a new epistemology of risk

The potentially systemic risks posed by climate change explain why it is in the interest of central banks, regulators and financial supervisors to ensure that climate-related risks are appropriately understood by all players (NGFS (2019a)). It is therefore not surprising that the first recommendation made by the NGFS in its first comprehensive report called for "integrating climate-related risks into financial stability monitoring and micro-supervision" (NGFS (2019a), p 4). This integration helps ensure that financial institutions and the financial system as a whole are resilient to climate-related risks (NGFS (2019a)).

Moreover, a systematic integration of climate-related risks by financial institutions could act as a form of shadow pricing on carbon, and therefore help shift financial flows towards green assets. That is, if investors integrate climate-related risks into their risk assessment, then polluting assets will become more costly. This would trigger more investment in green assets, helping propel the transition to a low carbon economy (Pereira da Silva (2019a)) and break the tragedy of the horizon by better integrating long-term risks (Aufauvre and Bourgey (2019)). A better understanding of climate-related risks is therefore a key component of Article 2.1.c of the Paris Agreement, which aims to "mak[e] finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development" (UNFCCC (2015)).

However, integrating climate-related risks into financial stability monitoring and prudential supervision presents a significant challenge: traditional approaches to risk management are based on historical data and assumptions that shocks are normally distributed (Dépoues et al (2019)). The fundamental financial concept of value-at-risk (VaR) captures losses that can be expected with a 95–99% level of confidence and over a relatively short-term horizon. Capital requirements are also typically calculated (through estimated PD, exposure at default and estimated LGD) on a one-year horizon and based on credit ratings that largely rely on historical track records of counterparties.

The problem is that extrapolating historical trends can only lead to mispricing of climate-related risks, as these risks have barely started to materialise: physical risks will become worse as global warming goes on, and transition risks are currently low given the lack of ambitious policies on a global scale. Moreover, climate-related risks typically fit fat-tailed distributions and concentrate precisely in the 1% not considered by VaR. Finally, climate change is characterised by deep uncertainty: assessing the physical risks of climate change is subject to uncertainties related to climate patterns themselves, their potentially far-reaching impacts on all agents in the economy, and complex transmission channels (NGFS (2019a,b)), especially in the context of globalised value chains; transition risks are also subject to deep or radical uncertainty with regard to issues such as the policies that will be implemented (eg carbon pricing versus command-and-control regulations), their timing, the unpredictable emergence of new low-carbon technologies or changes in preferences and lifestyles that could take place. All these issues are further discussed in Chapter 3.

As a result, the standard approach to modelling financial risk consisting in extrapolating historical values (eg PD, market prices) is no longer valid in a world that is fundamentally reshaped by climate change (Weitzman (2011), Kunreuther et al (2013)). In other words, green swan events cannot be captured by traditional risk management.

The current situation can be characterised as an "epistemological obstacle" (Bachelard (1938)). The latter refers to how scientific methods and "intellectual habits that were useful and healthy" under certain circumstances, can progressively become problematic and hamper scientific research. Epistemological obstacles do not refer to the difficulty or complexity inherent to the object studied (eg measuring climate-related risks) but to the difficulty related to the need of redefining the problem. For instance, as a result of the incompatibility between probabilistic and backward-looking risk management approaches and the uncertain and forward-looking nature of climate-related risks, "investors, at this stage, face a difficult task to assess these risks – there is for instance no equivalent of credit ratings for climate-related financial risks" (Pereira da Silva (2019a)).

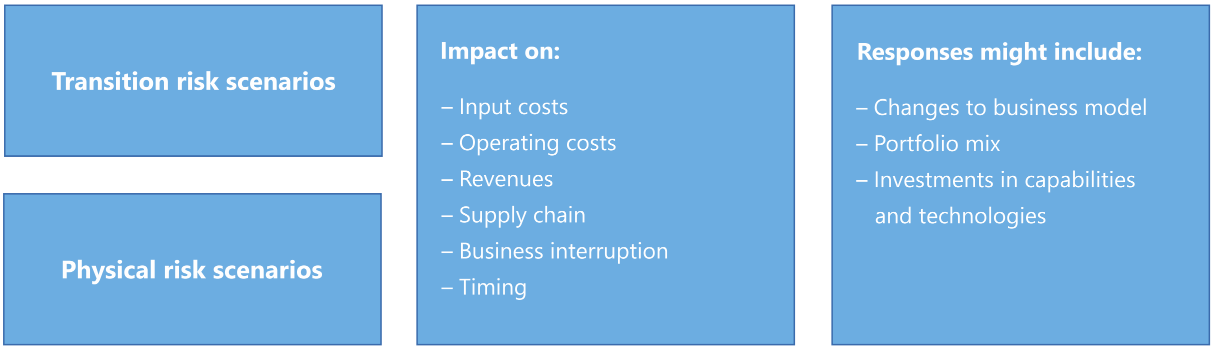
As scientific knowledge does not progress continuously and linearly but rather through a series of discontinuous jumps with changes in the meaning of concepts, nothing less than an epistemological break (Bachelard, 1938) or a "paradigm shift" (Kuhn (1962)) is needed today to overcome this obstacle and more adequately approach climate-relate risks (Pereira da Silva (2019a)).

In fact, precisely an epistemological break may be taking place in the financial sector: recently emerged methodologies aim to assess climate-related risks while relying on the fundamental hypothesis that, given the lack of historical financial data related to climate change and the deep uncertainty involved, new approaches based on the analysis of prospective scenarios are needed.[17] Unlike probabilistic approaches to financial risk management, they seek to set up plausible hypotheses for the future. This can help financial institutions integrate climate-related risks into their strategic and operational procedures (eg for the purpose of asset allocation, credit rating or insurance underwriting) and financial supervisors assess the vulnerability of specific institutions or the financial system as a whole.

A consensus is emerging among central banks, supervisors and practitioners involved in climate-related risks about the need to use such forward-looking, scenario-based methodologies (Batten et al (2016), DG Treasury et al (2017), TCFD (2017), NGFS (2019a), Regelink et al (2017)). As shown by the Task Force on Climate-related Financial Disclosures[18] (TCFD; Graph 7), managing climate-related risks through a forward-looking approach can lead financial institutions to test the resilience of corporations in their portfolios to potential materialisations of physical and transition risks, their impact on key performance indicators and the adaptive capacities of these firms.

Testing the resilience of corporations to potential materialisations of physical and transition risks

Graph 7



What scenarios (and narratives) are appropriate, given the exposures? Consider input parameters, assumptions, and analytical choices. What reference scenario(s) should be used?	Evaluate the potential effects on the organisation's strategic and financial position under each of the defined scenarios. Identify key sensitivities.	Use the results to identify applicable, realistic decisions to manage the identified risks and opportunities. What adjustments to strategic/financial plans would be needed?

Source: Adapted from TCFD (2017).

These methodologies may already be facilitating a more systematic integration of climate-related risks in the financial sector: some insurance companies are reassessing their cost of insuring physical risk; some rating agencies are increasingly re-evaluating credit risks in the light of growing climate-related risks; and some asset managers are becoming more selective and inclined to start picking green assets and/or ditching brown assets in their portfolio allocation (Bernardini et al (2019), Pereira da Silva (2019a)).

Hence, it is critical for central banks, regulators and supervisors to assess the extent to which these forward-looking, scenario-based methodologies can ensure that the financial system is resilient to climate-related risks and green swan events. The next chapter undertakes a critical assessment of these methodologies.

17 It is noteworthy that these methodologies have been produced by a variety of players including consulting firms, non-profit organisations, academics, international organisations and financial institutions themselves.

18 See www.fsb-tcfd.org/. The TCFD was set up in 2015 by the Financial Stability Board (FSB), to develop voluntary, consistent climate-related financial risk disclosures for use by companies, banks and investors in providing information to stakeholders.

3. MEASURING CLIMATE-RELATED RISKS WITH SCENARIO-BASED APPROACHES: METHODOLOGICAL INSIGHTS AND CHALLENGES

Thinking about future uncertainty in terms of multiple plausible futures, rather than probability distributions, has implications in terms of the way uncertainty is quantified or described, the way system performance is measured and the way future strategies, designs or plans are developed.

Maier et al (2016)

This chapter reviews some of the methodological challenges that financial institutions and supervisors face when conducting forward-looking, scenario-based analysis aimed at identifying and managing climate-related risks. It focuses on the main conceptual issues; a detailed discussion of the technical features of each existing methodology is beyond the scope of this book (for more exhaustive reviews see, for instance, Hubert et al (2018), UNEP-FI (2018a,b, 2019)). Also, our discussion is focused mostly on methodologies aimed at measuring transition risks,[19] although some challenges related to physical risks are mentioned.

Our key conclusion is that, despite their promising potential, forward-looking analyses cannot fully overcome the limitations of the probabilistic approaches discussed in the previous chapter and provide sufficient hedging against "green swan" events. That is, although the generalised use of forward-looking, scenario-based methodologies can help financial and economic agents to better grapple with the long-term risks posed by climate change, they will not suffice to "break the tragedy of the horizon" and induce a significant shift in capital allocation towards low-carbon activities. Two main limitations exist.

First, the materialisation of physical and transition risks depends on multiple nonlinear dynamics (natural, technological, societal, regulatory and cultural, among others) that interact with each other in complex ways and are subject to deep uncertainty. Climate-economic models are inherently incapable of representing all these interactions, and they therefore overlook many social and political forces that will strongly influence the way the world evolves. With this in mind, the outcomes of a scenario-based analysis should be assessed very cautiously and cannot suffice to guide decision-making. The broad range of results concerning the monetary value of stranded assets – one of the most prominent transition risks – are symptomatic of the complexity and uncertainty at stake (see Box 2 below).

In particular, the complex and multiple interactions between climate and socioeconomic systems are such that the task of identifying and measuring climate-related risks presents significant methodological challenges related to:

(i) The choice of scenarios describing how technologies, policies, behaviours, macroeconomic and even geopolitical dynamics and climate patterns may interact in the future (Chapter 3.2), especially given the intrinsic limitations of most equilibrium climate-economic models (Chapter 3.1);

(ii) The translation of such scenarios into granular sectoral and corporate metrics in an evolving environment where all firms and value chains will be impacted in largely unpredictable ways (Chapter 3.3).

[19] This choice is notably informed by the fact that physical risks arising from a global warming beyond 2°C can be so systemic that aiming to measure them quickly becomes impossible. Transition risks can therefore be seen as those that must arise if we decide to remain within safer climate boundaries. In practice, physical and transition risks are interconnected, as discussed in Chapter 2.3. However, current climate-related risk methodologies generally fail to analyse physical and transition risks jointly, in spite of recent efforts in this direction.

Second, and more fundamentally, climate-related risks will remain largely uninsurable or unhedgeable as long as system-wide action is not taken (Chapter 3.4). In contrast to specific areas where scenario analysis can help financial institutions avoid undesirable outcomes (eg avoiding a dam collapse for a hydropower project), climate-related scenario analysis cannot by itself enable a financial institution or the financial system as a whole to avoid and withstand "green swan" events. For instance, a financial institution willing to hedge itself against an extreme transition risk (eg a sudden and sharp increase in carbon pricing) in the current context of weak climate policies may simply be unable to find adequate climate-risk-free assets if these are not viable in the current environment ("green" assets and technologies are still nascent and also present significant risks).

The first limitation can be partially resolved through better data (Caldecott (2019), NGFS (2019a)) and through the development of new models, in particular non-equilibrium models that can better account for nonlinearity, uncertainty, political economy considerations and the role of money and finance (Mercure et al (2019), Monasterolo et al (2019)). However, the second limitation is a reminder that only a structural transformation of our global socioeconomic system can really shield the financial system against "green swan" events. This calls for alternative epistemological positions that can fully embrace uncertainty and the need for structural transformations, including through more qualitative and politically grounded approaches (Aglietta and Espagne (2016), Chenet et al (2019a, 2019b), Ryan-Collins (2019)).

This does not mean that the development of forward-looking methodologies is not useful. On the contrary, non-financial and financial firms alike will increasingly need to rely on them to explore their potential vulnerabilities. But for central banks, regulators and supervisors concerned about the resilience of the system as a whole, the development of forward-looking, scenario-based methodologies should be assessed with a more critical stance. Much like a carbon price and other policies, they are a critical step that can become fully operational only if a system-wide transition takes place, as further discussed in Chapter 4.

Box 2: Methodological uncertainty surrounding the monetary value of stranded assets

As discussed in Chapter 2, limiting global warming to less than 1.5°C or 2°C requires keeping a large proportion of existing fossil fuel reserves in the ground (Matikainen (2018)). The case has often been made that risks related to stranded assets are not reflected in the value of the companies that extract, distribute and rely on these fossil fuels. This could lead to a significant and sudden drop in their value if ambitious climate policies are adopted.

However, estimating precisely the current value of fossil fuel assets that may be stranded in the future is an exercise replete with uncertainty. As such, the diverging estimates obtained (eg between $1 trillion and $4 trillion according to Mercure et al (2018); around $1.6 trillion as estimated by Carbon Tracker (2018);[20] and up to $18 trillion according to IRENA (2017)) should be carefully assessed as they are based on different geographical scopes, assumptions and valuation methods, among others. For instance, some estimates (eg IRENA (2017)) cover the stranded value of fossil fuel assets (eg the discounted cash flows of future revenues that will be lost) whereas others (eg IEA (2014)) focus on the stranded capital, ie the losses related to the capital invested in a project subject to stranding.

One source of uncertainty has to do with today's valuation of fossil fuel reserves. Some methodologies assume that these reserves significantly contribute to the current valuation of fossil fuel companies. In contrast, IHS Markit (2015) argues that oil and gas companies' market valuations are mostly driven by commercially proved reserves that will be monetised over the next 10 to 15 years, and not so much by the resources that would be likely to be stranded over a longer-term horizon. If this is true, the market mispricing of fossil fuel assets may not be as large as often expected. Some studies also suggest that investors are already reacting to climate-related risks: based on the

[20] In a scenario with an increase in temperatures of 1.75°C.

performance of high-emissions industries in the S&P 500 index before and after the Paris Agreement, Ilhan et al (2018) suggest that investors are actually already incorporating information about climate-related risks when assessing risk profiles. Other studies also find that the risk premium of fossil fuel firms has increased following the Paris Agreement (de Greiff et al (2018)) and that this rise in risk premium is due to increased awareness of transition risks (Delis et al (2018)). In short, the extent to which stranded assets are already valued remains unclear.

Estimating the impacts of stranding fossil assets with geographical granularity is essential to appreciate which companies can be hit, yet it also requires making uncertain choices with regard to which resources will actually be stranded (McGlade and Ekins (2015)). In this respect, Mercure et al (2018) conduct a precise geographical analysis of stranded assets based on the costs of extraction of fossil fuels around the world, assuming that resources in locations with higher extraction costs will be stranded first. They find that Saudi Arabia could keep selling oil in a low-carbon scenario given its competitive prices, whereas Canadian and US unconventional oils could be stranded much faster, with potential significant impacts on their GDPs. In practice, the most vulnerable countries (Canada and the United States in this case) would probably be tempted to subsidise their fossil fuel production to avoid such negative impacts.

Financial institutions can also be impacted indirectly through complex cascades of stranded assets (Cahen-Fourot et al (2019a,b)). For instance, in addition to the direct risk borne by investors exposed to stranded assets, financial assets can also suffer from the economic impacts of the transition triggered by a fall in corporate profits in different sectors that rely on stranded assets and (Caldecott (2017), Dietz et al (2016)). For jurisdictions where fossil fuel companies are state-owned (and therefore not valued by markets), the main financial impacts may only be indirect, eg through loss of revenues that could affect sovereign risk and/or GDP growth.

When mixing geographical with indirect impacts, it appears that stranding assets could have significant geopolitical repercussions and potentially deeply transform existing global value chains, but such considerations remain largely out of the scope of current assessments. For instance, the scenario developed by Mercure et al (2018) asks the question of how OPEC members would recycle their oil-related surpluses. Similarly, if all coal resources were to be stranded, the immediate impacts would fall significantly on China, which consumed 50% of the world's coal in 2018 (BP (2019)); yet this could also have system-wide impacts on global value chains, including potential sharp price increases in advanced economies.

Finally, estimating the value of stranded assets while relying on climate-economic models can lead to paradoxical assumptions. In particular, and as discussed in Chapter 3.2, some climate-economic models rely so much on negative emissions technologies and on carbon capture and storage (CCS) to meet the 1.5°C or 2°C targets that fossil fuels may no longer need to be stranded that rapidly. Under certain scenarios, these technologies can increase the remaining carbon budget to reach a 2°C world by up to 290% (Carbon Brief (2018)). This poses the question of the technological assumptions supporting each assessment of stranded assets and for transition risks in general, as discussed in this chapter.

3.1 Climate-economic models versus deep uncertainty – an overview

The very first step in conducting a scenario analysis is to determine a narrative of how climate and socioeconomic factors will interact, so that they can be translated into a sectoral and firm-level scenario. For instance, to embed a climate-related shock into existing stress test methodologies (see Borio et al (2014)), the first step is to assess how such a shock would impact the economy (eg through variables such as GDP or interest rates), which in turn translates into impacts to the financial system. In the case of transition risks, some critical elements of the narrative of a scenario refer to:

– What climate target is sought: as of today, most transition scenarios rely on limiting global warming to 2°C above pre-industrial temperatures by 2100, but more scenarios based on a 1.5°C limit may emerge as this latter target is increasingly understood as the more "acceptable" upper limit (eg IPCC (2018));

– When mitigation measures start (eg immediately and relatively smoothly, or with delay and more abruptly) and over which time horizon they take place;

– What kind of "shock" is applied: for instance a policy shock (such as a carbon tax, but other regulations can also be used) or a technological shock (eg a technological breakthrough leading to declining cost of renewable energy, or on the contrary a situation where substitution between carbon-intensive and low-carbon technologies is limited).

These initial inputs can then be translated into macroeconomic and/or sectoral outputs. In order to do this, most methodologies rely on climate-economic models such as Integrated Assessment Models (IAMs). For instance, Oliver Wyman's (2019) and Carbon Delta's (2019)[21] respective transition scenarios apply data from IAMs such as REMIND[22], GCAM[23] and IMAGE[24], and Battiston (2019) relies on IAMs to conduct system-wide climate stress tests.

IAMs cover a great range of methodological approaches and sectoral and regional disaggregation, but at their core they generally combine a climate science module linking greenhouse gas (GHG) emissions to temperature increases, and an economic module linking increases in temperatures to economic and policy outcomes. Some key variables serve to link the climate and economic modules, such as: the accumulation of GHGs in the atmosphere; the evolution of mean temperatures; a measure of well-being (GDP); a damage function linking increases in global temperatures to losses in GDP; and a cost function generated by the policies aimed at reducing GHG emissions (eg a carbon tax).

Although IAMs are used by the UN Intergovernmental Panel on Climate Change (IPCC)[25] to explore some of the relationships between society and the natural world, their limitations with regard to economic modelling are increasingly recognised. In particular, critical assumptions about the damage functions (impacts of climate change on the economy) and discount rates (how to adjust for climate-related risk) have been subject to numerous debates (Ackerman et al (2009), Pindyck (2013), Stern (2016)), as further discussed below. Other oft-mentioned limitations include: the absence of an endogenous evolution of the structures of production[26] (Acemoğlu et al (2012, 2015), Pottier et al (2014)); the choice of general equilibrium models with unrealistic assumptions on well-functioning capital markets and rational expectations (Keen (2019)); the emphasis on relatively smooth transitions to a low-carbon economy and the quick return to steady state following a climate shock (Campiglio et al (2018)); and the suppression of the critical role of financial markets (Espagne (2018); Mercure et al (2019)).

[21] See www.carbon-delta.com/climate-value-at-risk/.

[22] REMIND is a global multi-regional model incorporating the economy, the climate system and a detailed representation of the energy sector. It allows for the analysis of technology options and policy proposals for climate mitigation. The REMIND model was developed by the Potsdam Institute for Climate Impact Research (PIK). www.pik-potsdam.de/research/transformation-pathways/models/remind/remind.

[23] The Global Change Assessment Model (GCAM) is a dynamic-recursive model with technology-rich representations of the economy, energy sector, land use and water linked to a climate model that can be used to explore climate change mitigation policies including carbon taxes, carbon trading, regulations and accelerated deployment of energy technology. The Joint Global Change Research Institute (JGCRI) is the home and primary development institution for GCAM. jgcri.github.io/gcam-doc/v4.2/.

[24] IMAGE is an ecological-environmental model framework that simulates the environmental consequences of human activities worldwide. It represents interactions between society, the biosphere and the climate system to assess sustainability issues such as climate change, biodiversity and human well-being. The IMAGE modelling framework has been developed by the IMAGE team under the authority of PBL Netherlands Environmental Assessment Agency. models.pbl.nl/image/index.php/Welcome_to_IMAGE_3.0_Documentation.

[25] The IPCC is composed of three working groups. Working Group I assesses scientific aspects of the climate system and climate change; Working Group II assesses the vulnerabilities of socioeconomic and natural systems to climate change, as well as their consequences and adaptation options; Working Group III assesses the options for limiting greenhouse gas emissions and mitigating climate change.

[26] It should be noted that some IAMs feature endogenous technological change (IPCC (2014, p 423)).

For all these reasons, it is increasingly recognised that "today's macroeconomic models may not be able to accurately predict the economic and financial impact of climate change" (NGFS (2019a, p 4), Weyant (2017)). This does not mean that IAMs and climate-economic models in general are not useful for specific purposes and under specific conditions (Espagne (2018)). In particular, a new wave of models embracing uncertainty and complexity seems better able to account for heterogeneity and nonlinearities, as well as for cascade effects, policy path dependency and interactions between macroeconomic and financial dynamics (see Dafermos et al (2017), Espagne (2017), Mercure et al (2019), Monasterolo et al (2019)). The central bank community could gain from exploring these new modelling approaches, as discussed in Chapter 3.5.

Nevertheless, the deep uncertainty related to physical and transition risks means that both the neoclassical approach of most IAMs and alternative approaches such as demand-led and non-equilibrium models will remain unable to capture many forces triggered by climate change. A corollary is that the outcomes of such models should be interpreted cautiously by both financial practitioners and financial regulators and supervisors. Some of the key sources of uncertainty with respect to climate-related physical and transition risks are outlined below and further detailed in Annexes 1 and 2.

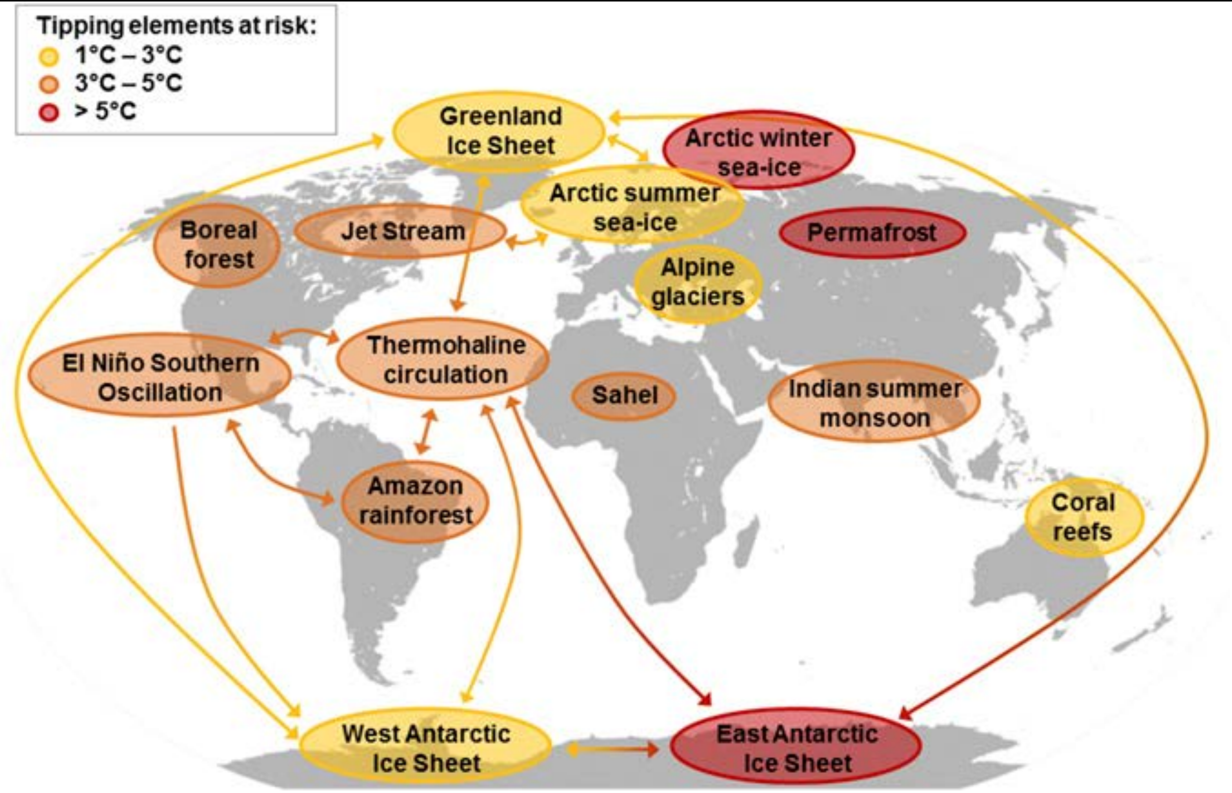
With regard to physical risks (see Annex 1), some of the main sources of modelling uncertainty relate to the following features:

- Deep uncertainty exists with regard to the biogeochemical processes potentially triggered by climate change. Climate scientists have shown not only that tipping points exist but remain difficult to estimate with precision, but also that they could generate tipping cascades on other biogeochemical processes, as shown in Graph 8 below. Evidence is now mounting that tipping points in the Earth system such as the loss of the Amazon forest or the West Antarctic ice sheet could occur more rapidly than was thought (Lenton et al (2019));
- The impacts of such biogeochemical processes on socioeconomic systems can be highly nonlinear, meaning that small changes in one part of the system can lead to large changes elsewhere in the system (Smith (2014)) and to chaotic dynamics that become impossible to model with high levels of confidence. For instance, it seems that climate change will mostly impact developing economies, which could increase global inequality (Diffenbaugh and Burke (2019)) and generate mass migrations and conflicts (Abel et al (2019), Bamber et al (2019), Kelley et al (2015)). These could have major implications for development across the world (Human Rights Council (2019)) but their probability of occurrence and degrees of impact remain largely impossible to appropriately integrate into existing models. However, advanced economies are not exempt from significant impacts either. For instance, Dantec and Roux (2019) assess how climate change may affect different French territories and demand multiple adaptation strategies in areas such as urban planning, water management or agricultural practices;
- In the light of these considerations, it has been argued that the damage functions used by IAMs are unable to account for the tail risks related to climate change (Calel et al (2015)), and in some cases lead studies to suggest "optimal" warming scenarios that would actually correspond to catastrophic conditions for the future of human and non-human life on Earth: for instance, while DICE (Dynamic Integrated Climate-Economy) modellers find that a 6°C warming in the 22nd century would mean a decline of less than 0.1% per year in GDP for the next 130 years, in practice such a rise in global temperatures could mean extinction for a large part of humanity (Keen (2019)). Similarly, the social cost of carbon (which adds up in monetary terms all the costs and benefits of adding one additional tonne of CO_2), and the choice of a rate of discount of future damages can provide "almost any result one desires" (Pindyck (2013, p 5)) and lead to outcomes and policy recommendations that are "grossly misleading" (Stern (2016)). Climate modellers typically embrace uncertainty by showing the great range of outcomes that can result from a specific event or pattern (eg a specific CO_2 atmospheric concentration can translate into different increases in global temperature and different sea level rises, with respective confidence intervals),

but this dimension tends be lost in climate-economic models based on benefit-cost analysis (Giampietro et al (2013), Martin and Pindyck (2015)).

Global map of potential tipping cascades

Graph 8



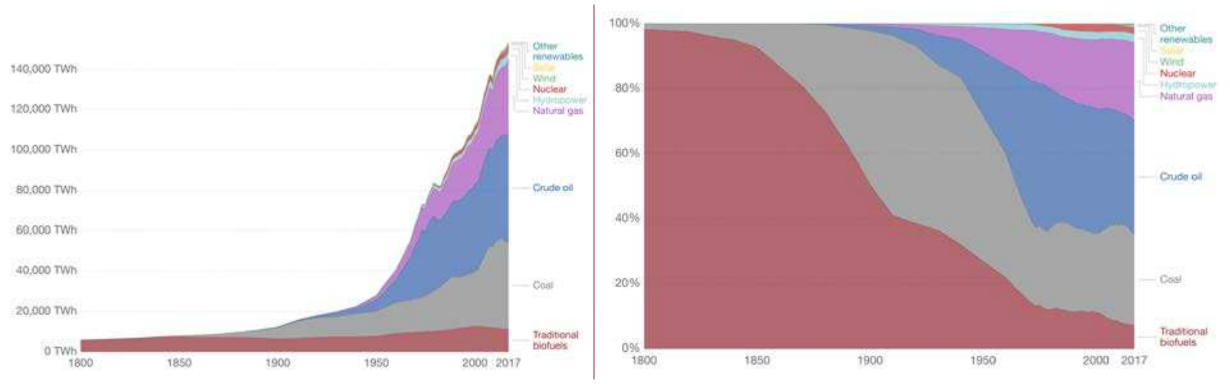
The individual tipping elements are colour-coded according to estimated thresholds in global average surface temperature. Arrows show the potential interactions among the tipping elements that could generate cascades, based on expert elicitation.

Source: Adapted from Steffen et al (2018).

With regard to transition risks (see Annex 2), one of the main sources of modelling uncertainty relates to the general use of economy-wide carbon prices as a proxy for climate policy in IAMs. This assumption tends to overlook many social and political forces that can influence the way the world evolves, as recognised by the IPCC itself (IPCC (2014, p 422)). As the history of energy and social systems shows (Bonneuil and Fressoz (2016), Global Energy Assessment (2012), Pearson and Foxon (2012), Smil (2010, 2017a)), the evolution of primary energy uses is deeply influenced by structural factors and requires deep transformations of existing socioeconomic systems (Graph 9, left-hand panel). Past transformations have responded to a variety of stimuli including relative prices but also many other considerations such as geopolitical (eg choice of nuclear energy by certain countries to guarantee energy independence) and institutional ones (eg proactive policies supporting urban sprawl and its related automobile dependency). Attempts to reverse these inertias through pricing mechanisms alone could be insufficient.

Moreover, all major energy transitions in the past (Graph 9, right-hand panel) have taken the form of energy additions in absolute terms (Graph 9, left-hand panel). That is, they were energy additions more than energy transitions. For instance, biomass (in green) has decreased in relative terms but not in absolute terms. This highlights the sobering reality that achieving a low-carbon transition in a smooth manner represents an unprecedented challenge with system-wide implications. With this in mind, estimating the social cost of carbon with confidence is all the more difficult "due to considerable uncertainties [...] and [results that] depend on a large number of normative and empirical assumptions that are not known with any certainty" (IPCC (2007, p 173)).

Evolution of energy systems, in absolute and relative terms Graph 9



Global primary energy consumption, measured in terawatt-hours (TWh) per year (left-hand panel) and in percentage by primary energy source (right-hand panel).

Note: "other renewables" are renewable technologies not including solar, wind, hydropower and traditional biofuels.

Source: Smil (2017b) and BP (2019). Published online at OurWorldInData.org. Retrieved from: https://ourworldindata.org/energy.

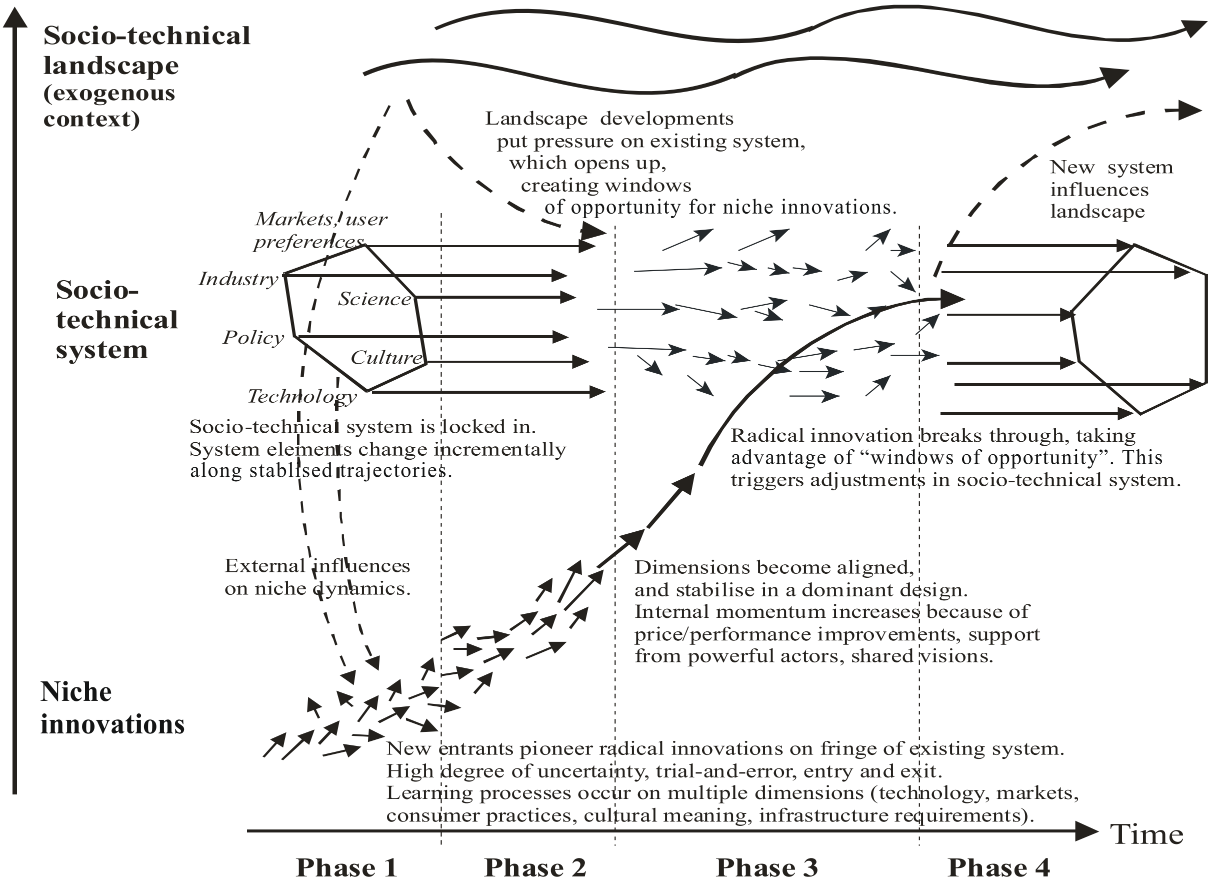
To account for this complexity, transdisciplinary approaches around concepts such as socio-technical systems and transitions (Geels et al (2017)) seem more appropriate to embrace the multiple dimensions involved in any climate change mitigation transition (Box 3). These approaches are concerned with "understanding the mechanisms through which socio-economic, biological and technological systems adapt to changes in their internal or external environments" (Lawhon and Murphy (2011, pp 356–7)). In particular, socio-technical transition scholars provide a framework for more sophisticated qualitative and quantitative approaches to three parameters that are essential to a low-carbon transition: technological niches, socio-technical regime, and socio-technical landscape (Graph 10).

In short, the physical and transition risks of climate change are subject to multiple forces (natural, technological, societal, regulatory and cultural, among others) that interact with each other and are subject to uncertainty, irreversibility, nonlinearity and fat-tailed distributions. Moreover, physical and transition risks will increasingly interact with each other, potentially generating new cascade effects that are not yet accounted for (Annex 3).

In the rest of this chapter, we discuss how to go beyond the limitations of climate-economic models as discussed above to better assess climate-related risks, especially with regard to: (i) the choice of scenarios regarding how technologies, policies, behaviours, and macroeconomic – and even geopolitical – dynamics will interact in the future (Chapter 3.2); (ii) the translation of such scenarios into granular sectoral and corporate metrics in an evolving environment where all firms and value chains will be impacted in unpredictable ways (Chapter 3.3); and (iii) the matching of climate-related risk assessments with appropriate financial decision-making (Chapter 3.4). One key finding is that alternative approaches are needed to fully embrace the uncertainty and the need for structural transformation at stake (Chapter 3.5).

Phases of transformations of existing socio-technical systems

Graph 10



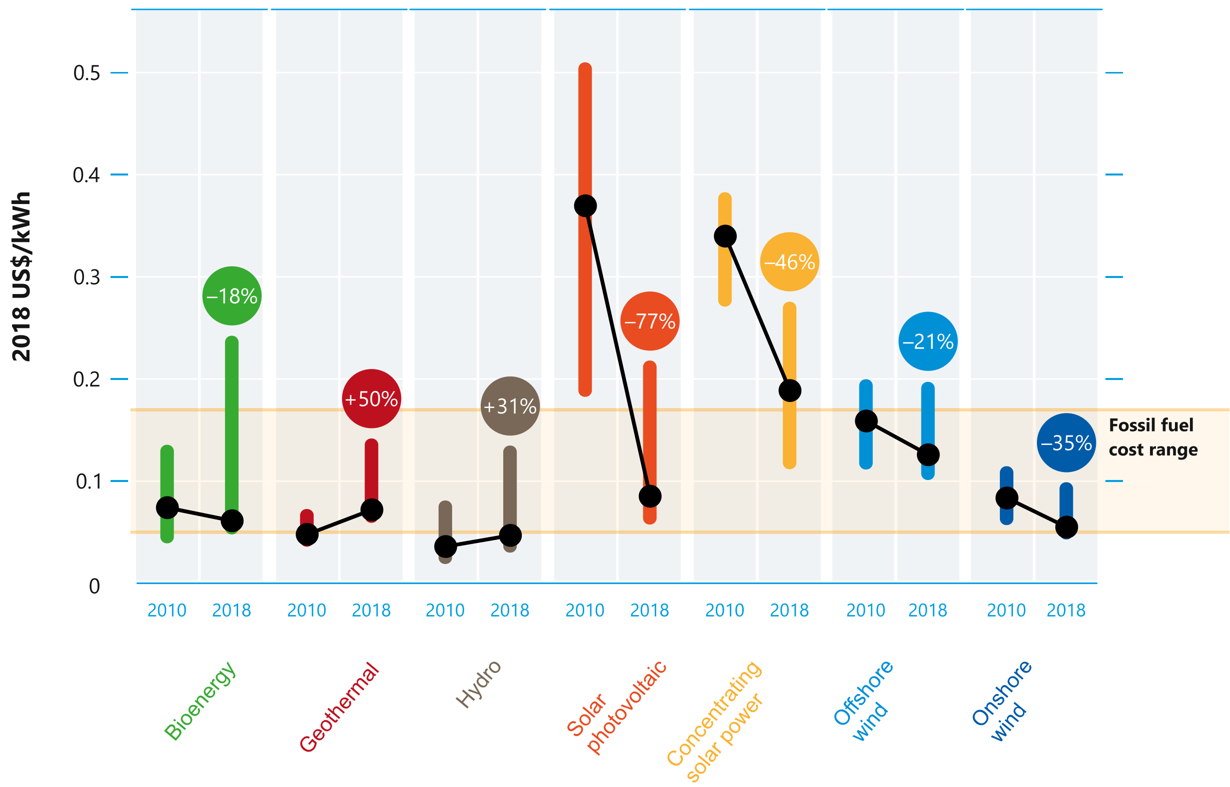
Source: Adapted from Geels et al (2017).

Box 3: A multi-layered perspective on socio-technical transition

Multi-layered perspectives on socio-technical transition can provide a framework for more sophisticated qualitative and quantitative approaches to the interactions between three layers that are essential to a low-carbon transition: technological niches, socio-technical regime, and socio-technical landscape (Graph 10).

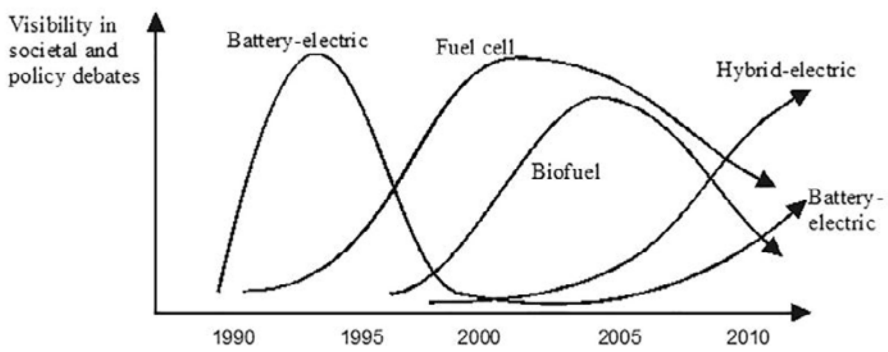
First, technological niches and innovations will, unsurprisingly, be a key parameter of a successful transition. Yet their representation in existing models fails to reflect the unpredictable and disruptive nature of technological innovations. As an example, the sharp increase of usage and cost variation in many renewable energy technologies over the past few years (Graph 3.A) has outpaced most predictions, and this seems to have responded more to massive investments in R&D and targeted subsidies to solar energy than to any ambitious carbon pricing mechanism (Zenghelis (2019)). In contrast, the intermittency of renewable energy remains a considerable problem that tends to be overlooked (Moriarty and Honnery (2016), Smil (2017a)). Moreover, other sectors may be impossible to decarbonise in the medium term regardless of carbon pricing, as we can observe (so far) not only with aviation or cement, but also with parts of the energy sector. In short, the type of technological solution that will prevail in a low-carbon world is largely unpredictable. A case in point is the transportation sector: the most promising technological alternatives have varied greatly over short time horizons (Graph 3.B) and with new technologies such as hydrogen fuel (Morris et al (2019), Li (2019), Xin (2019)).

Changes in global levelised cost of energy for key renewable energy technologies, 2010–18 — Graph 3.A



Source: UNEP (2019).

Changes in visibility of transportation technologies through time — Graph 3.B



Source: Geels et al (2017).

Second, the successful implementation of technologies does not depend only on their relative prices but also on the so-called socio-technical regimes in which they operate, ie the rules and norms guiding the use of particular technologies. For instance, once car-based transportation systems are set up in a city or country, they largely become self-sustaining "by formal and informal institutions, such as the preferences and habits of car drivers; the cultural associations of car-based mobility with freedom, modernity, and individual identity; the skills and assumptions of transport planners; and the technical capabilities of car manufacturers, suppliers, and repair shops" (Geels et al (2017, p 465)). Although pricing mechanisms can surely contribute to overcoming this institutional inertia, other regulations may be needed such as rules on the weight of new cars (to avoid rebound effects[27]) and proactive support to the development of public transportation to limit the number of personal vehicles. More broadly, some solutions may depend not on new technologies but rather on shifting social norms towards the use of already existing technologies (Bihouix (2015)). For instance, the recent "flight shame" movement in Sweden and its negative impact on airline companies (Fabre (2019)), along with positive impacts for the national rail operator (Henley (2019)), are responses to a "Greta Thunberg effect" rather than a technological breakthrough.

Third, technological, behavioural and regulatory changes do not take place in a vacuum but in specific socio-technical landscapes, ie in contexts comprising "both slow-changing trends (eg demographics, ideology, spatial structures, geopolitics) and exogenous shocks (eg wars, economic crises, major accidents, political upheavals)" (Geels et al (2017, p 465)). In other words, assessing specific transition paths requires integrating many real-world considerations into the scope of the analysis, which is particularly difficult for modellers whose objective is precisely to simplify the representation of the world for reasons of tractability. Some features of the current "socio-technical landscape" that will prove essential to consider for the transition (further developed in Annex 2) include:

– A rather weakened multilateral order that is an important barrier to address the multiple trade-offs that a global low-carbon transition will generate. For instance, stranding fossil fuels may require the United States and Canada to immediately stop extracting unconventional oil, with potentially significant impacts on the output of their national economies (Mercure et al (2018)). Similarly, as China consumed half of the world's coal in 2018 (BP (2019)) and Asia has accounted for 90% of new coal plants over the past two decades (IEA (2019)), stranding such assets could have major impacts on global value chains, for example with sharp increases in the price of imports for advanced economies, sharp decreases in corporate profits in Asia, and potential relocations of certain economic activities. These could have significant implications for global imbalances. With this in mind, aiming to strand these assets rapidly and in a fair manner would probably require unprecedented international cooperation, including significant compensation mechanisms for countries that do not exploit fossil fuel reserves. However, past experiences such as the Yasuni-ITT initiative in Ecuador show the difficulty of reaching agreements on compensation for not polluting (Martin and Scholz (2014), Warnars (2010)). Finally, a low-carbon transition could trigger new geopolitical tensions and potential conflicts, including conflicts related to the quest for resources needed for renewable energy (IRENA (2019), Pitron (2018)). Hence, existing models still have a long way to go to account for the international political economy of climate change and for the principle of "common but differentiated responsibilities" enshrined in international climate negotiations (UNFCCC (2015)).
– Significant transformations of market economies have taken place over the past decades, including a decrease in growth rates in advanced economies but also at the global level (despite rapid growth in emerging and developing economies). Discussions are under way about the causes of this slowdown (eg a new "secular stagnation", whether structural and possibly related to a long-term decline in productivity (Gordon (2012)), or a more conjunctural slowdown in aggregate demand that can be addressed by new macroeconomic policies). Other transformations include a shift in corporate governance towards maximisation of shareholder value and short-termism (Mazzucato (2015)) and increased inequalities within nations (Piketty (2014)) despite a relative decrease in inequalities among nations (Milanovic (2016)). These features pose significant questions such as the social acceptability of a low-carbon transition. For

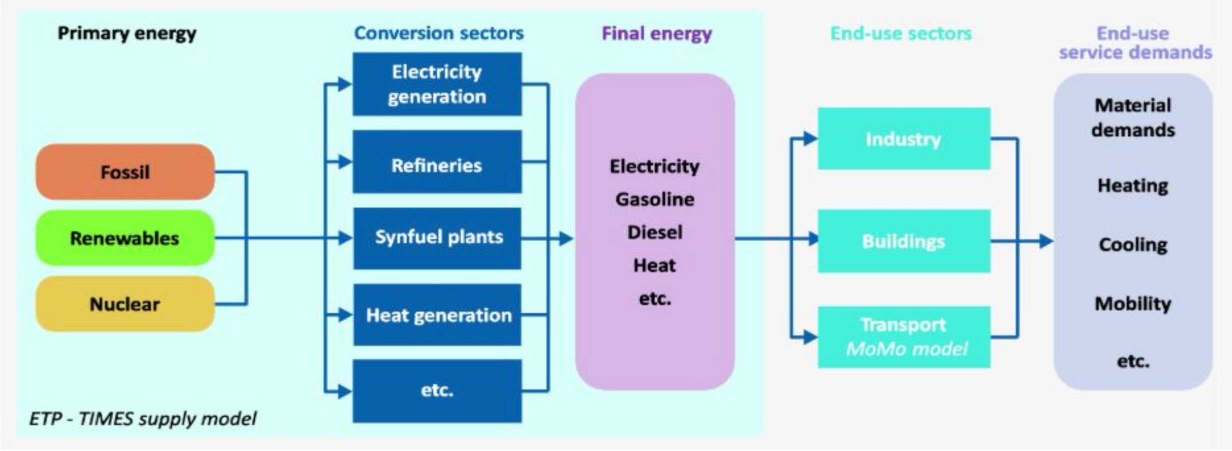
[27] In energy economics, rebound effects occur when initial energy efficiency gains are cancelled out by behavioural or systemic responses, for instance if a consumer uses the financial gains from increased housing energy efficiency to set higher temperatures or to increase energy use elsewhere. As a concrete example, increases in cars' energy efficiency over the past few years have been offset by the fact that households are buying larger cars and that the number of passengers per car is decreasing (IEA (2019)).

instance, given that such a transition requires "intensive public discussion" (Stern (2008, p 33)), it is unclear whether mechanisms such as revenue-neutral carbon taxes will be sufficient. Some argue that if inequalities were lower in the first place, it could become easier to reach consensus on difficult topics such as the burden-sharing efforts to mitigate and adapt to climate change (Chancel (2017), Otto et al (2019)). That is, without suggesting an optimal specific path, climate change needs to be considered as being embedded in a myriad of real-world socioeconomic challenges, not as an ad hoc challenge that should simply not interfere with other challenges.

3.2 Climate-related uncertainties and the choice of scenarios

Forward-looking approaches that are built around an IAM inevitably inherit all the limitations of the climate-economic models mentioned in the previous chapter. Here we focus mostly on technological uncertainties, given the difficulty of accounting for the other sources of uncertainty discussed above (eg international political economy uncertainties associated with the transition). It should also be noted that some methodology providers do not rely on IAMs but rather on "technologically-based" models. For instance, the ET Risk Project,[28] developed by a consortium of stakeholders, uses scenarios provided by the International Energy Agency (IEA) and adapts these based on bottom-up market analyses. The IEA produces scenarios on the development of energy technologies and the investments needed to upscale them under different climate pathways and policy tracks (regulations, carbon pricing, etc).[29] For instance, the IEA's 2017 *Energy Technology Perspectives* (ETP) report (Graph 11) seeks to offer a "technology-rich, bottom-up analysis of the global energy system" (IEA (2017)).

Structure of the ETP model — Graph 11



Source: IEA (2017).

[28] http://et-risk.eu/.

[29] These include a "Current Policies Scenario" akin to a "business as usual" setup, a "New Policies Scenario" focused on the Nationally Determined Contributions (NDCs) set by each country following the Paris Agreement (UNFCCC (2015)), and a more ambitious "Sustainable Development Scenario".

Whether they rely on IAMs or "technology-based" models, it is critical to assess which choices inform the selected technological pathway (eg development of carbon capture and storage (CCS) technologies, nuclear energy, price of renewable energy, gains obtained from energy efficiency, etc) as these strongly determine which sectors and companies could benefit from it. However, the representation of clean technology diffusion rates in energy-systems models is inherently subject to much uncertainty (Barreto and Kemp (2008)). Some scenarios rely on the rapid development of existing technologies to respond to increasing demand for energy (eg IEA (2017)), while others focus on the potential reduction in energy demand to be achieved through energy efficiency and modification of existing behaviours (eg Negawatt (2018)). Other technology-based scenarios include BP's Rapid transition scenario, IRENA's REmap scenario, Greenpeace's Advanced Energy Revolution scenario (for a comprehensive review of scenarios, see Colin et al (2019), The Shift Project and IFPEN (2019)) or, with a different approach, the Science-Based Targets Initiative.[30]

An important source of technological uncertainty has to do with the role allocated to negative emissions and to CCS technologies.[31] Their relative importance varies widely across models: in a subset of 2°C scenarios, between 400 and 1,600 gigatonnes of carbon dioxide ($GtCO_2$) can be compensated through negative emissions and CCS, corresponding to 10–40 years of current emissions (Carbon Brief (2018)). This increases the size of the remaining carbon budget by between 72 and 290%, compared to scenarios where negative emissions and CCS do not occur. In practice, however, significant uncertainty exists with regard to CCS technologies due to technological constraints, potentially high costs and environmental and health risks (IPCC (2014)).

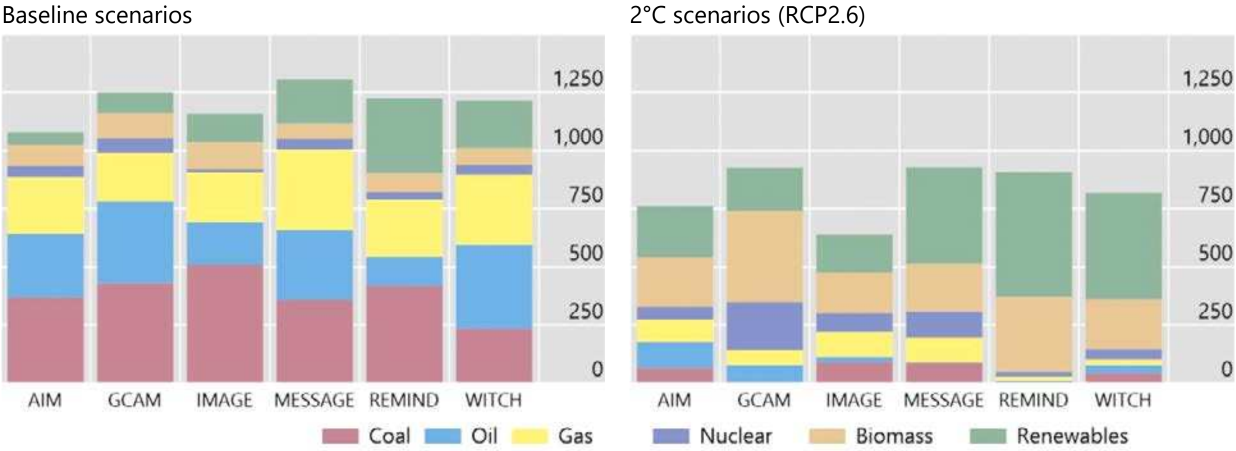
As a result, a scenario with a large role for negative emissions and CCS will naturally reduce the amount of assets that are stranded (eg the GCAM model in the graph below, for a 2°C scenario), whereas a scenario with less room for negative emissions will require a more massive development of renewables (as in the MESSAGE, REMIND and WITCH models) or considerable improvements in energy efficiency (as in IMAGE). This means that the financial impacts of a specific financial portfolio will be entirely different depending on which scenario is chosen.

30 The Science-Based Targets Initiative (sciencebasedtargets.org/) differs from the other listed scenarios. Instead of a comprehensive approach, it aims to provide companies with pathways to align their emissions to climate targets on a sectoral basis, based on current scientific knowledge.

31 CCS is technically not a "negative emissions" technology since it does not remove CO_2 from the atmosphere, but stores new emissions instead. That is, it avoids new emissions but does not capture past emissions. CCS is usually included in the category of BECCS (bioenergy with carbon capture and storage).

The 2100 primary energy mix

Exajoules of primary energy | Graph 12



The 2100 primary energy mix according to six IAMs, for SSP2 ("middle of the road") RCP2.6 scenarios. The energy mix in a "baseline" scenario is shown on the left, and scenarios that limit global warning to 2°C are shown on the right. Fossil fuel categories include CCS and non-CCS use.

Sources: Carbon Brief (2018); IIASA SSP Database.

Partially as a result of these sources of technological uncertainty, the volume of investments needed (a critical element to assess the risk and opportunities related to a low-carbon transition) can vary significantly. The survey of six models estimating the additional annual average energy-related investments needed to limit global warming to 1.5°C (over the period 2016 to 2050, compared to the baseline) finds significant variations, with values ranging from $150 billion ($2010) to $1,700 billion ($2010). Total investments (ie not just additional ones) in low-carbon energy also vary greatly, from $0.8 trillion ($2010) to $2.9 trillion ($2010; IPCC (2018, p 153)). Estimated needed investments vary even over shorter time horizons. For instance, global investments needed in sustainable infrastructure for the period 2015–30 range from less than $20 trillion to close to $100 trillion (Bhattacharya et al (2016, p 27)).

These estimates depend significantly on initial assumptions and methodological choices. For instance, in MESSAGE (the energy core of IIASA's[32] IAM framework), emissions-reduction investments occur in the models' regions and at the time they are cheapest to implement (assuming full temporal and spatial flexibility), based on the cost assumptions of 10 representative generation technologies (Zhou et al (2019)). In contrast, the New Climate Economy project estimates the investments needed in infrastructure by using existing technologies and investment patterns, assuming an exogenous growth rate of 3% and no productivity gains (Bhattacharya et al (2016)). Other assumptions are also critical, eg supply side investments could be lowered by up to 50% according to some studies if strong policies to limit energy demand growth are implemented (Grubler et al (2018), in IPCC (2018)).

Therefore, scenarios "should be considered illustrative and exploratory, rather than definitive [...]. It is important to remember that scenarios represent plausible future pathways under uncertainty. Scenarios are not associated with probabilities, nor do they represent a collectively exhaustive set of potential outcomes or actual forecasts" (Trucost ESG Analysis (2019, p 39)). Their "results are subject to a

[32] The International Institute for Applied Systems Analysis (IIASA)'s model is composed of five different models: the two most important that represent the energy system (MESSAGE) and land-use competition (GLOBIOM), and three that represent the macroeconomic system (MACRO), the climate system (MAGICC) and air pollution and GHG emissions (GAINS). The MESSAGE framework divides the world into 11 regions. For an overview, see: https://message.iiasa.ac.at/projects/global/en/latest/overview/index.html.

high degree of uncertainty" (Zhou et al (2019, p 3)) and cannot be allocated probabilities of occurrence, ie they should be assessed with extreme caution by finance supervisors engaged in financial stability monitoring.

3.3 Translating a climate-economic scenario into sector- and firm-level risk assessments

To incorporate climate-related risks into financial institutions' risk management procedures and financial stability monitoring, the main challenge to determining a reasonable scenario consists in translating it into granular metrics at the sector (see Box 4 below) and firm level. A firm-level assessment is critical as it can distinguish how firms with a similar exposure to climate scenarios have different adaptive capacities, making them more or less vulnerable. Indeed, the climate vulnerability of a firm does not depend only on its exposure to climate-related risks (which can be relatively similar for different firms in the same sector) but also on its sensitivity and its adaptive capacity to a specific scenario (eg its ability to develop new low-carbon technologies in response to climate-related risks, or to pass through additional costs to its suppliers or customers). For instance, two oil and gas companies may fall under the same industry classification but be exposed to transition risks in very different ways, depending on factors such as the likelihood of owning stranded assets (as discussed above) or their degree of diversification into renewable energy.

Box 4: The Netherlands Bank's climate stress test

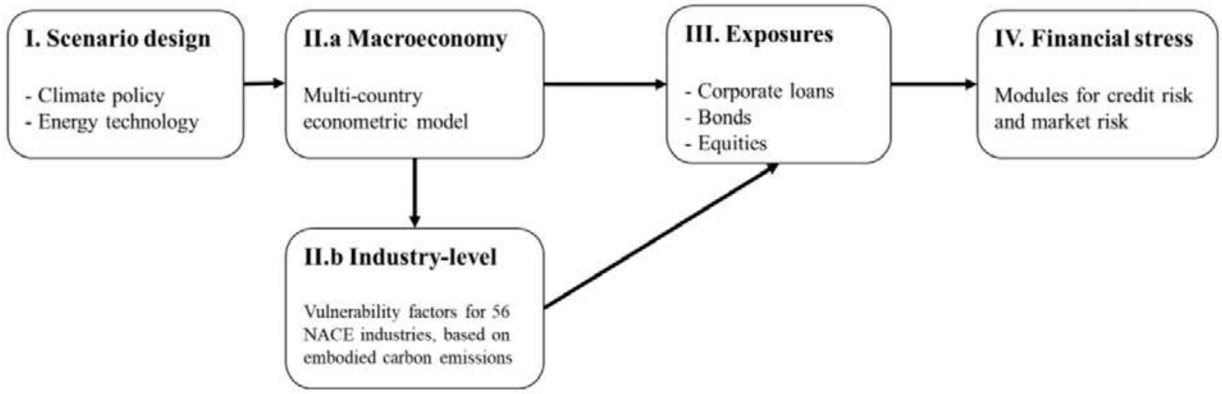
The Netherlands Bank's methodology (Vermeulen et al (2018, 2019)) first defines climate scenarios and shocks (mostly via carbon taxes and technological development paths) based on literature and validated by experts (block I in figure below). The policy shock consists in the abrupt implementation of a $100 carbon tax, and the technology shock in the rapid development of renewable energy, which leaves fossil fuel dependent technologies obsolete, resulting in capital stock write-offs. These shocks can be assessed separately or jointly (double shock); they can also lead to a negative confidence shock affecting the behaviour of consumers, producers and investors. These scenarios are translated into macroeconomic impacts on GDP, consumer prices, stock prices and interest rates through NiGEM (block II.a in Graph 4.A), a multi-country macroeconomic model. The central bank then estimates the vulnerability of each sector to transition risks, based on the embodied CO_2 emissions of 56 NACE industries[33] (ie including the emissions related to their value chain) weighted by their contribution to GDP (block II.b in the graph). The impact of the transition on each NACE industry is then connected to the national financial sector portfolios of corporate loans, bonds and equities (block III in the figure below). In the last step (block IV in Graph 4.A), the central bank calculates losses for financial institutions with the aid of traditional top-down approaches to stress testing. The results of the climate stress test indicate losses of up to 11% of assets for insurers and up to 3% for banks, potentially leading to a reduction of about 4 percentage points in Dutch banks' CET1 ratio[34].

[33] NACE is the industry standard classification system used in the European Union.

[34] Common Equity Tier 1 (CET1) is a component of Tier 1 capital that consists mostly of common stock held by a bank or other financial institution. It is the highest quality of regulatory capital, as it absorbs losses immediately when they occur. See: https://www.bis.org/fsi/fsisummaries/defcap_b3.pdf.

Overview of the stress test framework

Graph 4.A

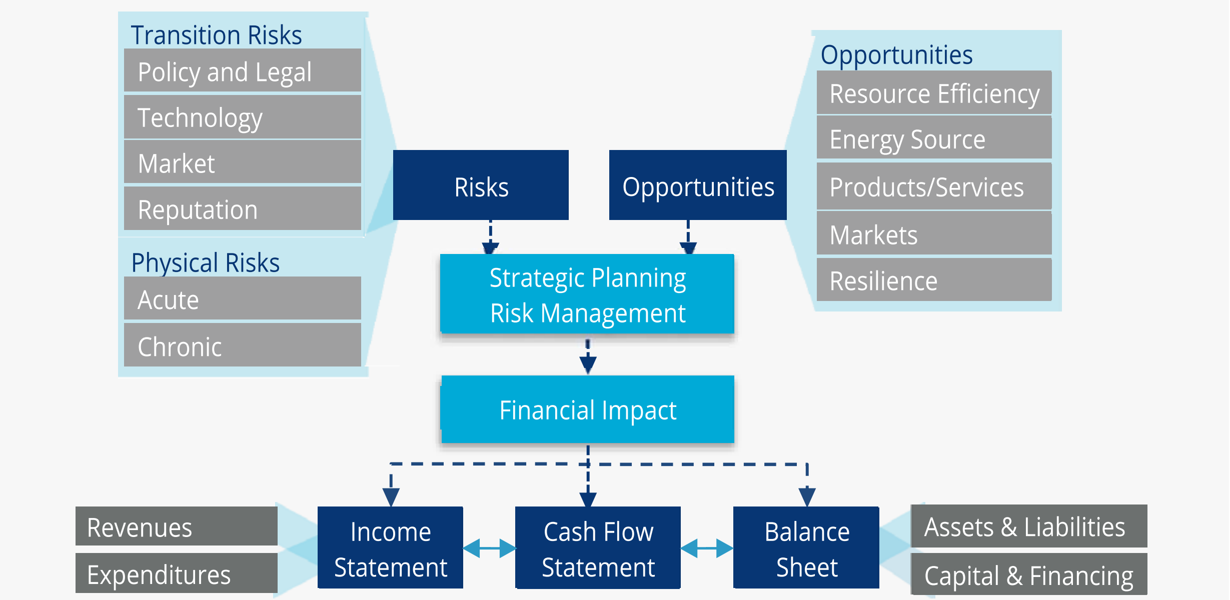


Source: Vermeulen et al (2019).

Climate change mitigation and adaptation also brings opportunities related to the development of low-carbon technologies and climate-friendly policies (see Graph 13), which are captured by several climate-related risk assessment methodologies (eg Mercer, Oliver Wyman and Carbon Delta). UNEP-FI (2019) estimates that profits generated by a 30,000-company universe in the transition to a 2°C world could amount to $2.1 trillion, although this number should be taken cautiously given the many sources of uncertainty discussed above. It is therefore important to assess how climate-related risks and opportunities will impact specific key performance indicators (KPIs) of a firm, such as its sales, operational and maintenance costs, capital expenditures, R&D expenditures, and potential impairment of fixed assets.

Climate-related risks, opportunities and financial impact

Graph 13



Source: TCFD (2017).

One of the main difficulties at this stage is determining how a firm is exposed to climate-related risks throughout its value chain. A firm can be exposed to these risks through: (i) direct, so-called "scope 1" emissions (particularly important in sectors such as mining, aviation or the chemical industry); (ii) indirect, so-called "scope 2" emissions resulting from purchased energy (eg real estate or energy-intensive industries); and (iii) other indirect emissions related to its entire upstream and downstream value chain, so-called "scope 3" emissions.[35] A case in point for scope 3 is the automotive industry, where the main exposure lies not so much with the sector's own emissions (scope 1) or its energy sources (scope 2), but with carbon combustion by end users (scope 3). For buildings, scope 3 emissions are twice as high as direct emissions (Hertwich and Wood (2018)). This is not to say that the emissions related to scopes 1, 2 and 3 are sufficient to assess the exposure of a firm. For instance, a firm with high emissions today could become decarbonised and seize many opportunities under specific transition paths. Still, focusing on scopes 1, 2 and 3 means that a comprehensive risk assessment should look at potential vulnerabilities throughout the entire value chain.

The assessment of a firm's exposure to its scope 1, 2 and 3 emissions and its translation into risk metrics can be conducted in quantitative or qualitative manners. The PACTA stress test model,[36] based on International Energy Agency (IEA) technological pathways up to 2050 compatible with a specific climate scenario (eg a 2°C or 1.75°C rise in temperatures) and on proprietary databases including existing investment plans at the firm level, determines how each firm within specific sectors may become aligned or misaligned with the scenario. This insight then informs a delayed stress test tool that calculates shocks based on alternative cash flows, discounted in a valuation or credit risk model. The assessment of the risk materiality by sector is a key dimension of this methodology, which involves technological, market and policy considerations.

Another methodology, developed by Carbon Delta (2019), proceeds by breaking down each country's emission reduction pledge (as indicated by its Nationally Determined Contribution, or NDC) into sector-level targets, and then assigning emission reduction quantities to a firm's production facilities based on its emission profile within each sector, using a proprietary asset location database. The costs relative to the transition are then obtained by multiplying the required GHG reduction amount by the price per tonne of carbon dioxide (tCO_2) obtained via IAMs for the scenario under analysis (eg for a 3°C, 2°C and 1.5°C rise in temperatures). In order to estimate the revenues that each firm could obtain from a low-carbon transition, Carbon Delta (2019) uses a database covering millions of low-carbon patents granted by authorities worldwide, and a qualitative assessment of each low-carbon patent portfolio as a proxy for firms' adaptive capacity.

Other approaches rely more extensively on qualitative judgments regarding the adaptive capacity of firms in each sector. For instance, Oliver Wyman (2019) resorts to experts' judgments to forecast how specific companies in the portfolio may adapt to climate-related risks, although it also includes quantitative tools to estimate impacts of scenarios on prices, volumes, cost, impairment and capital expenditure of counterparties. Carbone 4's (2016) bottom-up assessment considers firms' adaptive capacities to a low-carbon transition, relying on a mix of qualitative and quantitative indicators such as the investments made in R&D and the CO_2 reduction objectives of the firm related to its scope 1, 2 and 3 emissions. Allianz Global Investor integrates technological, regulatory and physical considerations qualitatively into its asset allocation procedures (IIGCC (2018)).

35 The GHG Protocol Corporate Standard classifies a company's GHG emissions into three "scopes". "Scope 1 emissions are direct emissions from owned or controlled sources. Scope 2 emissions are indirect emissions from the generation of purchased energy. Scope 3 emissions are all indirect emissions (not included in scope 2) that occur in the value chain of the reporting company, including both upstream and downstream emissions." Source: ghgprotocol.org/sites/default/files/standards_supporting/FAQ.pdf.

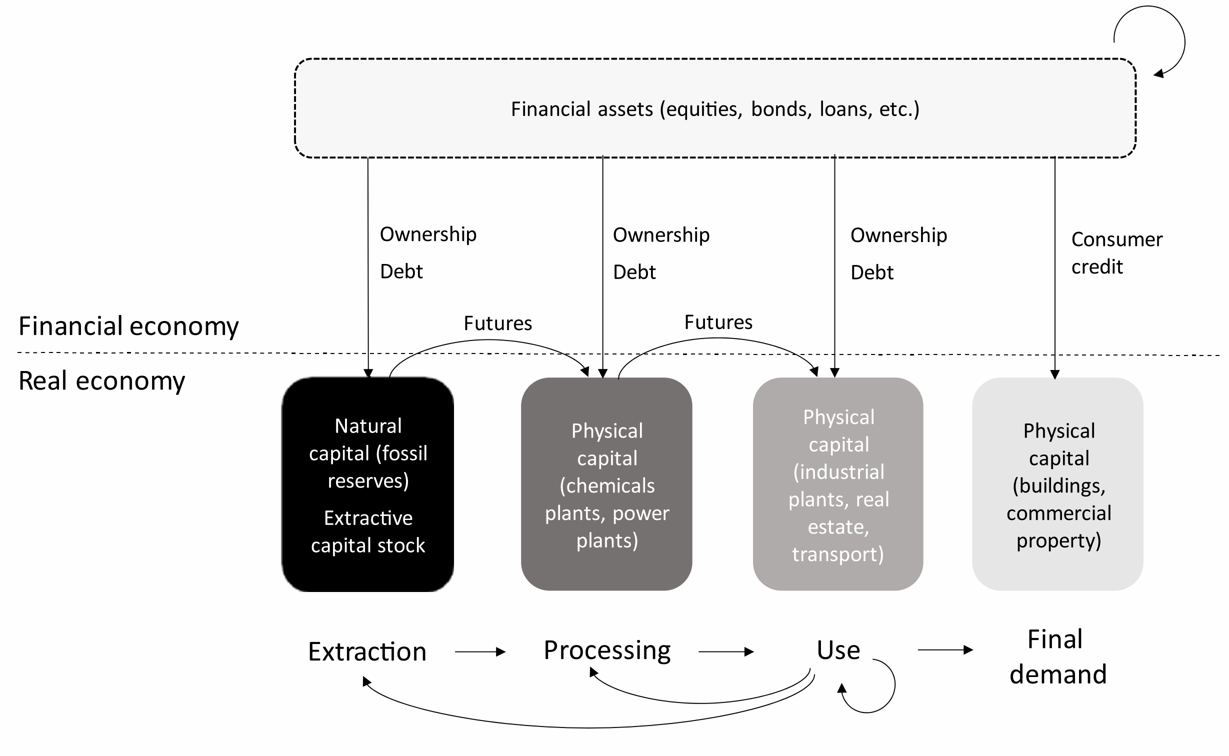
36 www.transitionmonitor.com/.

Other approaches have also emerged to better account for the indirect exposures to climate-related risks, without necessarily relying on scopes 1, 2 and 3. For instance, Battiston et al (2017) classify economic activities into six sectors (fossil-fuel, utility, energy intensive, transportation, housing, and finance) and twenty subsectors based on their relative vulnerability to climate transition risks (as a function of their emissions). They further map out the exposure of financial institutions (through equity and debt) to these different sectors, which enables them to capture potential knock-on effects within financial networks. When applying a sectoral shock (eg a carbon tax), the firms in sectors that have not adapted their business model to the energy transition face increased costs and reduced revenues, whereas the firms that have invested in alternative technologies are able to increase their profits. This methodology can be applied to the financial system as a whole or to specific financial institutions (Battiston et al (2017)), and to different asset classes such as equity, corporate and sovereign bonds (Battiston and Monasterolo (2019)), while capturing second-round effects related to the holding of financial assets.

Another way of estimating indirect exposures is to look at production networks, as suggested by Cahen-Fourot et al (2019a,b). Using input-output tables for 10 European economies and based on the monetary value of productive capital stocks (Cahen-Fourot et al (2019b)), the authors seek to provide a systemic perspective on how the reduction in production in one sector can cascade to physical stocks supporting the rest of the economic activity through chains of intermediate exchange. That is, as physical inputs stop flowing from one sector to another, more sectors along value chains are also impacted. For instance, the mining and quarrying sector (including the extraction of fossil fuels), although it accounts for a relatively low share of value added, tends to provide crucial inputs for many other downstream economic activities such as construction, electricity and gas, coke and refined petroleum products or land transport; in turn, these sectors are critical for the correct functioning of public administration, machinery and equipment and real estate activities; and so on. In short, stranding an asset in one specific sector can trigger a "cascade of stranded assets" affecting many other sectors of the economy.

While these two approaches bring critical insights into the interconnectedness among sectors and potential transmission channels of transition shocks and could greatly benefit from being combined (see Graph 14), applying them to future scenarios is not without its challenges. Indeed, relying on existing sectoral classifications and interconnections cannot be assumed to serve as a good proxy for future interconnectedness, given the need to change the very productive structures of the economy. In this sense, they are probably more tailored to the conduct of a climate stress test with a relatively short-term horizon (assuming a static portfolio) than as a tool to be used by financial institutions in a dynamic environment.

Natural, physical and financial assets at risk of stranding Graph 14



Source: Campiglio et al (2017).

Regardless of the approach chosen, some critical sources of uncertainty to keep in mind when conducting forward-looking risk assessments concern the ability to predict:

– *The development and diffusion of new technologies*: As new technologies that do not yet exist or are not yet widespread appear and scale up, they may reshape existing market structures in unpredictable ways. For instance, wholesale online distribution would have been unpredictable a few decades ago. With this in mind, it is difficult to predict how a specific firm will perform in a new environment that will be determined not only by its own strategy but also by multiple elements in its value chain;

– *Each firm's market power:* In response to climate regulations, some firms may be able to offset an increase in operating costs through their customers (by increasing final prices) or suppliers (by decreasing purchasing prices), while others may not have this market power. For instance, after the introduction of the EU Emissions Trading Scheme (ETS) in 2005, some electricity generators were able to pass through more than 100% of the cost increase to consumers (UNEP-FI (2019)). Determining each firm's market position and power and its related pass-through capacity in a dynamic environment remains a considerable task. Some methodologies (eg Oliver Wyman) aim to assess firms' ability to withstand a decrease in demand due to possible product substitutions and cost pass-through (based among other things on the estimated price elasticity of demand); others examine the adaptive capacity of firms based on the potential development of low-carbon and emissions abatement technologies (eg Carbone 4; ET Risk).

– *The exposure to liability risks that have not yet arisen:* Existing methodologies focus on physical and transition risks, but liability risks[37] may become increasingly important in the future. A case in point is PG&E (Baker and Roston (2019), Gold (2019)), the owner of California's largest electric utility, which filed for bankruptcy in early 2019 after wildfire victims sued the company for failing to adjust its grid to the risks posed by increasingly drier climate conditions. Several legal actions against energy and oil and gas companies (eg Drugmand (2019)) are also under way, often brought by cities or civil society organisations seeking compensation for climate-related disasters or the non-compliance of their business plans with the Paris Agreement (Mark (2018)). These examples show how in the future, firms may be exposed not only to the physical and transition risks of climate change, but also to legal risks. However, assessing liability risks is a major challenge not only because of their inherent uncertainty (eg predicting which lawsuits will be triggered by future uncertain events) but also because of variations in the legal framework of each jurisdiction. For instance, in some jurisdictions the government acts as reinsurer "of last resort" in the case of natural disasters; in this case the risks end up being borne by the government rather than the firm or insurer.

Overall, the outcomes provided by each methodology are therefore highly sensitive to the ways in which they account for specific scenarios and how they translate them into static or dynamic corporate metrics that take into account the scope 1, 2 and 3 emissions. Although the lack of data is commonly and rightly invoked as a barrier to the development of climate-related risk assessment, it is also important to emphasise that bridging the data gap will not fully "resolve" the sources of uncertainty discussed above.

3.4 From climate-related risk identification to a comprehensive assessment of financial risk

Once a scenario has been translated into specific metrics at the firm or sector level, there remains the challenging task of integrating such an analysis into a financial institution's internal risk management procedures/a supervisor's practices. In this respect, some methodologies provide a scorecard or climate risk rating and estimates of the carbon impact of a portfolio (eg Carbone 4). Other methodologies aim to calculate the specific impact on asset pricing or credit risks, for instance through the concept of climate value-at-risk (climate VaR), which compares a climate disaster scenario to a baseline scenario. For instance, Carbon Delta estimates future cash flows generated by each firm and discounts them to measure current values that can inform credit risk models (eg a Merton model).

Regardless of the method chosen, at least three main methodological challenges should be kept in mind when conducting such an exercise.

First, it is possible for investors to see the long-term risks posed by climate change, while remaining exposed to fossil fuels in the short term (Christophers (2019)), especially if they believe that hard regulations will not be put in place anytime soon. The identification of the risk is one thing; mitigation is entirely another. For instance, Lenton et al (2019) find that the emergency to act is not only a factor of the risk at stake but also the urgency (defined as reaction time to an alert divided by the intervention time left to avoid a bad outcome). In other words, even identifying all the risks (if even possible) would not necessarily suffice to "break the tragedy of the horizon". Accordingly, new approaches to risk such as MinMax rules (Battiston (2019)), where the economic agent takes a decision based on the goal of minimising losses (or future regrets) in a worst case scenario, may be needed. Other approaches to risk management such as real option analyses, adaptation pathways or robust decision analysis are also already used for specific projects such as infrastructure and large industrial projects (Dépoues et al (2019)).

[37] As described by Carney (2015): "the impacts that could arise tomorrow if parties who have suffered loss or damage from the effects of climate change seek compensation from those they hold responsible". It should be noted that in some approaches (eg TCFD (2017)), "legal" risks (which share similar features with liability risks) are captured under physical and/or transition risks.

However, there are no indications that financial institutions would naturally choose this approach (except in specific cases such as project finance), and it is unclear how regulators could promote its use by financial institutions. In other words, the question of how to adjust risk modelling approaches to allow for longer time horizons remains a challenging one (Cleary (2019, p 28)).

Second, it is possible for financial institutions to hedge individually against climate change, without reducing the exposure of the system as a whole as long as system-wide action is not taken. For instance, Kling et al (2018) find that climate-vulnerable countries exhibit a higher cost of debt on average. This means that as markets hedge against climate-related risks by increasing risk premiums, the risk is transferred to other players such as climate-vulnerable sovereigns, which also happen to be poorer countries on average. Carney (2015) had also noted that insurers' rational responses to physical risks can paradoxically trigger new risks: for instance, storm patterns in the Caribbean have left many households unable to get private cover, prompting "mortgage lending to dry up, values to collapse and neighbourhoods to become abandoned" (Carney (2015, p 6)). Another risk may have to do with the development of financial products in response to climate-related risks, such as weather derivatives: these may help individual institutions hedge against specific climate-related risks, but they can also amplify systemic risk (NGFS (2019b, p 14)). In short, reckoning climate-related risks can lead financial institutions to take rational actions that, while hedging them individually from a specific shock, do not hedge against the systemic risks posed by climate change. For central banks, regulators and supervisors, this poses difficult questions, such as the adequate prudential regulation that should be deployed in response.

Third, in order to fully appreciate the potential systemic dimension of "green swan" events or "climate Minsky moments", more work is still needed on how a climate-related asset price shock (eg stranded assets) could trigger other losses within a dynamic financial network, including contagion effects towards non-climate-related sectors. The 2007–08 Great Financial Crisis has shown how a shock in one sector, subprime mortgages, can result in multiple shocks in different regions and sectors with little direct exposure to subprimes (for instance, affecting German Landesbanken and southern Europe's banking systems and sovereign credit risks). In this respect, abrupt shifts in market sentiment related to climate change could affect all players, including those who were hedged against specific climate-related risks (Reynolds (2015)).

These challenges go a long way towards explaining the "cognitive dissonance" (Lepetit (2019)) between the increased acceptance of the materiality of climate-related risks by financial institutions, and the relative weakness of their actions in response. In short, accounting for the multiple transmission channels of climate-related risks across firms, sectors and financial contracts while reflecting a structural change of economic structures remains a task filled with uncertainty. As a result, the question of how much asset values are affected and how much credit ratings should be impacted today in the face of future uncertain events remains unclear for deeper reasons than purely methodological ones. Despite these limitations, scenario-based analysis will remain critical for financial and non-financial firms aiming to increase their chances of adapting to future risks. That is, these methodological obstacles should not be a pretext for inaction, since climate-related risks remain real.

3.5 From climate-related risk to fully embracing climate uncertainty – towards a second "epistemological break"

The previous analyses have highlighted that regardless of the approach taken, the essential step of measuring climate-related risks presents significant methodological challenges related to: (i) the inability of macroeconomic and climate scenarios to holistically capture a large range of climate, social and economic factors; (ii) their translation into corporate metrics within a dynamic economic environment; and (iii) the difficulty of matching the identification of a climate-related risk with the adequate mitigation action. Climate-economic models and forward-looking risk analysis are important and can still be improved, but they will not suffice to provide all the information required to hedge against "green swan" events.

As a result of these limitations, two main avenues of action have been proposed. We argue that they should be pursued in parallel rather than in an exclusive manner. First, central banks and supervisors could explore different approaches that can better account for the uncertain and nonlinear features of climate-related risks. Three particular research avenues (see Box 5 below) consist in: (i) working with non-equilibrium models; (ii) conducting sensitivity analyses; and (iii) conducting case studies focusing on specific risks and/or transmission channels. Nevertheless, the descriptive and normative power of these alternative approaches remain limited by the sources of deep and radical uncertainty related to climate change discussed above. That is, the catalytic power of scenario-based analysis, even when grounded in approaches such as non-equilibrium models, will not be sufficient to guide decision-making towards a low-carbon transition.

As a result of this, the second avenue from the perspective of maintaining system stability consists in "going beyond models" and in developing more holistic approaches that can better embrace the deep or radical uncertainty of climate change as well as the need for system-wide action (Aglietta and Espagne (2016), Barmes (2019), Chenet et al (2019a), Ryan-Collins (2019), Svartzman et al (2019)). The concept of "risk" refers to something that has a calculable probability, whereas uncertainty refers to the possibility of outcomes that do not lend themselves to probability measurement (Knight (2009) [1921], Keynes (1936)), such as "green swan" events. The question of decision-making under deep or radical uncertainty is making a comeback following the 2007–08 Great Financial Crisis (Webb et al (2017)). According to former governor of the Bank of England Mervyn King, embracing radical uncertainty requires people to overcome the belief that "uncertainty can be confined to the mathematical manipulation of known probabilities" (King (2017, p 87)) with alternative and often qualitative strategies aimed at strengthening the resilience and robustness of the system (see also Kay and King (2020)).

As such, a second "epistemological break" is needed to approach the role of central banks, regulators and supervisors in the face of deep or radical uncertainty. This demands a move from an epistemological position of risk management to one that seeks to build the resilience of complex adaptive systems that will be impacted in one way or another by climate change. What should then be the role of central banks, regulators and supervisors in this approach? In the next chapter, we argue that the current efforts aimed at measuring, managing and supervising climate-related risks will only make sense if they take place within an institutional environment involving coordination with monetary and fiscal authorities, as well as broader societal changes such as a more systematic integration of sustainability considerations into financial and economic decision-making.

Box 5: New approaches for forward-looking risk management: non-equilibrium models, sensitivity analysis and case studies

In order to better account for the specific features of climate-related risks (deep uncertainty, nonlinearity, multiple and complex transmission channels within and among transition and physical risks, etc), three complementary research avenues seem particularly promising. They consist in: (i) working with non-equilibrium models; (ii) conducting sensitivity analyses; and (iii) conducting case studies focusing on specific risks and/or transmission channels.

Non-equilibrium models:

Mercure et al (2019) find that "equilibrium" and "non-equilibrium" models tend to yield opposite conclusions regarding the economic impacts of climate policies. Equilibrium models (such as DSGE) remain the most widely used for climate policy, yet their central assumption that prices coordinate the actions of all agents (under constrained optimisation) so as to equilibrate markets for production factors fails to represent transition patterns (including some discussed above) in a consistent manner.

In this context, non-equilibrium models may be better positioned to address three critical features of the transition:

1. Path dependency: in non-equilibrium models, the state of the economy depends on its state in previous time steps. This approach seems particularly aligned with the purpose of scenario analysis, consisting as it does in describing the economy under different possible and diverging circumstances that are dependent on past and present decisions. For instance, it is easier to represent how socio-technical inertia shapes current behaviours, beyond and despite pricing mechanisms.

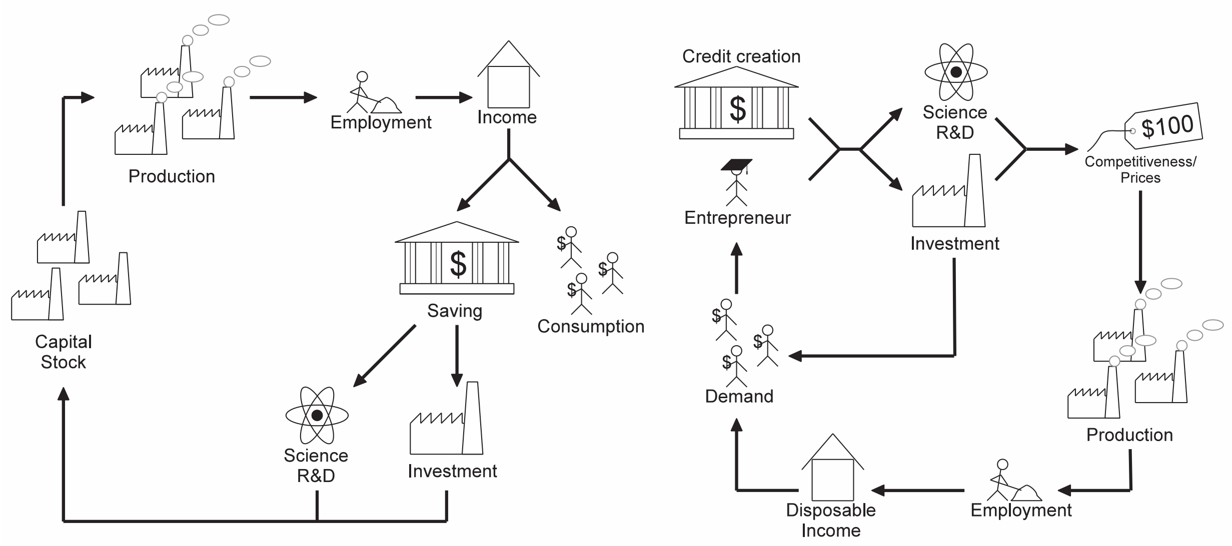
2. Role of money and finance: the need to better account for the dynamics of the financial sector has been widely discussed after the 2007–08 Great Financial Crisis, yet the discussion has only slightly permeated the field of climate economics so far (Mercure et al (2019)). A more central role is often attributed to finance in non-equilibrium models, particularly in the post-Keynesian school of thought through stock-flow consistent models: money is created by banks in response to demand for loans, and therefore investments are not constrained by existing savings (Graph 5.A). This may better represent the behavioural dynamics of financial institutions than DSGE (Dafermos et al (2017)), especially when merged with agent-based models (Monasterolo et al (2019)). For instance, financial institutions can expand lending and investments in times of economic optimism and restrict them when the perceived risk of default is too high, including because of climate-related issues.

3. Role of energy: standard economic theory, based on the cost share of energy in GDP, implies that a decrease in energy use reduces GDP but only to a limited extent. For instance, as energy costs typically represent less than 10% of GDP, a 10% reduction in energy use would lead to a loss in GDP of less than 1% (Batten (2018, p 28)). However, a growing literature suggests that the role of energy in production should not be treated as a third input independently from labour and capital (as in three-factor Cobb-Douglas production functions) but through a different "epistemological perspective" (Keen et al (2019)): energy is an input to labour and capital, without which production becomes impossible (Ayres (2016)). In this view, an improvement in energy efficiency may paradoxically lead (all other things being equal) to a sharp decrease in GDP. Given the critical role of energy for the transition, non-equilibrium models that can account for the peculiar role of energy in economics (Ayres (2016), Keen et al (2019), The Shift Project and IFPEN (2019)) may be critical for future scenario-based analysis.

Alternative models

Graph 5.A

Supply-led / Equilibrium | Demand-led / Non-equilibrium



Source: Mercure et al (2019).

Sensitivity analysis:

Conducting relatively simple scenario-based risk assessments, also called sensitivity analyses, may be another approach to capture some features of climate-related risks, especially transition risks. Sensitivity analyses "represent a fast and easy method for assessing the sensitivity of a portfolio to a given risk" (DG Treasury et al (2017, p 67)) and they do not need to rely on complex scenarios. The methodological difficulties related to scenario-based models "argue in favor of sensitivity analyses that measure the impact of a shock without necessarily incorporating it into a comprehensive scenario" (DG Treasury et al (2017, p 6)).

An example of such sensitivity analysis is ICBC (2016): the bank subjected firms in two sectors of its portfolio, thermal power and cement, to a selection of heavy, medium and light environmental stresses (tighter atmospheric pollution emissions limits for thermal power; tighter atmospheric pollutant emissions and discharges for cement). The test was carried out assuming that all other things remain equal, ie without factoring in the macroeconomic effects of such measures (eg carbon leakage to neighbouring countries). It estimated:

– The impacts of these regulatory shocks on the firms' costs, prices and quantity sold under each scenario;

– How credit ratings would be impacted;

– The possible changes in the firm credit rating and probability of default, and derived the change in the non-performing loan (NPL) ratio.

The recent climate stress test conducted by the UK's Prudential Regulation Authority (PRA (2019a)) takes a similar approach. The PRA translated three broad categories of climate scenarios (sudden and disorderly transition; progressive and orderly transition; no transition) into impacts on the asset side of insurance companies' balance sheets by applying a negative shock to the value of some companies they have in their investment portfolios. For instance, as part of the sudden and disorderly scenario (see Scenario A in Table 5.A), general insurance companies are required to simulate the impact of a valuation shock on their power generation firms (–65% for the coal sector, –35% for oil, –20% for gas, and +10% for renewable energy). Different shocks are applied to several sectors, such as fuel extraction (see below) but also transport, utilities, agriculture and real estate.

The PRA recognises that "the development of hypothetical values affecting investments are based on the interpretation of available literature by the PRA and discussions with specialists in the field" (PRA (2019a, p 50)), including several of the methodologies mentioned above. That is, the valuation shocks correspond to a coherent narrative aimed at signalling potential risks to financial institutions, rather than an attempt at precise modelling of the valuation shock.

Sensitivity analysis

Table 5.A

Sector	% of investment portfolio in following sectors	Assumptions	Transition risk			Physical risk		
			Scenario			Scenario		
			A	B	C	A	B	C
Fuel extraction	Gas/coal/oil (incl crude)	Change in equity value for sections of the investment portfolio comprising material exposure to the energy sector as below						
		Coal	–45%	–40%				
		Oil	–42%	–38%				
		Gas	–25%	–15%				
							–5%	–20%
Power generation		Coal	–65%	–55%				
		Oil	–35%	–30%				
		Gas	–20%	–15%				
		Renewables (incl nuclear)	+10%	+20%				
							–5%	–20%

Source: PRA (2019a).

Case studies:

A third avenue for forward-looking analyses in the presence of climate uncertainty consists in assessing the potential impacts of a climate-related transition or physical shock on one specific sector or region. This can provide a level of analysis that stands in between scenario analysis (which lacks granularity and suffers from many sources of uncertainty) and sensitivity analysis (which lacks a systemic view).

Along these lines, Huxham et al (2019) assess the transition risks for the South African economy in a scenario consistent with temperature rises well below 2°C above pre-industrial levels, by examining potential impacts of a reduction in demand and price of energy sources such as coal (which provides 91% of South African electricity and significantly contributes to the country's export revenues). For instance, infrastructure that supports carbon-intensive activities such as power plants and port infrastructure may have to be replaced or retired early, companies (assessed on an individual basis) and investors could be hurt and could lay off workers, leading to reduced demand for certain products. Governments could face lower tax revenues while also having to deal with increasing expenditures related to industries and workers in transition.

One advantage of such studies is that they can explore the vulnerability of firms and sovereigns to potential economic policies within a limited perimeter, which enables greater transparency regarding the assumptions made and greater detail in the narratives chosen. For instance, the South African case study considers the impact of government policies shifting fiscal incentives from climate-vulnerable sectors to low-carbon activities, and the support from international development finance institutions in this process.

4. POLICY RESPONSES – CENTRAL BANKS AS COORDINATING AGENTS IN THE AGE OF CLIMATE UNCERTAINTY

Rien n'est plus puissant qu'une idée dont l'heure est venue ("There is nothing more powerful than an idea whose time has come").

Attributed to Victor Hugo

Acknowledging the limitations of risk-based approaches and embracing the deep uncertainty at stake suggests that central banks may inevitably be led into uncharted waters in the age of climate change. On the one hand, they cannot resort to simply measuring risks (hoping that this will catalyse sufficient action from all players) and wait for other government agencies to jump into action: this could expose central banks to the real risk that they will not be able to deliver on their mandates of financial and price stability. In the worst case scenario, central banks may have to intervene as climate rescuers of last resort or as some sort of collective insurer for climate damages. For example, a new financial crisis caused by such "green swan" events severely affecting the financial health of the banking and insurance sectors could put central banks under pressure to buy their large set of assets devalued by physical or transition impacts.

But there is a key difference from an ordinary financial crisis, because the accumulation of atmospheric CO_2 beyond certain thresholds can lead to irreversible impacts, meaning that the biophysical causes of the crisis will be difficult if not impossible to undo at a later stage. While banks in financial distress in an ordinary crisis can be resolved, this will be far more difficult in the case of economies that are no longer viable because of climate change. A potential intervention as climate rescuer of last resort would then expose in a painful manner the limited substitutability between financial and natural capital, and therefore affect the credibility of central banks.

On the other hand, central banks cannot succumb to the growing social demand arguing that, given the severity of climate-related risks and the role played by central banks following the 2007–08 Great Financial Crisis, central banks could now substitute for many (if not all) government interventions. For instance, pressures have grown to have central banks engage in different versions of "green quantitative easing" in order to "solve" the complex socioeconomic problems related to a low-carbon transition. However, the proactive use of central bank balance sheets is highly politically controversial and would at the very least require rethinking the role of central banks with a historical perspective. Goodhart (2010) argues that central banks have had changing functional roles throughout history, alternating between price stability, financial stability and support of the State's financing in times of crisis. Central bankers in advanced economies have grounded their actions around the first role (price stability) over the past decades, and increasingly around the second role (financial stability) since the 2007–08 Great Financial Crisis. Proposals concerning "green quantitative easing" could be seen as an attempt to define a third role through a more explicit and active support of green fiscal policy.

Without denying the reality of evolutionary perspectives on central banking (eg Aglietta et al (2016), Goodhart (2010), Johnson (2016), Monnet (2014)) and the fact that climate change could perhaps be the catalyst of new evolutions, the focus on central banks as the main agents of the transition is risky for many reasons, including potential market distortions and the risk of overburdening central banks' existing mandates (Villeroy de Galhau (2019a), Weidmann (2019)). More fundamentally, mandates can evolve but these changes in mandates and institutional arrangements are also very complex issues because they require new sociopolitical equilibria, reputation and credibility. Central bankers are not elected officials and they should not replace or bypass the necessary debates in civil society (Volz (2017)). From a much more pragmatic perspective, mitigating climate change requires a combination of fiscal, industrial and land planning policies (to name just a few) on which central banks have no experience.

To overcome this deadlock, we advocate a third position: without aiming to replace policymakers and other institutions, central banks must also be more proactive in calling for broader and coordinated change, in order to continue fulfilling their own mandates of financial and price stability over longer time horizons than those traditionally considered. The risks posed by climate change offer central banks a special perspective that private players and policymakers cannot necessarily adopt given their respective interests and time horizons. In that context, central banks have an advantage in terms of proposing new policies associated with new actions, in order to contribute to the societal debates that are needed. We believe that they can best contribute to this task in a role that we call the five Cs: **c**ontribute to **c**oordination to **c**ombat **c**limate **c**hange. This coordinating role would require thinking concomitantly within three paradigmatic approaches to climate change and financial stability: the "risk", "time horizon" and "system resilience" approaches (see Table 3).

Embracing deep or radical uncertainty therefore calls for a second "epistemological break" to shift from a management of risks approach to one that seeks to assure the resilience of complex adaptive systems in the face of such uncertainty (Fath et al (2015), Schoon and van der Leeuw (2015)).[38] In this view, the current efforts aimed at measuring, managing and supervising climate-related risks will only make sense if they take place within a much broader evolution involving coordination with monetary and fiscal authorities, as well as broader societal changes such as a better integration of sustainability into financial and economic decision-making.

Importantly, central banks can engage in this debate not by stepping out of their role but precisely with the objective of preserving it. In other words, even though some of the actions required do not fall within the remit of central banks and supervisors, they are of direct interest to them insofar as they can enable them to fulfil their mandates in an era of climate-related uncertainty.

This chapter explores some potential actions that are needed precisely to preserve the mandate and credibility of central banks, regulators and supervisors in the long term. The purpose here is not to provide an optimal policy mix, but rather to contribute to the emerging field of climate and financial stability from the perspective of deep or radical uncertainty. We suggest two broad ranges of measures. First, as detailed in Chapter 4.1, we recall that central banks, supervisors and regulators have a role to play through prudential regulation related to their financial stability mandate. However, while assessing and supervising climate-related risks is essential, it should be part of a much broader political response aimed at eliminating the economy's dependence on carbon-intensive activities, where central banks cannot and should not become the only players to step forward.

We then suggest and critically discuss four non-exhaustive propositions[39] that could contribute to guaranteeing system resilience and therefore financial stability in the face of climate uncertainty: (i) Beyond climate-related risk management, central banks can themselves and through their relationship with their financial sectors proactively promote long-termism by supporting the *values* or *ideals* of sustainable finance in order to "break the tragedy of the horizon" (Chapter 4.2); (ii) Better coordination of fiscal, monetary and prudential and carbon regulations is essential to successfully support an environmental transition, especially at the zero lower bound (Chapter 4.3); (iii) Increased international cooperation on environmental issues among monetary and financial authorities will be essential (Chapter 4.4); (iv) More systematic integration of climate and sustainability dimensions within corporate

[38] This system resilience view holds that: (i) new analytical frameworks are needed to represent the interactions between humans and their natural environment; (ii) these interactions need transdisciplinary approaches (rather than multidisciplinary ones where each discipline continues to adhere to its own views when approaching another discipline requiring a different paradigm); and (iii) open systems are generally not in equilibrium, ie their behaviour is adaptive and dependent upon multiple evolving interactions.

[39] In particular, "command and control" policies are not discussed (given that their implementation tends to depend on specific national and subnational factors), although they also probably have a critical role to play in the transition.

and national accounting frameworks can also help private and public players manage environmental risks (Chapter 4.5). Some potential obstacles related to each proposition are also discussed.

We do not touch on carbon pricing not because we think it is not important. On the contrary, we take it as given that higher and more extensive carbon pricing is an essential part of the policy mix going forward, and that it will become both more politically accepted and more economically efficient if the other measures outlined here are implemented.

The five Cs – contribute to coordination to combat climate change:
The "risk", "time horizon" and "system resilience" approaches

Table 3

Responsibilities / Paradigmatic approach to climate change	Measures to be considered[1] by central banks, regulators and supervisors	Measures to be implemented by other players[2] (government, private sector, civil society)
Identification and management of climate-related risks **>> Focus on risks**	Integration of climate-related risks (given the availability of adequate forward-looking methodologies) into: – Prudential regulation – Financial stability monitoring	– Voluntary disclosure of climate-related risks by the private sector (TCFD) – Mandatory disclosure of climate-related risks and other relevant information (eg French Article 173, taxonomy of "green" and "brown" activities)
Limitations: – Epistemological and methodological obstacles to the development of consistent scenarios at the macroeconomic, sectoral and infra-sectoral levels – Climate-related risks will remain unhedgeable as long as system-wide transformations are not undertaken		
Internalisation of externalities **>> Focus on time horizon**	Promotion of long-termism as a tool to break the tragedy of the horizon, including by: – Integrating ESG into central banks' own portfolios – Exploring the potential impacts of sustainable approaches in the conduct of financial stability policies, when deemed compatible with existing mandates	– Carbon pricing – Systematisation of ESG practices in the private sector
Limitations: – Central banks' isolated actions would be insufficient to reallocate capital at the speed and scale required, and could have unintended consequences – Limits of carbon pricing and of internalisation of externalities in general: not sufficient to reverse existing inertia/generate the necessary structural transformation of the global socioeconomic system		

Structural transformation towards an inclusive and low-carbon global economic system **>> Focus on resilience of complex adaptive systems in the face of uncertainty**	Acknowledgment of deep uncertainty and need for structural change to preserve long-term climate and financial stability, including by exploring: – "Green" monetary-fiscal-prudential coordination at the effective lower bound – The role of non-equilibrium models and qualitative approaches to better capture the complex and uncertain interactions between climate and socioeconomic systems – Potential reforms of the international monetary and financial system, grounded in the concept of climate and financial stability as interconnected public goods	– Green fiscal policy (enabled or facilitated by low interest rates) – Societal debates on the potential need to revisit policy mixes (fiscal-monetary-prudential) given the climate and broader ecological imperatives ahead – Integration of natural capital into national and corporate accounting systems – Integration of climate stability as a public good to be supported by the international monetary and financial system

[1] Considering these measures does not imply full support to their immediate implementation. Nuances and potential limitations are discussed in the book. [2] Measures deemed essential to achieve climate and financial stability, yet which lie beyond the scope of what central banks, regulators and supervisors can do.

Source: Authors' elaboration.

4.1 Integrating climate-related risks into prudential supervision – insights and challenges

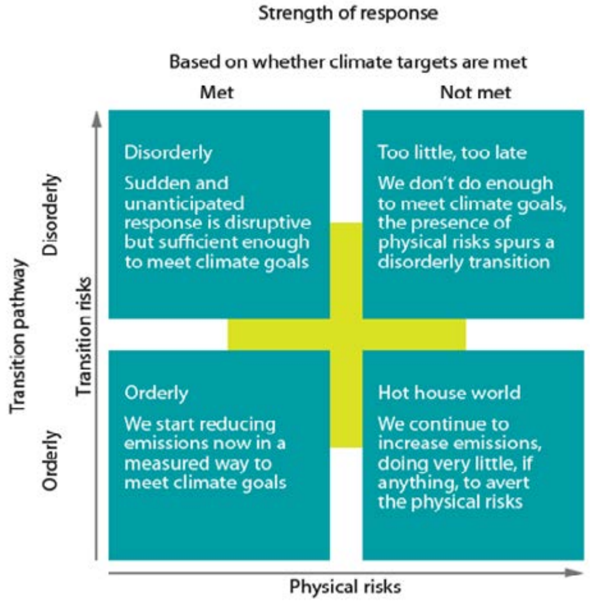
While acknowledging the methodological challenges associated with measuring climate-related risks and the need for alternative approaches (Chapter 3.5), central banks and supervisors should keep pushing for climate-related risks to be integrated into both financial stability monitoring and micro-supervision (NGFS (2019a, p 4)).

The first task, assessing the size of climate-related risks in the financial system, requires developing new analytical tools, for example by integrating climate scenarios into regular stress tests. In the same way that stress tests are conducted by regulatory authorities to assess the resilience of banking institutions in an adverse macro-financial scenario (Borio et al (2014)), proposals have been made over the past years to develop so-called "climate stress-tests" (eg ESRB (2016), Regelink et al (2017), Schoenmaker and Tilburg (2016), UNEP-FI (2019)). Some central banks, regulators and supervisors have already started to consider or develop climate risk scenario analyses for stress tests (Vermeulen et al (2018, 2019), EBA (2019), EIOPA (2019), PRA (2019a), Allen et al (2020)).

In practice, a stress test focusing on the physical risks of climate change (bottom-right scenario in Graph 15), which typically involves projections over several decades, seems particularly difficult to reconcile with the relatively short-term period considered under traditional stress tests (DG Treasury et al (2017, p 19)). In contrast, a climate stress test seems more adapted to manage abrupt transition risks (top-left scenario in Graph 15) that may occur over a relatively short-term horizon compatible with traditional stress tests.

In theory, if climate stress tests find that climate-related risks are material, systemic capital buffers could be applied to mitigate the exposure to climate-related risks (ESRB (2016)). In practice, the main use of these scenarios at this stage is to help financial institutions familiarise themselves with such exercises (Cleary (2019)) and to potentially create catalytic change as well as gaining experience through "learning by doing". A key task for supervisors is to establish a set of reference scenarios that could be used for climate stress tests, while identifying and disclosing the key sources of uncertainty attached to each scenario, as well as leaving flexibility for users to modify the assumptions and parameters of the scenario as deemed appropriate to their national and regional context.

Four representative high-level scenarios for climate stress tests — Graph 15



Source: NGFS (2019a).

The second task for central banks and supervisors consists in ensuring that climate-related risks are well incorporated into individual financial institutions' strategies and risk management procedures. In addition to initiatives based on the voluntary disclosure of climate-related risks such as the Task Force on Climate-related Financial Disclosures (TCFD), it is increasingly accepted that mandatory disclosure should be implemented to strengthen and systematise the integration of climate-related risks. Financial institutions should better understand climate-related risks and consider them in their risk management procedures and investment decisions, as well as in their longer-term strategies (NGFS (2019a)).

Discussions have emerged with regard to how the three pillars of the Basel Framework could integrate climate-related risks:[40]

[40] In the absence of a carbon price, it has also been suggested that the structure of capital of non-financial firms could be adjusted to reflect their exposure to climate-related risks (ESRB (2016), Bolton and Samama (2012)). If both financial institutions and non-financial firms need to align their capital requirements to their exposure to climate-related risks, the cost of capital could increase for non-financial firms and lead financial firms to assess risks differently. However, such an idea would necessitate much more careful analysis and would not necessarily fall under the remit of central banks and supervisors.

– *Pillar 1 on minimum capital requirements:* If being exposed to climate-related risks is seen as part of financial risks, then it might be appropriate to consider capital requirements to reflect such risks. In this respect, proposals have emerged in favour of either a "green supporting factor" (which would reduce capital requirements for banks with lower exposure to climate-related risks) or a "brown penalising factor", which would increase capital requirements for banks with higher exposure to exposed sectors (Thöma and Hilke (2018)). Although additional research is needed, it seems that discussions are evolving towards favouring a "brown penalising factor" as more appropriate. Exposure to "brown" assets can increase financial risks, but it is not obvious why being exposed to "green" sectors would necessarily reduce non-climate-related financial risks, and thereby justify lower capital requirements. In any case, regulations based on distinguishing "green" from "brown" assets require working on an agreed upon "taxonomy", defining which assets can be considered "green" (or "brown" if the goal is to penalise exposure to fossil fuels). China has already established a definition for green loans and the European Commission has tabled a legislative proposal to develop such a taxonomy (NGFS (2019a)). It is noteworthy that such a classification is not exempt from conflicting views over what is "green" (Husson-Traoré (2019)), and that classifications could differ significantly from one country or region to another.[41] Even more fundamentally, it should be recalled that the "greenness" or "brownness" of assets do not necessarily correspond to their vulnerability to climate-related risks. For instance, "green" assets are subject to both transition risks (eg because of the technological and regulatory[42] uncertainty related to the transition) and physical risks (eg a renewable power plant could be impacted by extreme weather events);

– *Pillar 2 on the supervision of institutions' risk management:* Regulators could prescribe additional capital on a case by case basis, *for instance* if a financial institution does not adequately monitor and manage climate-related risks. This would first require new expectations to be set in this regard. For instance, banks and insurers in the United Kingdom are now required to allocate responsibility for identifying and managing climate-related risks to senior management functions (PRA (2019b)). And Brazil's central bank requires commercial banks to incorporate environmental risks into their governance framework (FEBRABAN (2014));

– *Pillar 3 on disclosure requirements:* Supervisory authorities can contribute to improving the pricing of climate-related risks and to a more efficient allocation of capital by requiring more systematised disclosure of climate-related risks. As indicated in the NGFS first comprehensive report, "authorities can set out their expectations when it comes to financial firms' transparency on climate-related issues" (NGFS (2019a, p 27)). For this to happen, guidance is needed to ensure a more systematic, consistent and transparent disclosure of climate-related risks. Some regulators and supervisors have already paved the way for such systematic disclosure. Article 173 of the French Law on Energy Transition for Green Growth (*loi relative à la transition énergétique pour la croissance verte,* 2015) requires financial and non-financial firms to disclose the climate-related risks they are exposed to and how they seek to manage them.[43] In doing so, Article 173 encourages financial sector firms to become increasingly aware of how climate change can affect

[41] For instance, "green coal" or nuclear energy are subject to diverging interpretations from one jurisdiction to another. Moreover, the fact that an activity is deemed "green" does not necessarily mean that it is less risky: as discussed in the previous chapter, the uncertainty regarding future technologies is such that some "green" sectors and technologies may not succeed in the transition. It is therefore important to keep in mind that taxonomies cannot replace or be conflated with a climate-related risk analysis, although the two topics are often discussed together.

[42] For instance, renewable energy capacity can be affected by a change in feed-in tariffs. "Feed-in tariff" refers to a policy instrument offering long-term contracts to renewable energy producers (households or businesses).

[43] Paragraph V of Article 173 requires banks to identify and disclose their climate-related risks and tasks the French government with providing guidance on the implementation of a scenario to conduct climate stress tests on a regular basis; paragraph VI requires institutional investors and asset managers to report on the integration of ESG (environmental, social and governance) criteria and climate-related risks into their investment decision processes (DG Treasury et al (2017)).

their risk management processes and supervising authorities to follow these developments closely (ACPR (2019)). And the European Commission has set up a Technical Expert Group (TEG) on sustainable finance that seeks, among other things, to provide guidance on how to improve corporate disclosure of climate-related risks (UNEP-FI (2019)).

Some developing and emerging economies have already started developing climate-related regulations (see D'Orazio and Popoyan (2019)), although no measures on capital requirements have yet been implemented. Different categories of intervention can be found across developing and emerging economies (Dikau and Ryan-Collins (2017)), such as credit guidance (Bezemer et al (2018)), which reflects the often broader mandate of central banks in these countries. For instance, commercial banks and non-bank financial institutions in Bangladesh are required to allocate 5% of their total loan portfolio to green sectors (Dikau and Ryan-Collins (2017)). Other countries such as China and Lebanon have established (or are in the process establishing) differentiated reserve requirements in proportion to local banks' lending to green sectors (D'Orazio and Popoyan (2019)).

The potential impacts of climate-related prudential regulation remain unclear. Most of the proposals discussed above remain subject to accurately assessing climate-related risks, as discussed in Chapter 3. More fundamentally, the role of prudential policy is to mitigate excessive financial risks on the level of individual financial institutions and the financial system as a whole, not to reconfigure the productive structures of the economy (ESRB (2016)); nevertheless, the latter is precisely what is needed to mitigate climate-related risks. The SME Supporting Factor introduced in the European Union in 2014 (reducing capital requirements for loans to small and medium-sized enterprises) does not seem to have generated major changes in bank lending to SMEs (EBA (2016), Mayordomo and Rodríguez-Moreno (2017)), although it demanded far less structural transformation than decarbonising our global economic system. Hence, adopting climate-related prudential regulations such as additional capital buffers may only very partially contribute to hedging financial institutions from "green swan" events.

Perhaps even more problematically, trade-offs could appear between short-term and long-term financial stability in the case of ambitious transition pathways. As stated by Bank of England Governor Mark Carney (Carney (2016)), the "paradox is that success is failure": extremely rapid and ambitious measures may be the most desirable from the point of view of climate change mitigation, but not from the perspective of financial stability over a short-term horizon. Minimising the occurrence of "green swan" events therefore requires a more holistic approach to climate-related risks, as discussed in the rest of this chapter.

4.2 Promoting sustainability as a tool to break the tragedy of the horizon – the role of values

Beyond approaches based strictly on risks, central banks and supervisors can help disseminate the adoption of so-called environmental, social and governance (ESG) standards in the financial sector, especially among pension funds and other asset managers.[44] The definition of ESG criteria and their integration into investment decisions can vary greatly from one institution to another, but it generally involves structuring a portfolio (of loans, bonds, equities, etc) in a way that aims to deliver a blend of financial, social and environmental benefits (Emerson and Freundlich (2012)). ESG-based asset allocation has grown steadily over the past years, and now funds that consider ESG in one form or another total $30.7 trillion of assets under management.[45]

[44] As stated by the NGFS, central banks and supervisors "may lead by example by integrating sustainable investment criteria into their portfolio management (pension funds, own accounts and foreign reserves), without prejudice to their mandates" (NGFS (2019a, p 28)).

[45] Estimated by the Global Sustainable Investment Alliance (2019).

Some central banks have also started to lead by example by integrating sustainability factors into their own portfolio management. For instance, the Banque de France and Netherlands Central Bank have adopted a Responsible Investment Charter for the management of own funds as well as pension portfolios, and are in the process of integrating ESG criteria into their asset management. Moreover, central banks are increasingly looking at "green" financial instruments as an additional tool for their foreign exchange (FX) reserve management. In a context of a prolonged period of low returns on the traditional safe assets (eg negative yields on a significant portion of government fixed income instruments), the requirements of liquidity, return and sustainability/safety need to be gauged against the properties of these new instruments. The eligibility of green bonds as a reserve asset will depend on several evolving factors such as their outstanding amount (still relatively small) and their risk-return profile. Fender et al (2019) suggest that the results of an illustrative portfolio construction exercise show that including both green and conventional bonds can help generate diversification benefits and hence improve the risk-adjusted returns of traditional government bond portfolios.

This being said, one should not confuse ESG- or green-tilted portfolios with hedging climate-related risks. As a general matter, ESG and green filters consider the impact of a firm on its environment rather than the potential impacts of climate change on the risk profile of the firm (UNEP-FI (2019)). Moreover, the integration of ESG metrics with pure risk-return considerations is far from straightforward. Some studies find that ESG and socially responsible investment (SRI) can enhance financial performance and/or reduce volatility (eg Friede et al (2015)), while others find that divesting from controversial stocks reduces financial performance (eg Trinks and Scholtens (2017)). Revelli and Viviani's (2015) meta-analysis of 85 papers finds that the consideration of sustainability criteria in stock market portfolios "is neither a weakness nor a strength compared with conventional investments", and that results vary considerably depending on the thematic approach or the investment horizon among other factors.

The main benefit of promoting a sustainable finance approach, including through ESG, may actually not lie in the greater impetus for asset managers to reduce their exposure to climate-related risks, but rather in broadening the set of values driving the financial sector. The financial industry has in recent decades mostly focused on financial risks and returns, and has often been criticised for its increased short-termism. By accepting potentially lower financial returns in the short run to ameliorate longer-term social and environmental results, time can be valued in a manner that better corresponds to environmental systems' "own patterns of time sequences for interactions among parts, abilities to absorb inputs, or produce more resources" (Fullwiler (2015, p 14)). This can promote long-termism in the financial sector and thereby contribute to overcoming the "tragedy of the horizon" (and therefore indirectly reduce climate-related risks). As such, the recent rise in the sustainable finance movement may offer "an opportunity to build a more general theory of finance" (Fullwiler (2015)) that would seek to balance risk-return considerations with longer-term social and environmental outcomes.

An additional ambitious and controversial proposal is to apply climate-related considerations to central banks' collateral framework. The goal of this proposal is not that central banks should step out of their traditional role when implementing monetary policies, but rather to recognise that the current implementation of market neutrality, because of its implicit bias in favour of carbon-intensive industries (Matikainen et al (2017), Jourdan and Kalinowski (2019)) could end up affecting central banks' very own mandates in the medium to long term. Honohan (2019) argues that central banks' independence will be more threatened by staying away from greening their interventions than by carefully paying attention to their secondary mandates such as climate change. Thus, and subject to safeguarding the ability to implement monetary policy, a sustainable tilt in the collateral framework could actually contribute to reducing financial risk, ie it would favour market neutrality over a longer time horizon (van Lerven and Ryan-Collins (2017)).

In this spirit, several proposals and initiatives have started to emerge. For instance, Monnin (2018) relies on a specific climate-related risks methodology to measure how the European Central Bank's corporate sector purchase programme (CSPP, which stood at €176 billion as of November 2018) could have differed from the current model if assessment of climate-related risks had been conducted. The study finds that about 5% of the issuers within the ECB's CSPP portfolio would fall out of the investment grade category if climate-related risks were factored in. The author suggests that the ECB could integrate such procedures not only into its unconventional monetary policies but also into its collateral framework. Following a simpler approach for the management of its FX reserves, the Swedish central bank recently decided to reject issuers with a "large climate footprint" (Flodén (2019)), for instance by selling bonds issued by a Canadian province and two Australian states.

Although legal opinions have yet to be issued on this matter, it appears that in many cases central banks already do have a legal mandate for considering the type of assets to use as collateral when implementing monetary policy. For instance, in the case of the Eurosystem the primary responsibility of central banks is to maintain price stability, with a secondary responsibility to support economic growth. In turn, the definition of economic growth by the European Union includes the sustainable development of Europe (Schoenmaker (2019)). The mandates of several central banks other than the ECB also include broader socioeconomic goals than price stability (Dikau and Volz (2019)).

However, the potential impact of such actions is still under debate and needs a cautious approach. It is true that a reweighting of eligible collateral towards low-carbon assets is likely to reduce the credit spread of newly eligible companies (Mésonnier et al (2017)) and to provide a powerful signalling effect to other financial market participants (Braun (2018), Schoenmaker (2019)). Nevertheless, the main challenge in the short run with regard to climate change is not the cost of credit of green projects but their insufficient number in the first place. It is therefore not entirely obvious how large an effect the greening of central banks' collateral framework could have. In fact, the ECB has already bought almost one quarter of the eligible public sector green bonds and one fifth of the eligible corporate green bonds (Cœuré (2018)). This may have already encouraged more issuers to sell green debt (Stubbington and Arnold (2019)), yet central bank monetary operations are clearly insufficient and do not even seek to trigger structural changes in the "real economy". Even if central bank actions could lead to downgrading of the price of carbon-intensive assets that are not compatible with a low-carbon trajectory, only climate policy can ensure that they simply disappear.

Governments could play a much more critical role in supporting sustainable investments. In this respect, it is noteworthy that the European Commission's (2018) action plan on sustainable finance also seeks to mainstream sustainability into investment decisions, and promote "long termism" among financial institutions. Many measures could be taken in this regard. For instance, the French Economic, Social and Environmental Council (ESEC (2019)) recommends that household savings should be channelled towards long-term sustainable investments through fiscal incentives (see also Aussilloux and Espagne (2017)). And Lepetit et al (2019) further recommend offering a public guarantee on all household savings channelled to long-term SRI vehicles (and certified as such). Therefore, even if investments in a low-carbon economy were to provide lower returns and/or returns over a longer time horizon than current market expectations (Grandjean and Martini (2016)), those could then be partially offset by a lower risk for households.

4.3 Coordinating prudential regulation and monetary policy with fiscal policy – Green New Deal and beyond

In addition to promoting sustainable investments, direct government expenditures will also be an opportunity to develop new technologies in a timely fashion and to regulate their use in ways that guarantee lower-carbon production and consumption patterns (eg by avoiding rebound effects in the transportation sector, as discussed above). This is not a reason for central banks not to address climate change; rather, it is a simple observation of the fact that fiscal policies are key to climate change mitigation and that prudential and monetary tools can only complement these policies (Krogstrup and Oman (2019)). Indeed, the public sector is usually in a better position to fund investments in R&D for early-stage technologies with uncertain and long-term returns. In a series of case studies across different sectors (eg nanotech and biotech), Mazzucato (2015) has shown how government investment in high-risk projects has proved essential to create the conditions for private investments to follow.

Sustainable public infrastructure investments are also fundamental as they lock in carbon emissions for a long time (Arezki et al (2016), Krogstrup and Oman (2019)). They can provide alternative means of production and consumption, which would then enable economic agents to change their behaviour more effectively in response to a carbon price (Fay et al (2015), Krogstrup and Oman (2019)). Indeed, carbon prices alone may not suffice to shift individual behaviour and firms' replacement of physical capital towards low-carbon alternatives until infrastructures suited for alternative energies are in place. For instance, building an efficient public transit system may be a precondition to effective taxation of individual car use in urban areas.

It is noteworthy that under this approach, government action would not seek to manage climate-related risks optimally but rather to steer markets "in broadly the right direction" (Ryan-Collins (2019)). In turn, such a proactive shift in policymaking could lead market players to reassess the risks related to climate change. Public investments in the low-carbon transition could "become the next big technological and market opportunity, stimulating and leading private and public investment" (Mazzucato and Perez (2015)), and potentially create millions of jobs that could compensate for those that might be lost due to the changes in labour markets caused by technological progress (Pereira da Silva (2019a)).

In spite of a rapidly growing literature pointing towards better coordination between fiscal, monetary and prudential regulation, arguments regarding the optimal climate policy mix remain scarce. However, and as a general matter, fiscal tools are critical to accelerate the transition, whereas prudential and monetary tools can mostly support and complement them (Krogstrup and Oman (2019)). Public banks may also have an important role to play in providing a significant part of the long-term funding needed for the transition (Aglietta and Espagne (2016), Campiglio (2016), Marois and Güngen (2019)). In this regard, the European Investment Bank (EIB (2019)) announcement that it will cease financing fossil fuel energy projects by the end of 2021 could be a major landmark.

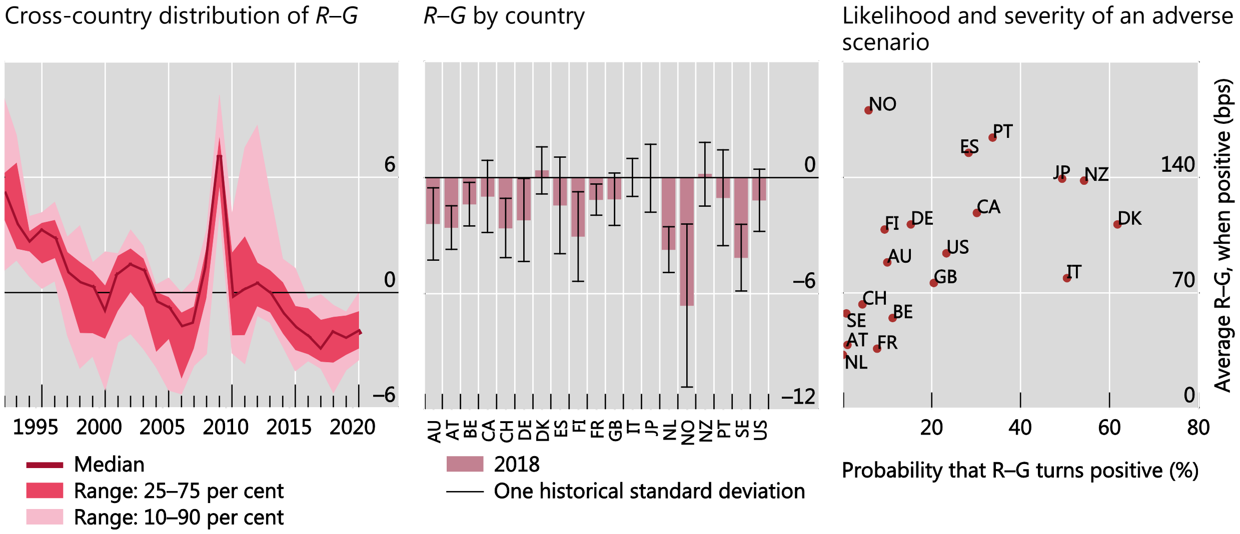
The key question that has arisen with regard to fiscal policy is that of how governments could fund such investments, and what kind of policy mix this could entail. Revisiting the nature of the interactions between fiscal and monetary policy (and prudential regulation) is precisely what has been suggested by some proponents of a Green New Deal in the United States (eg Kelton (2019), Macquarie (2019)), which partly relies on Modern Monetary Theory (MMT), also known as Neo-Chartalism. One key argument of MMT is that currency is a public monopoly for any government, as long as it issues debts in its own currency and maintains floating exchange rates. Following that reasoning, the sovereign could use money creation to achieve full employment (or a climate-related objective) by a straightforward financing of economic activity. The obvious risk of inflation can be addressed subsequently by raising taxes and issuing bonds as the policy goes to remove excess liquidity from the system. A government that by definition issues its own money cannot be forced to default on debt denominated in its own currency. The major underlying assumption is therefore that of "seigniorage without limits": governments can incur deficit spending "without" limits other than those imposed by biophysical scarcity, without automatically generating inflation (Wray (2012)). MMT scholars are generally considered to be outliers in the broader post-Keynesian school, and some of their claims related to the unlimited spending power of governments have been criticised by other post-Keynesian or closely related authors (Lavoie (2013), Palley (2019)). Some of them have suggested more traditional green countercyclical fiscal and monetary policy instead (Harris (2013), Jackson (2017)). Other commentators have pointed out (Summers (2019a), Krugman (since 2011, but more recently 2019)), that MMT poses significant problems. It would undermine the complex set of institutional and contractual arrangements that have maintained price and financial stability in our societies. Moreover, numerous experiments in the history of hyperinflation in advanced economies and mostly in developing countries show that, while outright default in a country's own central bank currency might be avoided, the value of domestic assets including money could be reduced to almost zero.

From a very different perspective, and without sharing the conceptual premises of MMT, several economists have recently argued that financing the low-carbon transition with public debt is both politically more feasible than through carbon taxation and economically more sustainable in the current low interest rate environment, which provides several countries with a larger than previously anticipated fiscal room for manoeuvre (Bernanke (2017), Borio and Song Shin (2019), DeLong and Summers (2012), Blanchard (2019), Summers (2019b)). McCulley and Pozsar (2013) suggest that what matters in times of crisis is not monetary stimulus per se but whether monetary policy helps the fiscal authority maintain stimulus. In this respect, the fact that central banks in advanced economies are globally setting interest rates near or even below zero at a time where massive investments are needed is probably the greatest contribution from central banks to governments' capability to play their role in combating climate change.

As zero or negative interest rates may remain in place for a long period (Turner (2019)), financing the transition to a low-carbon economy via government debt presents fewer risks and would not threaten the mandate of central banks, as long as private and public debt growth continues to be closely monitored and regulated (Adrian and Natalucci (2019)) and there is fiscal space. When it is measured by the cost of servicing debt (*R*) minus the output growth (*G*) rate or (*R* – *G*) to assess the sustainability of debt-to-GDP, there is room in many advanced economies. Over the last 25 years there has been a secular downward trend in government funding costs relative to nominal growth. Graph 16 shows that the difference between government effective funding costs and nominal growth became negative for the median advanced economy around 2013 (left-hand panel) and has since then gone deeper and deeper into negative territory. And, according to the most recent data available (2018), almost all advanced economies now pay an effective interest cost of debt that is below their nominal GDP growth rate. In particular, lower funding costs for the government mean that previously accumulated debts will be cheaper to refinance than previously expected. That is, lower government funding costs mean that the primary balance required to stabilise public debt as a ratio of GDP also falls, down to the point where governments could even run primary deficits while keeping public debt (as a share of GDP) constant.

Government interest burden and snapback risk

In percentage points | Graph 16



Using current government yields. AU = Australia; AT = Austria; BE = Belgium; CA = Canada; CH = Switzerland; DE = Germany; DK = Denmark; ES = Spain; FI = Finland; FR = France; GB = United Kingdom; IT = Italy; JP = Japan; NL = Netherlands; NO = Norway; NZ = New Zealand; PT = Portugal; SE = Sweden; US = United States.

Sources: OECD, *Economic Outlook*; BIS calculations.

Combating climate change and financing the set of policies with public debt could perhaps be the way out of the existing conundrum for policymakers in advanced economies (Pereira da Silva (2019b)): low unemployment coexisting with low inflation for a prolonged period of time despite low interest rates. Reigniting growth through investment in low-carbon technologies is most probably more sustainable from a macroeconomic and environmental perspective than any of the previous consumption-led and household debt-based recoveries (Pereira da Silva (2016)). Some of the investments that could foster productivity in the long run include long overdue infrastructure spending, including in projects that are necessary to develop a low-carbon economy. For example, this type of fiscal stimulus may help create the necessary new science/technology/engineering/maths (STEM) jobs in new green industries, services and infrastructure. These jobs might be able to compensate for the jobs that are very likely to be significantly curtailed by technological progress in the new digital economy. Finally, where fiscal space is available, financing the transition to a lower-carbon economy with public debt could build greater social consensus for eventually accepting carbon taxation.

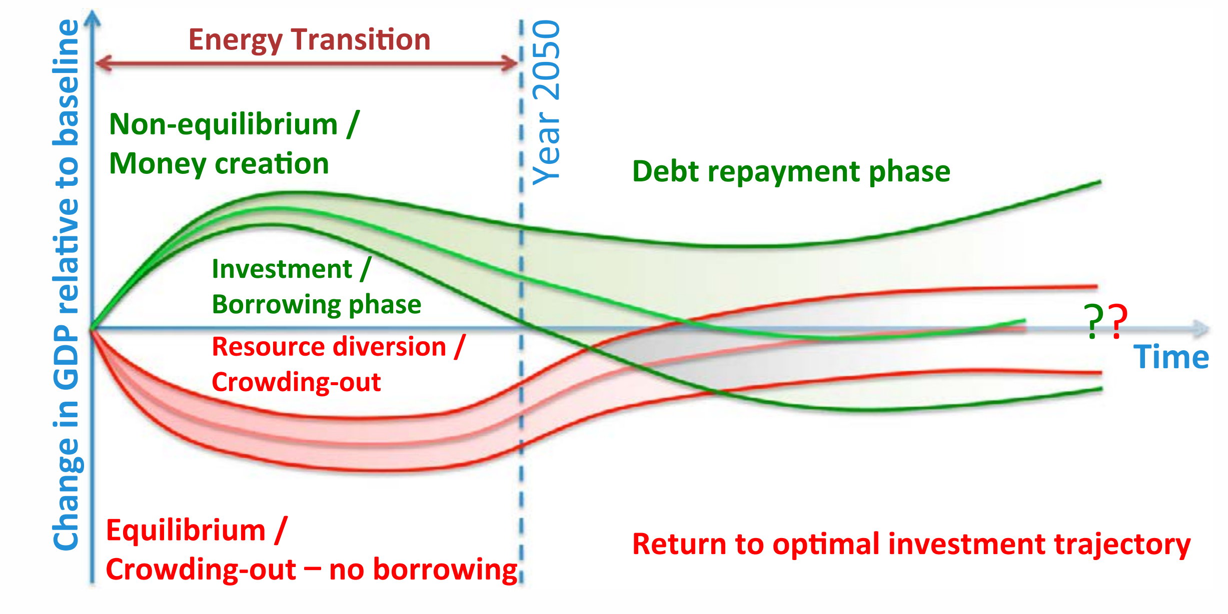
All this should not lead us to consider that there is a "silver bullet" and that the transition to a low-carbon economy can – under current financial circumstances – be easily funded through fiscal policy, as if we had a "free lunch". There could be a risk of a yield snapback. But there are other issues too. In particular, most of the literature calling for fiscal policy action assumes in a more or less explicit manner that it will have a positive impact on economic growth, employment and environmental outcomes, without paying attention to potential technical and institutional limitations and trade-offs between those goals. For instance, the strong reliance of a low-carbon economy on labour-intensive activities may strengthen the "Baumol's cost disease" effect and contribute to slowing down productivity and economic growth (Jackson (2017)). Moreover, the slowdown in productivity gains could be structural (Gordon (2012), Cette et al (2016)) and it is far from clear how the low-carbon transition will reverse it: most of the low-carbon investments needed in advanced economies aim to replace business-as-usual (more carbon-intensive) expected investments, without necessarily creating the conditions for a new boost in productivity. Some have gone further by casting doubt on whether it is even technically possible to decouple economic growth from environmental harm, including but not limited to CO_2 emissions (Jackson (2017), Hickel (2019), Macquarie (2019), OECD (2019b), Parrique et al (2019)).

These potential limitations, in turn, pose major questions for macroeconomic theory, such as estimating the size of the investment multiplier in a low-carbon transition. For instance, an improvement in energy efficiency could lead to a sharp decline in the supply side investments needed for the transition (Grubler et al (2018), in IPCC (2018)), and the latter could paradoxically lead (all other things being equal) to a decrease in GDP, especially if we rely on models where energy plays a critical and non-substitutable role in production (See Box 5 in Chapter 3.5). With this in mind, arguing that public investments will naturally crowd in private investments seems to rely on optimistic (or at least uncertain) assumptions regarding the nature of the transition. Moreover, a "crowding in" effect could paradoxically lead to undesirable (and still poorly accounted for) rebound effects (eg Gillingham et al (2016), Ruzzenenti et al (2019)): savings related to energy efficiency improvements can lead to an increase in the consumption of other fossil-intensive goods and services. In fact, assumptions about crowding out (in supply-led equilibrium models) or crowding in (in demand-led non-equilibrium models) may both (Graph 17) fail to discuss the specific technological, institutional and behavioural assumptions that specific transition paths entail.

These considerations suggest that the low-carbon transition consists in much more than just an investment plan, and that the socio-technical transition needed involves broader considerations than an optimal policy mix, including other ways of measuring system resilience and performance in the context of a low-carbon transition (Fath et al (2015), Ripple et al (2019), Svartzman et al (2019), UNEP (2019)). Without aiming for exhaustiveness, we discuss two of these broader considerations next: potential reforms of the international monetary and financial system in the light of climate considerations and the integration of sustainability into corporate and national accounting.

Impacts of the energy transition on GDP in non-equilibrium (demand-led) vs equilibrium (supply-led) models

Graph 17



Source: Mercure et al (2019).

4.4 Calling for international monetary and financial cooperation

Climate stability is a global public good, which raises difficult questions regarding international policy coordination and burden-sharing between countries at different stages of economic development. Unfair or poorly coordinated international action may simply incentivise some countries to free-ride (Krogstrup and Obstfeld (2018)). Achieving a smooth transition where all countries do their fair share means that a significant compensation mechanism must be agreed upon between developed and developing and emerging economies. As mentioned earlier, these economies need to see that their support for action combating climate change takes into account their stage of industrialisation.

Thus, climate change mitigation actions need to be built on international cooperation between advanced and developing countries (Villeroy de Galhau (2019b)) and recognition of the need for technology transfers and increases in official development assistance to developing countries. So far, developed countries have committed to jointly mobilise $100 billion per year by 2020 for climate action in developing countries (UNFCCC (2015)). But will this commitment be honoured, as current pledges are still far from this amount (OECD (2019c))? And will they suffice to trigger the massive investments needed in developing economies? If not, what are the implications and likely repercussions?

A sober assessment of international cooperation is that there has been uneven progress so far in mitigating climate change. On the one hand, collective action and stated commitments have flourished in multilateral conferences and internationally agreed commitments such as the Paris Agreement (UNFCCC (2015)). For instance, the recently created Coalition of Finance Ministers for Climate Action and the signing of the "Helsinki Principles"[46] could become a critical platform to articulate the need for fiscal policy and the use of public with prudential and monetary action and international coordination. The creation of the Network for Greening the Financial System (NGFS) is another success of such cooperation, possibly in the

[46] See www.cape4financeministry.org/coalition_of_finance_ministers.

very spirit of Bretton Woods (Villeroy de Galhau (2019c)). On the other hand, recent global debates have been dominated by a reaction against multilateralism (BIS (2017)). This mindset obviously does not help in combating climate change and delays collective action on the real problems. For instance, although coal, oil and gas are the central drivers of climate change, they are rarely the subject of ad hoc international climate policy and negotiations (SEI et al (2019)).

Inspiration for overcoming these limitations can be found in the literature on the commons and more precisely in Elinor Ostrom's (1990, 2010) principles for the governance of Common Pool Resources (CPRs). CPRs are "systems that generate finite quantities of resource units so that one person's use subtracts from the quantity of resource units available to others" (Ostrom (2002)). In this sense, the remaining stock of carbon that can be used while still having a fair chance of remaining below 1.5°C or 2°C can be considered as a CPR: burning fossil fuels in one place decreases the carbon budget available to others. One of Ostrom's key insights was to show that the over-exploitation of CPRs is due not so much to the lack of property rights, as often believed (Hardin (1968)), as to the lack of an adequate governance regime regulating the use of CPRs.

Building on Ostrom's insights, which are increasingly being adopted in both the climate and economic communities,[47] central banks along with other stakeholders could implement a governance regime based on CPRs by: (i) further identifying the risks to these resources (eg over-exploitation of the carbon budget); (ii) finding actions that reduce climate-related risks at the global and local levels; and (iii) monitoring these arrangements through the design and enforcement of rules for system stability. This implies coordination, local participation, some sense of fairness in burden-sharing, incentives and penalties, among others.

Given the difficulty of managing global commons (Ostrom et al (1999)), one concrete way of moving towards such a global joint governance of climate and financial stability would be to set up a new international agency (Bolton et al (2018)) that would play a role on two levels with: (i) a financial support mechanism between countries in case of severe climate events; and (ii) supervision of the climate policies being put in place. The theoretical justification of such an agency lies in the fact that, similarly to the creation of an international institutional framework after World War II to face the major global challenges of the time (such as postwar reconstruction), there is now a need for ad hoc institutions to tackle the new global challenges posed by climate change. In a similar spirit, Rogoff (2019) calls for the creation of a World Carbon Bank, which would constitute a vehicle for advanced economies to coordinate aid and technical transfers to developing countries.

Rather than creating new ad hoc institutions, other proposals have focused on embedding climate concerns within existing international institutions such as the International Monetary Fund (IMF), as part of their responsibilities to manage the international monetary and financial system. In particular, proposals have been made to issue "green" Special Drawing Rights (SDRs) through the IMF to finance green funds (Aglietta and Coudert (2019), Bredenkamp and Pattillo (2010), Ferron and Morel (2014), Ocampo (2019)). For instance, Aglietta and Coudert (2019, p 9) suggest creating "Trust Funds in which unused SDRs could be invested to finance the guaranteed low-carbon investment program. A more ambitious method consists of SDR loans to national and international public development banks being pledged to finance the national intentions of carbon emission reductions under the Paris Agreement".[48] Scaling up these "commons-based" mechanisms may require a major overhaul of the global governance system; yet they could become essential to build a "green" and multilateral financial system capable of channelling savings from all parts of the world to finance the low-carbon transition (Aglietta and Coudert (2019), Aglietta and Espagne (2018)).

47 The third part of the IPCC (2014) report was dedicated to Elinor Ostrom, who was also awarded the Nobel Memorial Prize in Economic Sciences in 2009.

48 A prerequisite to such a system would be for the IMF to take on the role of a "green" international lender of last resort, by issuing SDRs in exchange for excess reserves held by central banks and governments.

4.5 Integrating sustainability into corporate and national accounting frameworks

Beyond mechanisms aimed at financing the low-carbon transition, the severity of climate and other environmental crises has led a flourishing stream of research to reconsider how to account for economic value in an age of increasing ecological degradation. In particular, accounting standards at the corporate and national levels have increasingly been criticised for their incapacity to value the role of natural capital in supporting economic activity (see Costanza et al (1997)).

The concept of natural capital refers to "the stock of natural ecosystems on Earth including air, land, soil, biodiversity and geological resources … (which) underpins our economy and society by producing value for people, both directly and indirectly" (Natural Capital Coalition[49]). In turn, this stock of natural ecosystems provides a flow of services, called ecosystem services. These consist of provisioning, regulating, cultural and supporting services (Graph 18). For instance, a forest is a component of natural capital; the associated timber (provisioning service), climate regulation (regulating service) and touristic activities (cultural service) are examples of the ecosystem services it provides; and the forest nutrient cycle is a supporting service that enables all of the above.

Ecosystem services – an overview

Graph 18

Source: Millennium Ecosystem Assessment (2005).

Natural capital and ecosystem services are essential to economic activity in many forms and their degradation (eg soil erosion due to climate change) can have a major impact on human and produced capital (UN Environment (2018)). Important efforts and new frameworks have emerged in the past few years to integrate natural capital into accounting standards at the corporate level and into national accounts, as respectively outlined below.

With regard to corporate accounting, some suggest that a key step in getting companies to achieve a better trade-off between their financial objectives and their environmental and social impact is to transform corporate accounting, ie how companies report their performance to investors (de Cambourg (2019), Rambaud and Richard (2015)). A first encouraging development is the more systematic reporting of carbon emissions by companies under the standardised greenhouse gas protocol.[50] Another

[49] See www.naturalcapitalcoalition.org.

[50] See ghgprotocol.org/.

encouraging development is the creation of the Task Force on Climate-related Financial Disclosures (TCFD), which (as discussed above) seeks to coordinate and standardise reporting of company exposures to climate-related risks so as to allow investors to better manage their exposures to these risks. A third encouraging development is the rise of the integrated reporting movement (see Eccles et al (2015), UN Environment (2018)), which seeks to expand standardised accounting statements to include both financial and non-financial performance in a single integrated annual report. A particularly important initiative in this respect is the creation of the Sustainability Accounting Standards Board (SASB),[51] which already proposes standards for the reporting of non-financial ESG metrics.

In order to systematise integrated reporting approaches, regulatory action will be needed to induce or compel companies to systematically report their environmental and social performance according to industry-specific reporting standards. Few examples exist but some exceptions can be found, eg in the case of Article 173 of the French Law on Energy Transition for Green Growth (discussed above) and the recent support from French public authorities for the development of environmental and social reporting (de Cambourg (2019)). More debate will also be needed to streamline the reporting requirements. For instance, a specific question concerns whether natural capital should remain confined to extra-financial considerations or lead to changes in existing accounting norms, such as in the CARE/TDL model (see Rambaud (2015)).

Nevertheless, there is still a long way to go, as the fiduciary duties of CEOs and asset managers must be redefined and firms' non-financial performance metrics put on par with accounting measures of financial performance. An internationally coordinated effort to encourage the adoption of these standards would significantly accelerate the transition towards integrated reporting and/or new ways of accounting for natural capital. Such efforts would benefit central banks and supervisors as standardised accounting measures can allow investors to make relative comparisons across companies' respective exposure to environmental and social risks.

With regard to the integration of natural capital into national accounts, one of the main arguments put forward has to do with the fact that GDP accounts for only a portion of a country's economic performance. It provides no indication of the wealth and resources that support this income. For example, when a country exploits its forests, wood resources are identified in national accounts but other forest-related services, such as the loss in carbon sequestration and air filtration, are completely ignored. Several steps have been made towards better integration of natural capital into national accounts. The Inclusive Wealth Report (UN Environment (2018)) evaluates the capacities and performance of the national economies around the world, based on the acknowledgment that existing statistical systems are geared to measure flows of income and largely miss the fact that these depend upon the health and resilience of capital assets like natural capital. The World Bank Group has also spearheaded a partnership to advance the accounting of natural wealth and ecosystem services.[52]

Better accounting systems for natural capital are necessary to internalise climate externalities, but it should be recognised that the concepts of natural capital and ecosystem services are difficult to define precisely. For instance, pricing and payment mechanisms for ecosystem services can hardly account for the inherent complexity of any given ecosystem (eg all the services provided by a forest) and often lead to trade-offs by valuing a subset of services only, sometimes to the detriment of others (Muradian and Rival (2012)). They can also fail to provide the desired incentives if they are not designed in ways that recognise the complexity of socio-ecological systems (Muradian et al (2013)) and the need to strengthen cooperation in governing the local and global commons (Ostrom (1990, 2010), Ostrom et al (1999)). Hence, rather than envisaging it as an easy solution, accounting for natural capital and its related ecosystem services should constitute but one among a diverse set of potential solutions (Muradian et al (2013)).

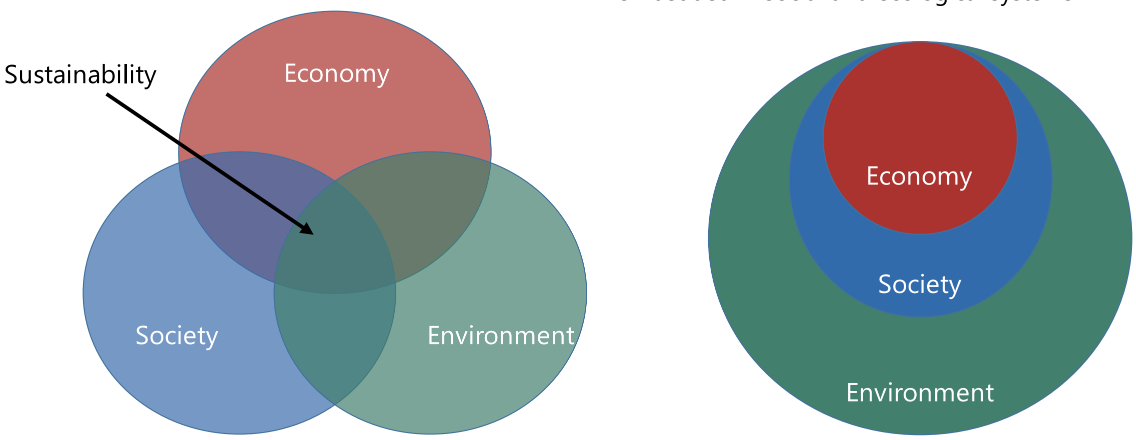
51 See www.sasb.org/.

52 See www.wavespartnership.org/.

Another significant limitation of the concept of natural capital has to do with the common assumption that it is substitutable for other forms of capital (Barker and Mayer (2017)). According to this assumption, what matters is that capital as a whole increase, not which components make up the increase. If, for example, an increase in manufactured capital (eg machines and roads) exceeds the depletion of natural capital, then the conclusion would be that society is better off. This view has been coined the "weak sustainability" approach. In contrast, proponents of an alternative "strong sustainability" argue that the existing stocks of natural capital and the flow of ecosystem services they provide must be maintained because their loss cannot be compensated by an increase in manufactured or human capital (Daly and Farley (2011)). For instance, the depletion of natural capital in a warming world cannot be compensated by higher income. In this view, the economy is embedded in social and biophysical systems (Graph 19, right-hand panel); it is not a separate entity as the traditional approach to sustainable development is framed (Graph 19, left-hand panel).

Two approaches to sustainability | Graph 19

"Weak sustainability" approach | "Strong sustainability" approach – economic system is embedded in social and ecological systems



Source: Authors' elaboration.

Instead of seeking to "internalise" external costs in order to correct market failures, proponents of the "strong sustainability" approach, including ecological economists, suggest "a more fundamental explanation" (OECD (2019b, p 13)) of the dependence of economic systems upon the maintenance of life support ecosystem services (such as climate regulation). Bringing the economic system back within Earth's "sustainability limits" therefore involves much more than marginal changes in the pricing and accounting systems, and could entail re-evaluating the notion of endless economic growth itself (Georgescu-Roegen (1971), Martinez-Alier (1987), Daly and Farley (2011), Jackson (2017), Spash (2017)). Rethinking macroeconomic and financial systems in the light of these considerations is still an underdeveloped area of research in most of the economic discipline, although great progress has been achieved in recent times towards mainstreaming this question (eg OECD (2019b)).

New approaches will be needed in the process of mainstreaming these questions (see Annex 4). In particular, the development of systems analysis has been identified as a promising area of research that should inform economic policies in the search for fair and resilient socio-ecological systems in the 21st century (Schoon and van der Leeuw (2015), OECD (2019a)). In contrast to risk management, a system resilience approach "accepts that transitions to new phases are part of its nature and the system will not return to some previous equilibrium. New normals are normal" (OECD (2019a, p 3)). Greater focus on institutional and evolutionary approaches and on political economy considerations may also be needed

(Gowdy and Erickson (2005), Vatn (2007)), as overcoming the roadblocks to sustainability can be seen as requiring an evolutionary redesign of worldviews, institutions and technologies (Beddoe et al (2009)).

Notwithstanding these important limitations, the ways in which accounting norms incorporate (or not) environmental dimensions remains critical: accounting norms reflect broader worldviews of what is valued in a society (Jourdain (2019)), at both the microeconomic and macroeconomic level. From a financial stability perspective, it therefore remains critical to integrate biophysical indicators into existing accounting frameworks to ensure that policymakers and firm managers systematically include them in their risk management practices over different time horizons.

5. CONCLUSION – CENTRAL BANKING AND SYSTEM RESILIENCE

Mitigating and adapting to climate change while honoring the diversity of humans entails major transformations in the ways our global society functions and interacts with natural ecosystems.

Ripple et al (2019)

Climate change poses an unprecedented challenge to the governance of socioeconomic systems. The potential economic implications of physical and transition risks related to climate change have been debated for decades (not without methodological challenges), yet the financial implications of climate change have been largely ignored.

Over the past few years, central banks, regulators and supervisors have increasingly recognised that climate change is a source of major systemic financial risks. In the absence of well coordinated and ambitious climate policies, there has been a growing awareness of the materiality of physical and transition risks that would affect the stability of the financial sector. Pursuing the current trends could leave central banks in the position of "climate rescuers of last resort", which would become untenable given that there is little that monetary and financial flows can do against the irreversible impacts of climate change. In other words, a new global financial crisis triggered by climate change would render central banks and financial supervisors powerless.

Integrating climate-related risks into prudential regulation and identifying and measuring these risks is not an easy task. Traditional risk management relying on the extrapolation of historical data, despite its relevance for other questions related to financial stability, cannot be used to identify and manage climate-related risks given the deep uncertainty involved. Indeed, climate-related risks present many distinctive features. Physical risks are subject to nonlinearity and uncertainty not only because of climate patterns, but also because of socioeconomic patterns that are triggered by climate ones. Transition risks require including intertwined complex collective action problems and addressing well known political economy considerations at the global and local levels. Transdisciplinary approaches are needed to capture the multiple dimensions (eg geopolitical, cultural, technological and regulatory ones) that should be mobilised to guarantee the transition to a low-carbon socio-technical system.

These features call for an epistemological break (Bachelard (1938)) with regard to financial regulation, ie a redefinition of the problem at stake when it comes to identifying and addressing climate-related risks. Some of this break is already taking place, as financial institutions and supervisors increasingly rely on scenario-based analysis and forward-looking approaches rather than probabilistic ones to assess climate-related risks. This is perhaps compounding a new awareness that is beginning to produce a repricing of climate-related risks. That, in turn, can contribute to tilting preferences towards lower-carbon projects and might therefore act, to some extent, as a "shadow price" for carbon emissions.

While welcoming this development and strongly supporting the need to fill methodological, taxonomy and data gaps, the essential step of identifying and measuring climate-related risks presents significant methodological challenges related to:

(i) The choice of a scenario regarding how technologies, policies, behaviours, geopolitical dynamics, macroeconomic variables and climate patterns will interact in the future, especially given the limitations of climate-economic models.

(ii) The translation of such scenarios into granular corporate metrics in an evolving environment where all firms and value chains will be affected in unpredictable ways.

(iii) The task of matching the identification of a climate-related risk with the adequate mitigation action.

In short, the development and improvement of forward-looking risk assessment and climate-related regulation will be essential, but they will not suffice to preserve financial stability in the age of climate change: the deep uncertainty involved and the need for structural transformation of the global socioeconomic system mean that no single model or scenario can provide sufficient information to private and public decision-makers. A corollary is that the integration of climate-related risks into prudential regulation and (to the extent possible) into monetary policy would not suffice to trigger a shift capable of hedging the whole system again against green swan events.

Because of these limitations, climate change risk management policy could drag central banks into uncharted waters: on the one hand, they cannot simply sit still until other branches of government jump into action; on the other, the precedent of unconventional monetary policies of the past decade (following the 2007–08 Great Financial Crisis), may put strong sociopolitical pressure on central banks to take on new roles like addressing climate change. Such calls are excessive and unfair to the extent that the instruments that central banks and supervisors have at their disposal cannot substitute for the many areas of interventions that are necessary to achieve a global low-carbon transition. But these calls might be voiced regardless, precisely because of the procrastination that has been the dominant modus operandi of many governments for quite a while. The prime responsibility for ensuring a successful low-carbon transition rests with other branches of government, and insufficient action on their part puts central banks at risk of no longer being able to deliver on their mandates of financial (and price) stability.

To address this latter problem, a second epistemological break is needed. There is also a role for central banks to be more proactive in calling for broader change. In this spirit, and grounded in the transdisciplinary approach that is required to address climate change, this book calls for actions beyond central banks that are essential to guarantee financial (and price) stability.

Central banks can also play a role as advocates of broader socioeconomic changes without which their current policies and the maintenance of financial stability will have limited chances of success. Towards this objective, we have identified four (non-exhaustive) propositions beyond carbon pricing:

(i) Central banks can help proactively promote long-termism by supporting the *values* or *ideals* of sustainable finance.

(ii) Central banks can call for an increased role for fiscal policy in support of the ecological transition, especially at the zero lower bound.

(iii) Central banks can increase cooperation on ecological issues among international monetary and financial authorities.

(iv) Central banks can support initiatives promoting greater integration of climate and sustainability dimensions within corporate and national accounting frameworks.

Financial and climate stability are two increasingly interdependent public goods. But, as we enter the Anthropocene (Annex 4), long-term sustainability extends to other human-caused environmental degradations such as biodiversity loss, which could pose new types of financial risks (Schellekens and van Toor (2019)). Alas, it may be even more difficult to address these ecological challenges. For instance, preserving biodiversity (often ranked second in terms of environmental challenges) is a much more complex problem from a financial stability perspective, among other things because it relies on multiple local indicators despite being a global problem (Chenet (2019b)).

The potential ramifications of these environmental risks for financial stability are far beyond the scope of this book. Yet, addressing them could become critical for central banks, regulators and supervisors insofar as the stability of the Earth system is a prerequisite for financial and price stability. In particular, the development of systems analysis has been identified as a promising area of research that should inform economic and financial policies in the search for fair and resilient complex adaptive systems in the 21st century (Schoon and van der Leeuw (2015), OECD (2019a)). Future research based on institutional, evolutionary and political economy approaches may also prove fundamental to address financial stability in the age of climate- and environment-related risks.

Faced with these daunting challenges, a key contribution of central banks and supervisors may simply be to adequately frame the debate. In particular, they can play this role by: (i) providing a scientifically uncompromising picture of the risks ahead, assuming a limited substitutability between natural capital and other forms of capital; (ii) calling for bolder actions from public and private sectors aimed at preserving the resilience of Earth's complex socio-ecological systems; and (iii) contributing, to the extent possible and within the remit of the evolving mandates provided by society, to managing these risks.

6. ANNEXES

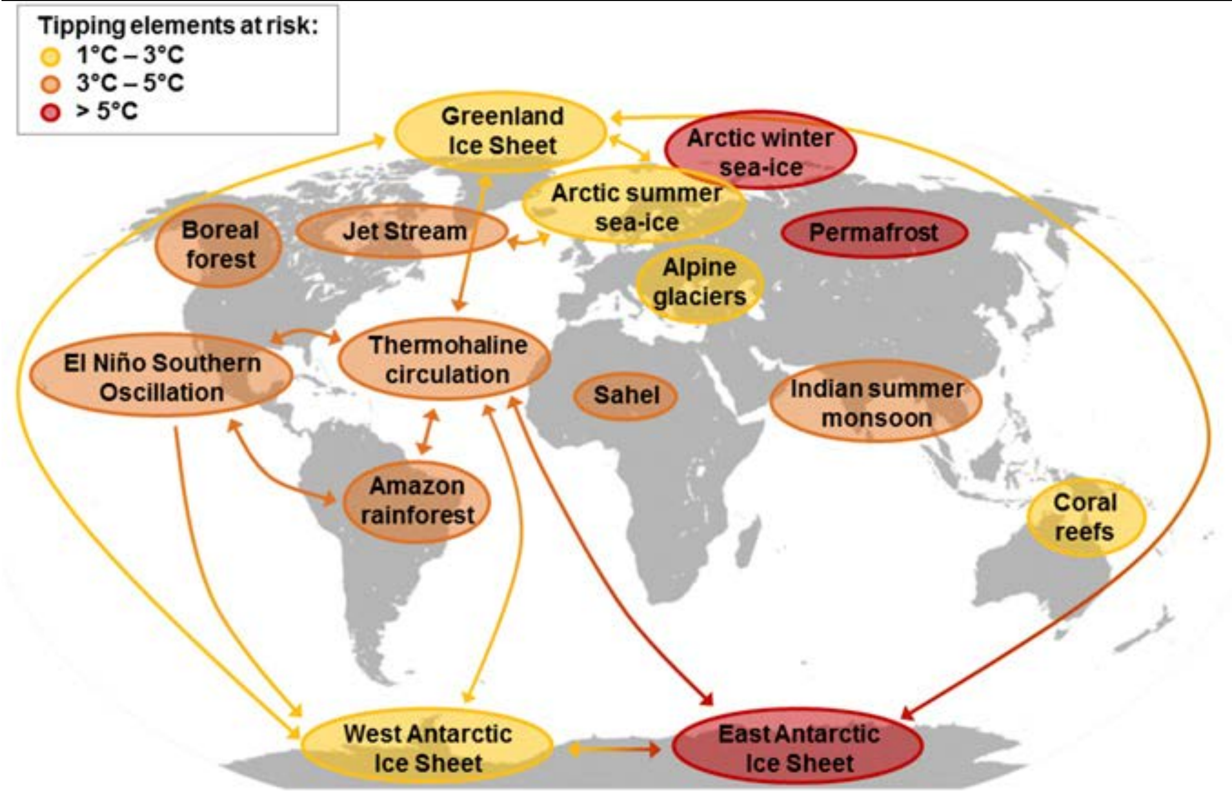
ANNEX 1 – Uncertainties related to physical risks: Earth's climate as a complex, nonlinear system

The Earth's climate system is a complex system, with multiple interacting subsystems that can give rise to so-called emerging properties, which refer to new endogenous collective responses. A fundamental (for the purpose of this book) source of emerging properties tied to climate change is irreversibility, ie changes that persist even when the original forcing (eg amount of atmospheric CO_2) is restored (Schneider (2003)). Moreover, the effects of climate change on the planet are "highly nonlinear, meaning that small changes in one part can lead to much larger changes elsewhere" (Smith (2014)).

Highly nonlinear systems can lead to chaotic dynamics, which are extremely difficult to model with any accuracy and confidence. As global warming continues, we face a situation of deep uncertainty related to the biogeochemical processes that can be triggered by climate change. The *IPCC Special Report on Global Warming of 1.5°C* (IPCC (2018)) indicates that beyond 2°C of global warming, the chances of reaching tipping points (such as a melting of the permafrost) become much more likely, which could in turn trigger multiple chain reactions between different ecosystems.

As shown in the graph below, some potential tipping cascades are more likely to occur if there is global warming of between 1°C and 3°C, whereas others are more likely to occur if global warming exceeds 3°C or 5°C. It is noteworthy that many tipping points may occur even if we manage to keep global warming below 2°C (Steffen et al (2018)). Indeed, climate change models predict significant and robust differences between a 1.5°C and a 2°C world. These include increases in intensity of extreme temperature events in most inhabited areas, with a higher frequency and intensity of heavy precipitation and drought events from one region to another (Masson-Delmotte and Moufouma-Okia (2019)).

Global map of potential tipping cascades Graph A.1



The individual tipping elements are colour-coded according to estimated thresholds in global average surface temperature. Arrows show the potential interactions among the tipping elements based on expert elicitation that could generate cascades.

Sources: Adapted from Steffen et al (2018).

Estimates of when certain tipping point cascades could be triggered are regularly reassessed by the scientific community. For instance, a recent study (Bamber et al (2019)) found that due to accelerated melting in Greenland and Antarctica, global sea levels could rise far more than predicted by most studies so far, potentially leading to other tipping cascades that have not been anticipated. Other studies find that rainforests, which act as a critical climate stabiliser by absorbing and storing CO_2, may be losing their ability to do so faster than expected (eg Fleischer et al (2019)), which could trigger important increases in global warming and other cascades.

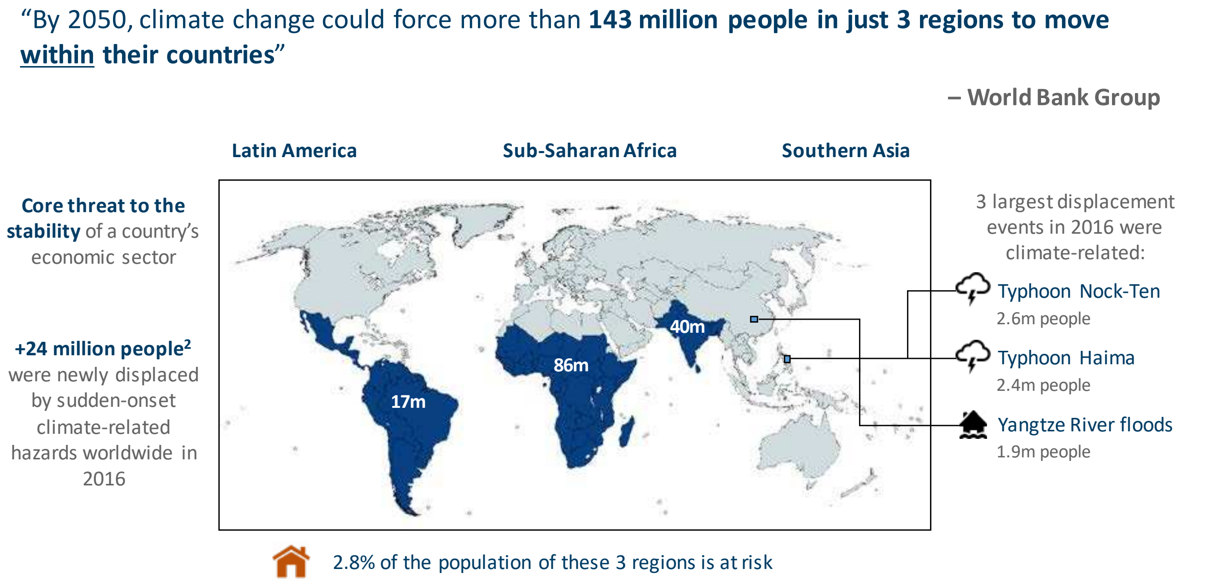
In the light of these challenges, the case has often been made that the damage functions used by IAMs are unable to capture the full uncertainty and complexity of the effects of climate change. In particular, they do not incorporate the high probabilities of extreme risks (or fat-tailed distribution of risks) relative to normal distributions (Calel et al (2015), Thomä and Chenet (2017)), especially those resulting from crossing tipping points that trigger knock-on effects on other biophysical subsystems (Curran et al (2019)). For instance, the DICE model (one of the most famous IAMs) assumes that damages are a quadratic function of temperature change, ie that there are no discontinuities and tipping points (Keen (2019)). This can lead to predictions at odds with all scientific evidence: while DICE modellers find that a 6°C warming in the 22nd century would mean a decline of less than 0.1% per year in GDP for the next 130 years, in practice such a rise in global temperatures could mean extinction for a large part of humanity (Keen (2019)).

The physical impacts of climate change will also lead to complex social dynamics that are not only difficult to predict but also problematic to address from an ethical perspective, especially when it comes to translating them in economic terms. Climate change poses critical intergenerational equity issues as damages will tend to increase throughout time, thereby affecting people who are not yet born. Of particular importance for macroeconomic modelling of climate change is the choice of the discount rate applied to future damages, which are supposed to reflect our current economic valuation of the welfare of these future generations (Heal and Millner (2014)). But finding the "accurate" discount rate of future damages is subject to many interpretations. For instance, Nordhaus (2007) finds an optimal increase in temperatures of 3.4°C by using market-based discount rates. More recently, finance-based studies that take into account the pricing of risk and separate risk aversion from intertemporal substitution (eg Daniel et al (2019)) find lower risk-adjusted discount rates, meaning that immediate and drastic action is needed to avoid physical damages stemming from climate change.

Regardless of the rate of discount chosen, climate-economic models can hardly provide accurate responses to many intergenerational ethical issues posed by climate change. Climate change could lead to an increase in human migrations (see image below), conflicts (Abel et al (2019), Bamber et al (2019), Burke et al (2015b), Kelley et al (2015)) and deaths. For instance, the World Bank (2018) estimates that there could be at least 143 million migrants due to climate change by 2050 (taking into account only South America, Africa and India). These trends could also widen global inequality (Burke et al (2015a), Diffenbaugh and Burke (2019)). Although the top 10% wealthiest individuals generate 45% of greenhouse gas emissions while the 50% least affluent individuals generate 13% of them (Chancel (2017)), climate-related shocks will very likely have adverse consequences concentrated in countries with relatively hot climates, which include most low-income countries (IMF (2017)). A recent report commissioned by the United Nations (Human Rights Council (2019)) estimates that climate change could lead to the reversal of all the progress made in the last 50 years in terms of poverty reduction.

Migration risks of climate change

Environmental changes cause an increasing number of human displacements — Graph A.2



Sources: Adapted from World Bank Group (2018).

While these developments speak for themselves from an ethical perspective, their translation into economic variables is not obvious and can be dangerously misleading. From a mainstream economic perspective, the losses incurred due to climate-related physical impacts in low-income economies could be compensated, eg if economic agents in high-income economies show a strong willingness to pay for adaptation. However, this is at odds with scientific evidence: climate change can lead to irreversible patterns and impacts, which may be only very partially compensated by cash transfers, regardless of their amount.

As a result of these sources of uncertainty, the social cost of carbon (which attempts to quantify in monetary terms the costs and benefits of emitting one additional tonne of CO_2) varies considerably from one model to another (Pindyck (2013)). The selection of parameter values that inform the damage functions as well as the rate of discount rely on arbitrary choices, and IAMs "can be used to obtain almost any result one desires" (Pindyck (2013), p 5). Going further, Lord Nicholas Stern now argues that IAMs are "grossly misleading" (Stern (2016)). Rather than simply rejecting them, we need at least a more nuanced and contextualised support to IAMs (Espagne (2018)).

In any case, addressing climate change adequately requires that we consider it a moral issue (much like avoiding a war or any other major threat to human and non-human lives), not a purely economic one. Assessing these trends merely through discounted individual preferences and/or damage functions, all the more while using cost-benefit analysis, can hardly provide any meaningful insight into what matters most: finding socially fair solutions to guarantee that greenhouse gas atmospheric concentration remains as far as possible from any tipping point. Fighting climate change is therefore a paramount ethical issue that cannot be reduced to a calibration exercise of an IAM.

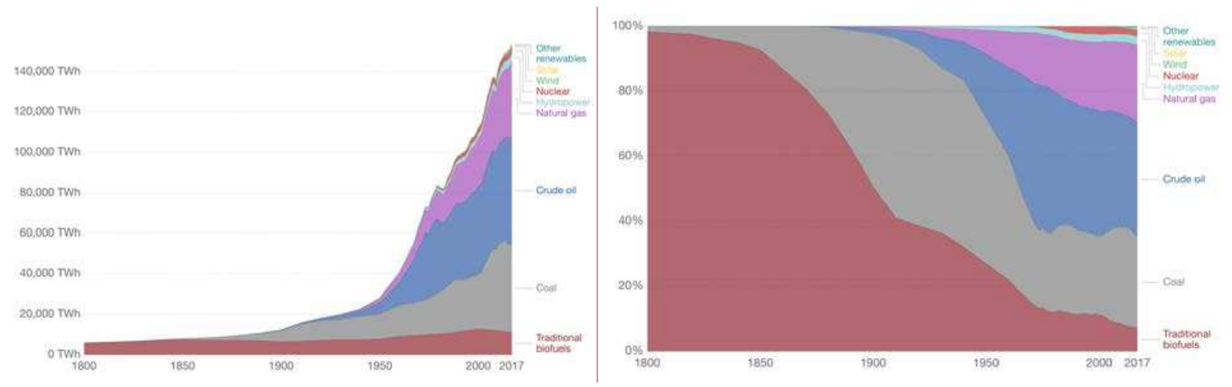
ANNEX 2 – Uncertainties related to transition risks: towards comprehensive approaches to socio-technical transitions

The textbook solution to mitigating climate change is a globally coordinated Pigovian carbon tax that reflects the shadow social cost of carbon emissions. However, as discussed in the Introduction, the prospects for an adequate carbon price as an effective, immediate policy intervention to combat climate change look dim, for the following reasons. First, it is far-fetched to assume that a significant global carbon tax will be implemented in the current political and economic environment, which is sufficient reason in itself to look for other interventions. Second, given the importance of the climate externality ("the greatest market failure ever seen", according to Stern (2007)), estimating the adequate level of a carbon tax and its potential impacts (eg its ability to elicit the desired behaviours and technological breakthroughs without unintended consequences) is a delicate exercise. And third, the decarbonisation paths we need to take may involve such a dramatic shift in the productive structures of the global economic system that climate change may be best understood as more than an externality.

Focusing on the last two points, it is increasingly understood that climate change is a source of structural change in the global economy (NGFS (2019a)). Mitigating climate change in order to avoid its worst physical impacts amounts to nothing less than an unprecedented socioeconomic challenge, requiring the replacement of existing technologies, infrastructure and life habits over a very short time frame. The scale and timing of this required transition has even led some to analyse it in terms of a war mobilisation or rapid urbanisation, rather than the typical transformation of modern economies (Stiglitz (2019)).

In support of the view that a low-carbon transition involves much more than just pricing mechanisms, the history of energy (eg Bonneuil and Fressoz (2016), Global Energy Assessment (2012), Pearson and Foxon (2012), Smil (2010, 2017a)) indicates that the evolution of primary energy uses is intricately related to deep transformations of human societies and economic systems (Graph A.3, left-hand panel. Today's challenge brings an additional layer of complexity, as it requires not only a reduction in the proportion of fossil fuels in the share of global primary energy (right-hand panel) but also a reduction in absolute terms, something that has never been done up to now: as the left-hand panel shows, the energy history of the past centuries has always involved adding new energy sources to old ones (energy additions), not in transitioning from one to another in absolute terms (energy transition). For instance, the share of biomass decreased from almost 100% to less than 10% of total primary energy use between 1850 and the 21st century, but its use in absolute terms has remained more or less constant.

Evolution of energy systems, in absolute and relative terms | Graph A.3



Global primary energy consumption, measured in terawatt-hours (TWh) per year (left-hand panel) and in percentage by primary energy source (right-hand panel).

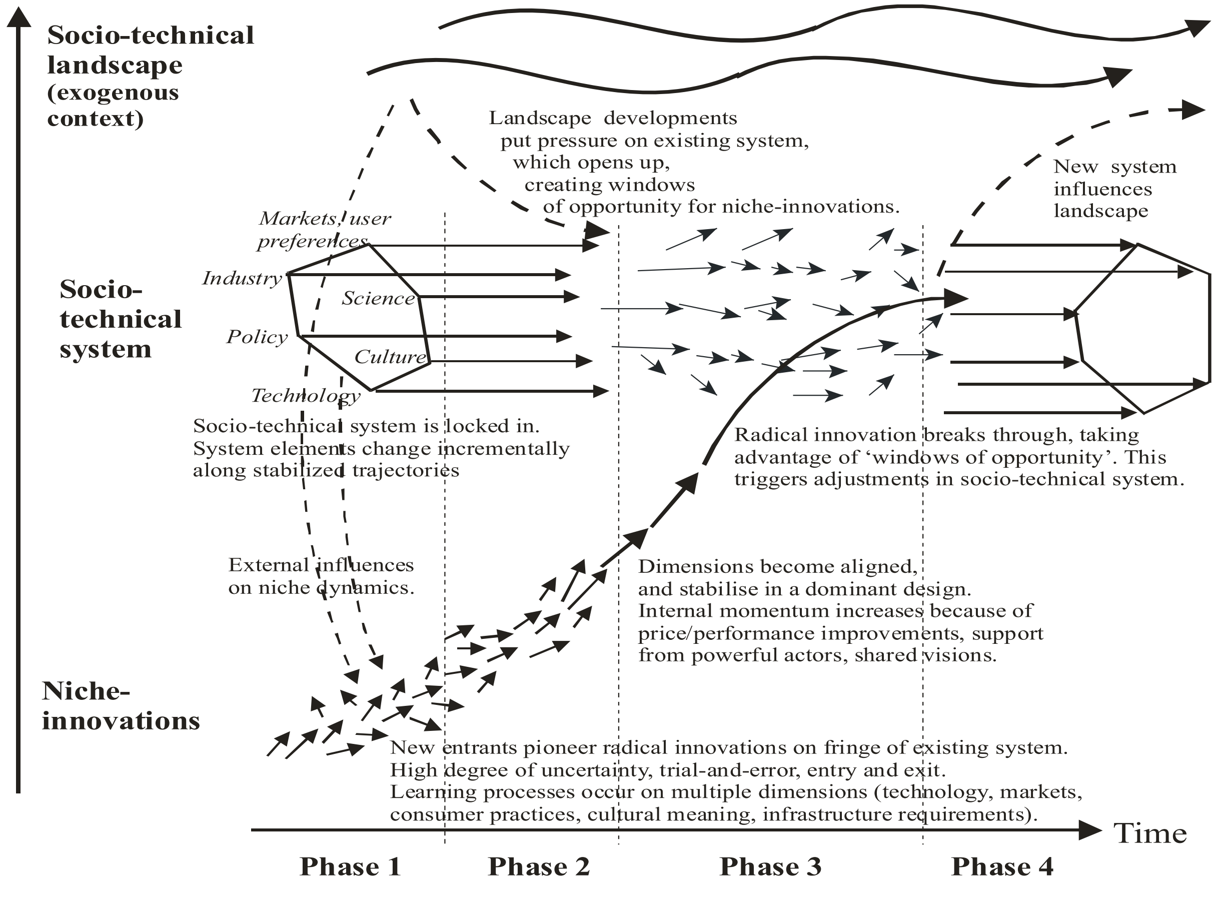
Note: "other renewables" are renewable technologies not including solar, wind, hydropower and traditional biofuels.

Source: Smil (2017b) and BP (2019). Published online at OurWorldInData.org. Retrieved from: https://ourworldindata.org/energy.

Hence, the use of a global, economy-wide carbon price as a proxy for climate policy in IAMs (Carbon Brief (2018)) tends to "not structurally represent many social and political forces that can influence the way the world evolves" (IPCC (2014), p 422). In particular, a low-carbon transition will probably involve a broad range of actions guided not only by cost-benefit calculations and revolving around carbon prices, as put forward by a transdisciplinary group of scholars using the concept of socio-technical transition (Geels et al (2017)). Socio-technical transition scholars are concerned with "understanding the mechanisms through which socio-economic, biological and technological systems adapt to changes in their internal or external environments" (Lawhon and Murphy (2011), p 356–7). Prices surely play a role in these processes, but a far more limited one than in most IAMs.

In the quest for more comprehensive accounts of how transitions may come about, socio-technical systems scholars show that a low-carbon transition could result from complex interactions within and between three levels (Graph A.4): technological niches, socio-technical regime and socio-technical landscape, as respectively discussed below.

Phases of transformations of existing socio-technical systems — Graph A.4

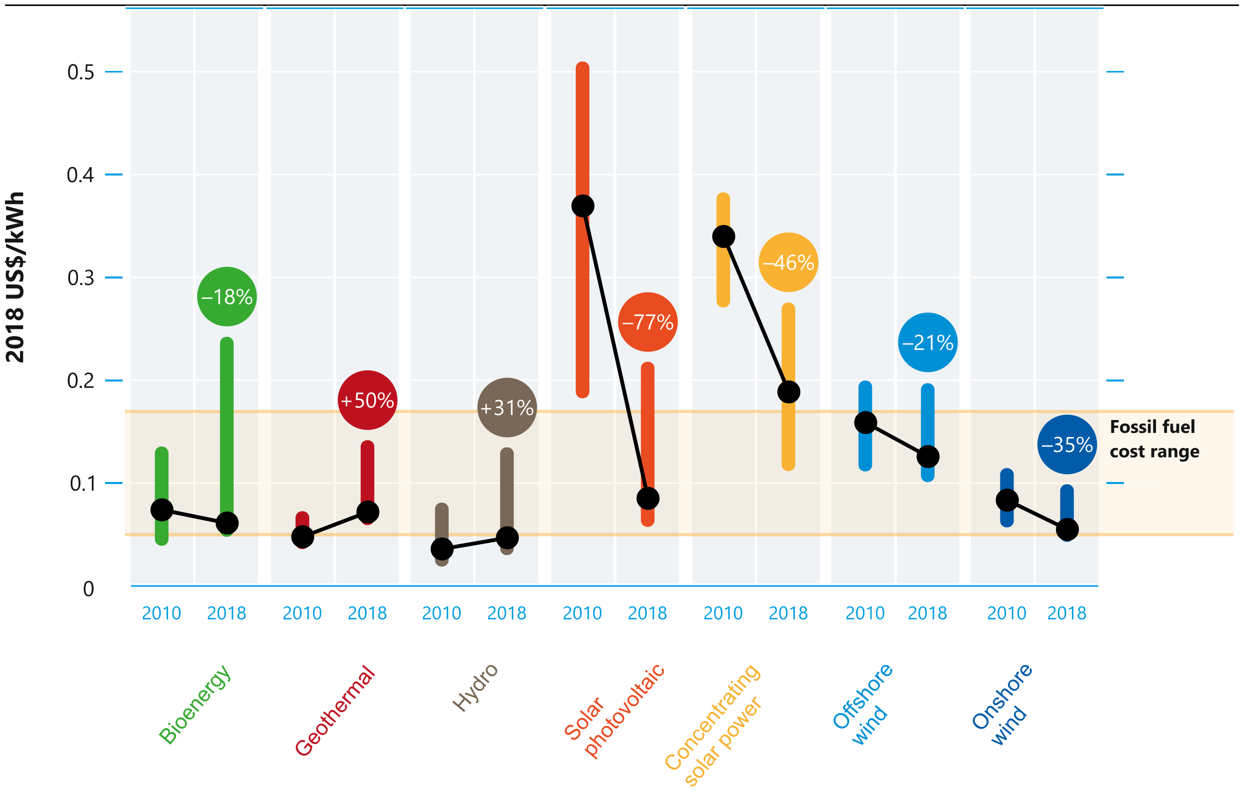


Source: adapted from Geels et al (2017).

First, at the lowest level, niche-innovations are innovations that "differ radically from the prevailing socio-technical system and regime, but are able to gain a foothold in particular applications, geographical areas, or markets" (Geels et al (2017), p 465). In this respect, the path of development of low-carbon technologies is unsurprisingly a key parameter for the transition. Yet it is also a significant source of uncertainty, with both potential barriers and breakthroughs to a rapid and smooth transition. The rapidly declining levelised costs of many renewable energy technologies (Graph A.5) is an example of unpredictable technological development. Moreover, technologies that are still unknown today may emerge and develop much more quickly than usually assumed in IAMs (Curran et al (2019)).

Changes in global levelised cost of energy for key renewable energy technologies, 2010–18

Graph A.5

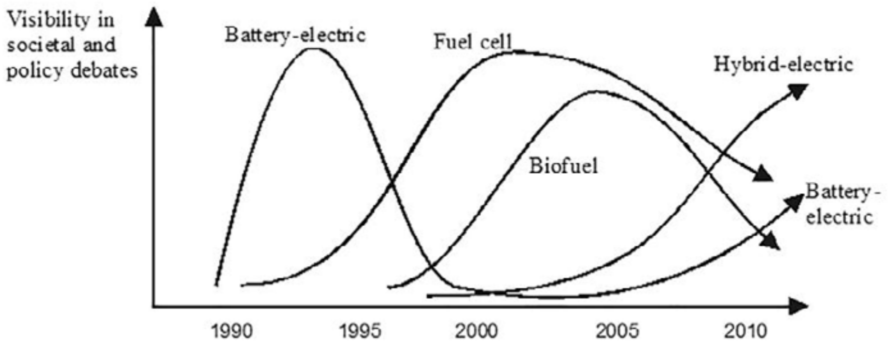


Source: UNEP (2019).

On the other hand, renewable energy is still subject to potential barriers to its development, such as intermittent and unpredictable power output (Moriarty and Honnery (2016)), which requires major improvements in current energy storage technologies (and/or maintaining backup conventional energy capacity). Developing renewable energy capacity may also demand transforming existing land uses, as energy sources such as solar and wind require larger land masses than oil, gas and coal (Smil (2017a)). In addition, the cost of hydropower (the main source of renewable energy so far) could increase because of the physical impacts of climate change (eg increased frequency in droughts could lead to water shortages). In short, many barriers could stand in the way of smooth development of renewable energy capacity.

Modelling technological development paths is a delicate exercise, which can greatly vary over time. For instance, with regard to transportation technologies (Graph A.6), biofuel-powered vehicles were seen as a technological alternative to fossil-powered vehicles more than a decade ago, while today it seems that electric vehicles are a more promising alternative, despite potentially significant limitations with regard to resources and pollution (Pitron (2018)). But these assessments could also be challenged by emerging solutions such as hydrogen (Morris et al (2019)), not represented in the graph below although countries such as China may already be moving towards hydrogen fuel (Li (2019), Xin (2019)). Biofuels could also be discussed again, with the development of third- and fourth-generation biofuels (Aro (2016)) that would not compete with food security in terms of use of land and resources. In short, predicting which technologies will prevail is far from obvious, regardless of the price on carbon. This calls for a very prudent use of IAMs and the technological assumptions informing them, as explained in Chapter 3.2.

Changes in visibility of transportation technologies throughout time — Graph A.6



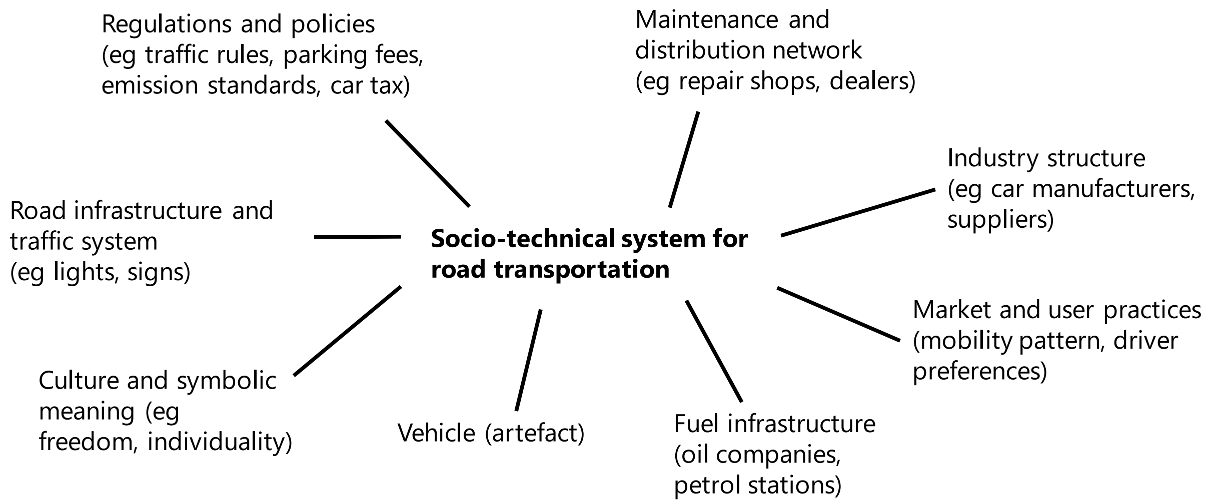
Source: Geels et al (2017).

Second, the middle level of Graph A.4 corresponds to socio-technical regimes, which are "constituted by the conventions, rules, and norms that guide the uses of particular technologies and the everyday practices of the producers, workers, consumers, state agencies, scientists, societal groups, and business people who participate in the regime" (Lawhon and Murphy (2011), p 357). This includes the process leading to the implementation of a carbon price or any other climate-related regulation, eg a feed-in tariff to accelerate the speed of renewable energy capacity installation.

Modelling a realistic transition may require better accounting for many dimensions of the current socio-technical system and the institutional inertia it generates. For instance, reducing the number of individual cars (which may be an important part of the solution along with developing cleaner fuels) is much more difficult once cities and suburbs have been planned on the basis of individual vehicle ownership. Indeed, once car-based transportation systems are institutionalised, they become self-sustaining (Graph A.7) "by formal and informal institutions, such as the preferences and habits of car drivers; the cultural associations of car-based mobility with freedom, modernity, and individual identity; the skills and assumptions of transport planners; and the technical capabilities of car manufacturers, suppliers, and repair shops" (Geels et al (2017), p 465).

Although pricing mechanisms can contribute to addressing these issues, other regulations may be needed, such as rules on the weight of new cars and improved public transportation to limit the amount of personal vehicles (The Shift Project and IFPEN (2019)) and potential rebound effects. Other solutions may not even depend on new technologies but rather on shifting social norms towards the use of already existing technologies (Bihouix (2015)). For instance, the recent "flight shame" movement in Sweden and its negative impact on airline companies (Fabre (2019)) along with positive effects for the national rail operator (Henley (2019)) are responses to the so-called "Greta Thunberg effect" rather than a technological breakthrough.

Socio-technical system of auto-mobility Graph A.7



Source: Adapted from Geels et al (2017).

An additional element of the socio-technical regime has to do with the social acceptability of carbon taxes, which is closely tied to its perceived fairness, and more generally to the fairness of the current wealth distribution. Some argue that designing a carbon tax that varies with household income and between urban and rural areas will be critical to ensure that the worst off households are not disproportionately affected (Bureau et al (2019)). Others argue that the link between carbon pricing and inequalities is even deeper: reducing economic inequalities may be a pre-condition for an effective carbon tax, as it may be easier for a group to collectively reach a consensus on difficult topics (such as burden-sharing efforts for climate mitigation) when inequalities are considered to be within acceptable boundaries in the first place (Chancel (2017)). Alternatively, carbon mitigation efforts may need to focus first on the lifestyles of the wealthiest individuals, since they are the biggest emitters by far (Otto et al (2019)). These considerations suggest that the transformation of an existing socio-technical system requires an even deeper dive into the third level of socio-technical transitions.

Third, the upper level of socio-technical transitions refers to the socio-technical landscape, which considers "the broader contextual developments that influence the socio-technical regime and over which regime actors have little or no influence. Landscape developments comprise both slow-changing trends (e.g., demographics, ideology, spatial structures, geopolitics) and exogenous shocks (e.g., wars, economic crises, major accidents, political upheavals)" (Geels et al (2017), p 465). In particular, complex issues of coordination and well known collective action problems arise when there is a common pool of resources (such as the remaining stock or budget of carbon that can be used) to be administered. In a nutshell, there is a political economy of climate change. That is about who will pay for what, and, inter alia, when and how to share the burden of abatement and transition costs, and how climate-related considerations can be incorporated into practical decision-making processes in a way that is sustainable from a sociopolitical viewpoint.

Historically, advanced economies' emissions were responsible for a larger share of the depletion/consumption of the stock of carbon. They are now enjoying a higher standard of living, while climate change demands us to limit future GHG emissions. Thus, limiting emissions raises obvious issues of fairness in burden-sharing across nations (Millar et al (2017)). How should we respond to developing countries' claims for rights to emissions since they are now beginning to industrialise and thus are increasingly responsible for the new flows? Many textbook solutions (eg taxes and subsidies for carbon pricing and trading, even when adjusted for the respective levels of economic development) might create political economy difficulties and, if so, delay decisions and create inertia. The implementation of the principle of "common but differentiated responsibilities" (UNFCCC (2015)) enshrined in international climate negotiations is still an unresolved conundrum.

If no common but differentiated responsibilities or burden-sharing principles prevail on climate negotiations, ambitious climate action from one country could lead to free-riding behaviours from others and/or to outsourcing production to less stringent jurisdictions, potentially offsetting the gains in one country with an increase in GHG emissions elsewhere. One way of mitigating this would be to link trade agreements to climate change mitigation (Bureau et al (2019), German Council of Economic Experts (2019)). In particular, climate clubs (agreements between groups of countries to introduce harmonised emission reduction efforts and sanction non-participants through low and uniform tariffs on exports to countries in the club) could help limit free-riding behaviour by countries (Krogstrup and Oman (2019)). Yet this could lead to potential tensions between climate progress and gains from trade (Pisani-Ferry (2019)). For instance, as China consumed about 50% of the world's coal in 2018 (BP (2019)) and Asia contains 90% of coal plants built over the past two decades (IEA (2019)), it remains unclear how a rapid phase-out of coal would impact global value chains, and how it could take place without impinging on poorer countries' development path.

In this context, the geopolitical dimension of the socio-technical landscape is critical yet particularly difficult to grasp through climate-economic models. For instance, models aiming to estimate the amount of stranded assets need to make assumptions about which sources of fossil fuels will remain stranded, as discussed in the next chapter. While assuming that fossil fuels that are more expensive to extract will be stranded first makes sense from an economic standpoint (eg Canadian and US unconventional oil in Mercure et al (2018)), it is doubtful that countries sitting on these reserves will resort to exploiting them, at least not if major coordination and compensation schemes are designed at the international level. In this regard, the Yasuni-ITT initiative is a striking example of how difficult it can be to design compensation mechanisms: the Ecuadorian government proposed an innovative scheme in 2007, seeking $3.6 billion in contributions from foreign governments to maintain a moratorium on oil drilling in an Amazon rainforest preserve that is also home to indigenous people. The plan was abandoned in 2013 after actual donations and pledges barely exceeded $100 million (Martin and Scholz (2014), Warnars (2010)).

Still at the geopolitical level, it has been argued that a transition away from fossil fuels could significantly reshape geopolitical patterns. The International Renewable Energy Agency released a recent report (IRENA (2019)) arguing that the rise of renewable energy can affect the balance of power between states, reconfigure trade flows and transform the nature of conflicts, eg with fewer oil-related conflicts but possibly more conflicts related to access to minerals. Handling such transition risks smoothly (ie avoiding a conflict-prone transition) requires an unprecedented level of international cooperation, possibly requiring important international fiscal transfers. One step in this direction is the commitment by developed countries to jointly mobilise $100 billion per year by 2020 for climate change mitigation in developing countries (UNFCCC (2015)). However, this amount will surely fall short of being sufficient and, more importantly, current pledges are still far from this target (OECD (2019c)).

Going further into the assessment of the socio-technical landscape in which the low-carbon transition should take place, another major issue is the increasingly limited capabilities of governments to cope with the climate change challenge and the energy transition. Several disturbing developments in the current economic environment are worth mentioning briefly in this respect:

(i) Governments have not changed the way they operate much since the 1970s (Collier (2018)): they are still chasing a redistribution of growth that is now reduced and they must face widening inequalities, high levels of long-term unemployment and higher levels of debt. The transition to low carbon emissions adds an additional layer of complexity to this, as it is unclear whether climate change mitigation will represent a way out of current low growth rates[53] and therefore boost governments' power or, on the contrary, an additional drag toward the possibility of a secular stagnation (Gordon (2012)), as discussed in Chapter 4. In advanced economies in particular, most investments needed for the transition are expected to replace business-as-usual investments, not come as additional investments. Regardless of the price on carbon, the articulation between monetary, fiscal and prudential policy may be critical (as discussed in Chapter 4) to address these issues while fighting climate change.

(ii) Other major transformations of capitalism may also be worth considering when addressing the question of which strategy is realistically the most adequate to tackle climate change. For instance, the shift since the 1970s in the objectives of corporates with a narrow focus on shareholder value maximisation and the still-prevailing dominance of the efficient market hypothesis (Mazzucato (2015)) may lead to a situation where corporates are structurally unable to fully embrace the old and new responsibilities associated with their growing power. The "continued erosion of workers' bargaining power" (BIS (2019) p 9) is another, related major structural force that should not be forgotten when devising strategies for a socially fair low-carbon transition. Others argue that the evolution to societies driven more by passions than by reason (Dupuy (2013)) and by the pursuit of self-interest at the expense of the common good (Collier (2018)) is particularly disturbing as climate change demands social responsibility of all the players.

As a result, the fight against climate change must take place at a time when the global institutional framework established after World War II and some of the values it officially promotes (such as democracy and multilateralism) are increasingly under pressure. These patterns are significant institutional roadblocks to the low-carbon transition, which requires unprecedented participation and coordination. As Lord Nicholas Stern puts it, "it is intensive public discussion that will […] be the ultimate enforcement mechanism" (Stern (2008), p 33). Or as David Pitt-Watson, the former Chair of the United Nations Environmental Program Finance Initiative (UNEP-FI) elegantly observed: "When it comes to climate change we are all players, we are not spectators" (cited in Andersson et al (2016), p 29). Climate-economic models still have a long way to go to grasp these fundamental international political economy dimensions. In order to embrace these features and the international and national political economy dimensions of a low-carbon transition discussed above, inspiration can be found in Elinor Ostrom's principles for governance of common pool resources (CPRs), as discussed in Chapter 4.

It is noteworthy that the Shared Socioeconomic Pathways (SSPs), a group of five narratives built by an international team of climate scientists, economists and energy systems modellers (Carbon Brief (2018)), aim precisely to capture some of these patterns. SSPs notably provide qualitative narratives describing alternative socioeconomic developments. They suggest, for instance, that a strong pushback against multilateralism would make ambitious climate targets almost impossible to achieve. SSPs still need to be fully coupled with Representative Concentration Pathways (RCPs), which describe different levels of greenhouse gases and other radiative forcings that might occur in the future. In spite of representing a significant step forward, it is unclear how simply considering the narratives put forth by the SSPs could lead climate-economic models to embrace the socio-technical patterns discussed above. It seems that SSPs could be better tailored to alternative analytical approaches and models such as those discussed in Chapter 3.5 (non-equilibrium models, case studies and sensitivity analyses) and in Chapter 4.

[53] Environmental policy can boost innovation, with positive spillover effects leading to increased competitiveness at the national scale (Porter (1991)). For instance, climate change mitigation and adaptation could lead to the creation of millions of jobs in green industries, services and infrastructure, which could even compensate for the jobs threatened by technological progress (Pereira da Silva (2019a)).

ANNEX 3 – Multiple interactions between physical and transition risks

Although physical and transition risks are usually treated separately, these are likely to interact with each other in practice. There could be multiple interactions and feedback loops within and among three subsystems: socio-ecological systems, socioeconomic systems and regulatory systems.[54] These interactions can generate new, complex cascade effects that cannot be captured by physical or transition risks separately. We present some examples below, which do not intend to be exhaustive but rather to exemplify the largely unpredictable patterns that can arise when the uncertain, complex and nonlinear patterns of Earth's systems and human ones are combined.

First, with regard to socio-ecological systems: climate change can have multiple impacts, as detailed in Annex 1. For instance, it can generate water scarcity, which in turn can trigger agricultural losses and cause food insecurity (IPCC (2019)). These knock-on effects, in turn, can feed back into climate patterns, as shown by the recent IPCC report on climate change and land use (IPCC (2019)). For instance, current land exploitation accounts for almost a quarter of GHGs emitted through human activity, but it is also responsible for soil erosion (due to intensive agricultural practices) that end up reducing the soil's ability to absorb carbon; the latter then contributes to accelerating climate change, which will further contribute to land degradation (eg increased rainfall can result in more surface run-off and subsequent losses in organic matter and nutrients (Lugato et al (2018)).

Second, with regard to socioeconomic systems, climate change can have multiple impacts such as increases in deaths due weather extremes (Mora et al (2018)), migrations (World Bank (2018)), inequalities within and between countries (Burke et al (2015a)) and violence and conflicts (Burke et al (2015b)). All these forces can generate emerging properties and chaotic forces such as asset destruction or reduction of economic growth. Conversely, they can trigger societal responses leading to new consumer behaviours and/or more investments in R&D in renewable energy, with potential nonlinear technological breakthroughs (eg utility-scale solar is now cheaper on a lifetime basis than the marginal cost of running nuclear or coal plants).

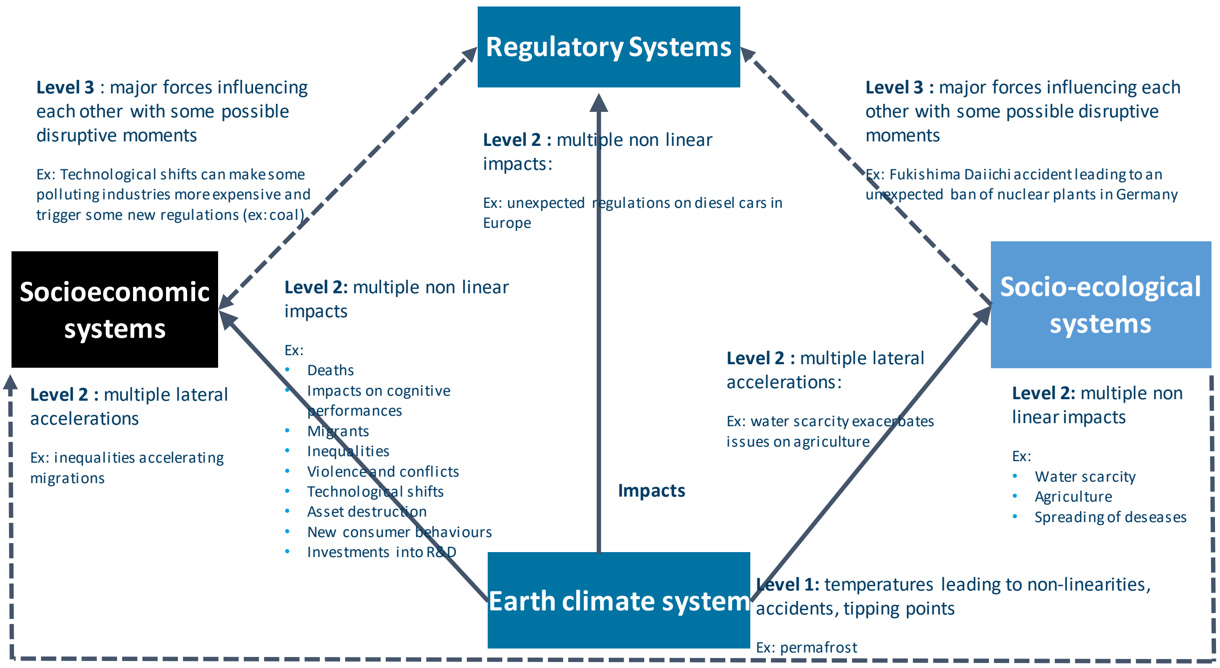
Third, with regard to regulatory and legal systems: climate change has already led to multiple but limited regulatory responses and laws. These can generate positive cascade effects, but they can also put some countries at risk if their economy is mainly based on fossil fuel reserves (McGlade and Ekins (2015)). For diesel cars, for example, the restrictive Corporate Average Fuel Economy (CAFE) regulation requires that EU fleet-wide average emissions be 95 g CO_2/km by 2020. This, in turn, will trigger many chain reactions within the industry; for instance, several large automobile groups are facing heavy potential fines as they are currently unable to meet these stringent new standards.

Lastly, these three subsystems (socio-ecological, socioeconomic and regulatory) interact with each other and generate new chain reactions (Graph A.8). For example, water scarcity could affect some corporates if water is allocated giving priority to basic human needs, or affect humans if it is allocated to corporates based on their ability to pay for it without any equity considerations. Similarly, extreme weather events could have major impacts on socioeconomic systems and lead to unexpected new regulations (such as the Fukushima Daiichi accident leading to an unexpected ban of nuclear plants in Germany). In turn, millennials' mobilisation against climate change (see the numerous climate marches across the world or the eruption of new social movements such as Extinction Rebellion) could increase the pressure on policymakers and lead to new rounds of unpredictable regulatory measures.

[54] We acknowledge that regulatory systems can be considered as part of socioeconomic systems. Nevertheless, we consider them as separate subsystems for the purposes of this annex.

Chain reactions at all levels

Graph A.8



Source: Authors' elaboration.

Box A1. Example of disruptive moment driven by regulation: the automotive industry

Today most changes are driven by consumers and technologies. The automotive industry is experiencing a crucial evolution driven by regulatory constraints and pressure from public opinion: the energy transition.

The Kyoto Protocol adopted by COP 3 in 1997 was the starting point of legally binding reduction targets in GHG emissions. However, the EU target was divided between its member states according to the burden-sharing agreement, while at the sectoral level the automobile sector was considered to not be doing enough to reduce emissions despite sectoral commitments set in 1998 by the ACEA (European Automobile Manufacturer's Association). However, forcing the automotive industry to reduce emissions drove the European Commission to pursue an integrated approach across the EU and pushed auto makers to achieve technological improvements in motor vehicle technology.

An example is the Volkswagen emissions scandal of September 2015, known as Dieselgate. It highlighted the weaknesses of an industry that had not sufficiently addressed the consequences of the technological revolution in relation to the energy transition pushed by regulators. On the financial side, while stock value collapsed, and credit spreads widened, residual value risk increased on captive finance units. This has changed the entire landscape for car makers. Europe has experienced less diesel use while seeing efforts to reduce CO_2 emissions hit by a boom of SUV commercialisation and a shift towards petrol engines. The additional pressure from public opinion and more stringent local regulators with the implementation of a diesel ban and ban on combustion engines in a mid-term horizon also contributed: car manufacturers had to adapt abruptly in order to propose new products and relevant technologies to address the EU's 2021 target of 95 g of CO_2/km.

Nevertheless, demand for electrified cars is still very low while capex and R&D investments remain very high, leading to pressure on company cash flow generation. Thus, uncertainty about the future profitability of electrified vehicles implies margin pressure for car manufacturers in a period of unfavourable timing due to the end of the cycle: more than 300 electric vehicle models are expected to be available on the European market by 2025.

The industry is at a time of change, driven by stronger regulation which will foster industry consolidation, alliance and M&A operations, for example PSA and FCA transactions. A key factor will be the cost of sector transition as operations driven by cost-sharing are increasing (eg the alliance between Ford and Volkswagen on vans and commercial vehicles).

At auto suppliers, the shift towards electric vehicles has led to lower valuations of their historical powertrain businesses and spin-off transactions. New entrants in the industry, like battery producers and mobility providers, will challenge traditional car manufacturers and suppliers by competing on multiple fronts, increasing the complexity of an already competitive landscape.

ANNEX 4 – From climate-related risk management to a systems view of resilience for the Anthropocene

Fighting climate change is paramount to preserve financial stability, but it should not be forgotten that climate change is only the "tip of the iceberg" (Steffen et al (2011)). Other biogeochemical cycles than the carbon cycle that are critical to life on Earth are also being altered, and may present even higher risks than climate change. For instance, the accelerating decline of the Earth's natural life support systems also poses significant risks to human societies (in addition to the ethical problems related to the erosion of non-human forms of life). The UN Global Assessment Report on Biodiversity and Ecosystem Services (IPBES (2019)) found that human activity caused a catastrophic decline in Earth's biodiversity, unprecedented in human history (for instance, the biomass of wild mammals fell by 82% since the pre-industrialisation era, and about a third of reef-building corals is threatened with extinction). Other risks include pressures on freshwater availability and soil erosion, which is becoming a vital stake for humanity according to the United Nations Convention to Combat Desertification (UNCCD).

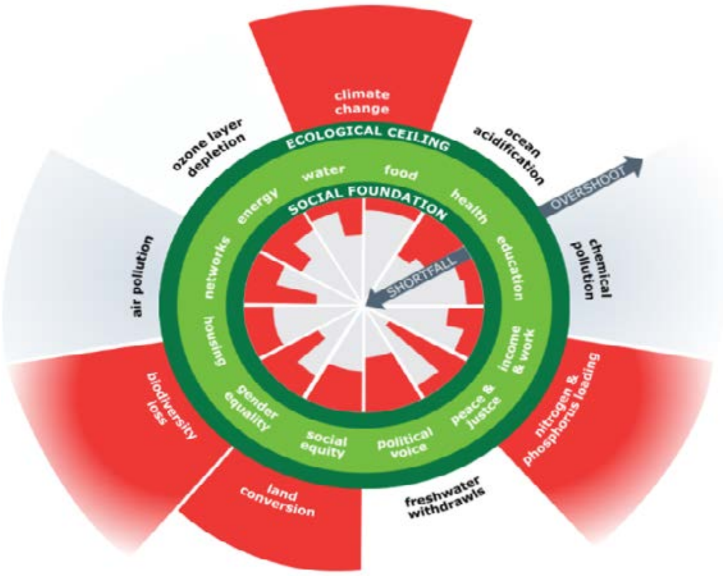
Rockström et al (2009) have identified and quantified nine planetary boundaries, which define the "safe operating space for humanity" associated with the planet's biophysical subsystems or processes. These subsystems are "particularly sensitive around threshold levels of certain key variables. If these thresholds are crossed, then important subsystems, such as a monsoon system, could shift into a new state, often with deleterious or potentially even disastrous consequences for humans" (Rockström et al (2009), p 472).

The dramatic and unprecedented changes in the Earth system caused by human activity have led many to consider that we have entered the Anthropocene,[55] an age in which "human impacts on essential planetary processes have become so profound that they have driven the Earth out of the Holocene epoch in which agriculture, sedentary communities, and eventually, socially and technologically complex human societies developed" (Steffen et al (2018)). In 2017, a group of 15,000 scientists (Ripple et al (2017)) issued a "warning to humanity", reminding that runaway consumption by a growing population in a world of limited resources and waste absorption capacity is now posing an existential threat.

In this context, avoiding the unmanageable risks that may arise if we cross different planetary boundaries requires nothing less than creating a stabilised Earth pathway, which "can only be achieved and maintained by a coordinated, deliberate effort by human societies to manage our relationship with the rest of the Earth System, recognizing that humanity is an integral, interacting component of the system" (Steffen et al (2017)). This requires finding an "environmentally safe and socially just space in which humanity can thrive", between social foundations and ecological ceilings (Raworth (2017); Graph A.9). Ecological ceilings map into nine planetary boundaries set out by Rockström et al (2015), while "the social foundations are derived from internationally agreed minimum social standards, as identified by the world's governments in the Sustainable Development Goals in 2015. Between social and planetary boundaries lies an environmentally safe and socially just space in which humanity can thrive" (Raworth (2017)).

[55] The term Anthropocene is used acknowledging that different societies around the world have contributed differently to pressures on the Earth system, as reminded by different authors critical of the narrative behind this term (eg Malm and Hornborg (2014)).

A comprehensive approach to social foundations and ecological ceilings | Graph A.9



Source: Raworth (2017).

To be sure, such an approach raises difficult questions as to which "planetary stewardship strategies are required to maintain the Earth System in a manageable" state (Steffen et al (2018)), and which set of worldviews, institutions and technologies will be up to the task (Beddoe et al (2009), Vatn (2006)). Moreover, a systems approach would require shifting the focus from handling specific environmental crises (eg climate change) on a case by case basis to a much more holistic view that can better account for the cascading effects of system failure (OECD (2019a)).

It is noteworthy that the IPCC's Shared Socio-Economic Pathways (SSP) implicitly support revisiting GDP growth rates, as part of a broader socio-technical transition touching upon several points discussed in this book: the SSP1 "Sustainability" narrative, corresponding to the road towards a low-carbon world, strongly emphasises international cooperation and education to manage the global commons and the demographic transition, and shifts emphasis from economic growth towards other indicators such as human well-being and reduced inequalities (Carbon Brief (2018)).

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Formerly, he oversaw Corporate Equity Derivatives within Crédit Agricole Corporate Investment Banking in New York and Paris. During his tenure, he developed and implemented the first international leveraged employee share purchase programme, a system now widely used among French companies.

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Financing Infrastructure

SUMMARY

This paper proposes an institutional solution that can help unlock the flow of low yielding long-term savings towards high-return infrastructure investments. The solution is to transform public–private partnerships (PPPs) in infrastructure as well as the classic model of multilateral development banks. Instead of thinking of PPPs as bilateral contracts between a private concession operator and a government agency, we argue that they should be conceived as partnerships that also involve a development bank and long-term institutional investors as partners. We propose a new model for development banks, which is to transform them into originate-and-distribute banks for PPP infrastructure projects. The new model allows them to conserve their valuable capital and leverage their expertise and capabilities by making them available to long-term institutional investors.

JEL codes: H49, H54, G30, G38

—Rabah Arezki, Patrick Bolton, Sanjay Peters, Frédéric Samama and Joseph Stiglitz

Economic Policy April 2017 Printed in Great Britain

From global savings glut to financing infrastructure

Rabah Arezki, Patrick Bolton, Sanjay Peters, Frédéric Samama and Joseph Stiglitz

International Monetary Fund, Columbia University; Columbia University; Amundi Asset Management; Columbia University

1. INTRODUCTION

Several years after the great recession the global economy is in an appalling predicament. The needs and benefits of infrastructure investment have never been greater. At the same time accumulated global savings has? never been higher. They are now so high that we have a global "savings glut," with a larger and larger fraction of

We gratefully acknowledge the support of the Rockefeller Foundation, who hosted a meeting in Bellagio on sustainable investment in infrastructure in May 2014 that provided invaluable background for this paper. We are also grateful to the Editor, Refet S. Gürkaynak, and three anonymous referees for their helpful comments. We also thank Bertrand Badré, Olivier Blanchard, Erik Berglof, Lorenzo Bernasconi, Alex Chirmiciu, Hubert Frédéric, Thierry Déau, Roger Guesnerie, Huang Haizhou, Christopher Knowles, Jin Liqun, Prakash Loungani, Maury Obstfeld, Amadou Sy, Julien Touati, Tunç Uyanik, Waide Warner, David Wood, and the Bellagio workshop participants for many helpful comments. Finally, we are grateful to Timothée Jaulin and Vanessa Diaz Montelongo for excellent research assistance. The views expressed in this paper are those of the authors and do not necessarily reflect the position of the International Monetary Fund or the Crédit Agricole Group.

The Managing Editor in charge of this paper was Refet Gürkaynak.

Economic Policy April 2017 pp. 221–261 Printed in Great Britain

government bonds trading at negative yields. We also appear to be facing a "secular stagnation", with very low forecasted productivity growth. Yet, these problems could be better addressed if there were a way to better channel the trillions of dollars in savings of long-term institutional investors that are currently allocated to low-yielding, fixed-income assets towards infrastructure investments. These investments are known to produce some of the highest gains in productivity and they typically generate very high social rates of return.

This article identifies the main institutional obstacles to the flow of savings towards infrastructure investment and proposes one key institutional fix to unlock the current savings glut and reverse the recent trend of secular stagnation. The solution is to reshape public–private partnerships (PPPs) in infrastructure as well as the classic model of multilateral development banks (MDBs). Traditionally, PPPs have been conceived as bilateral contracts between a private concession operator and a government agency. And the mandate of development banks has been to offer financing to projects that could not attract private funding, but had a high development impact. The new model we propose is to reframe PPPs as partnerships that involve three, or even four partners, with the new partners being a development bank and long-term institutional investors. The new model for development banks would transform them into originate-and-distribute banks for PPP infrastructure projects.

Apart from the major efforts in infrastructure development in China and a few other Asian countries, infrastructure development in most parts of the world has been seriously lagging over the past three decades. The initial hopes that the privatization wave of the 1980s would fuel a private-sector funded greenfield infrastructure investment boom have fallen well short of expectations (see Estache and Fay, 2007; and Iossa and Martimort, 2012). Yet, the economic motivations behind the privatization push were solid. The experience with public sector infrastructure up to the 1980s in low-income countries and advanced economies was one of poor governance, large cost overruns, poor maintenance, and corruption (see Vickers and Yarrow, 1991). Too many infrastructure projects turned out to be white elephants. Moreover, the early evidence of privatization was encouraging: it resulted in greater efficiency, better maintenance, and new sources of funding with the development of PPPs. A total of over 2,700 PPP projects were initiated in developing countries between 1990 and 2003 (see Hammami et al., 2006). However, the most recent evidence clearly points to a relative slowdown in infrastructure development and a leveling of the flow of new PPPs in many parts of the world (see Figures 1 and 2).

While aging infrastructure facilities deteriorate, populations continue to grow, and urbanization trends carry on, so that growing infrastructure needs remain unfulfilled. The plain reality is that the global privatization experiment of the past three decades has held back the supply of new, large-scale infrastructure projects in many parts of the world. Moreover, private sector funding of infrastructure will not be forthcoming in sufficient quantity under the current PPP models to meet the rising global infrastructure demand. Indeed, if the current trajectory of underinvestment continues, it is estimated

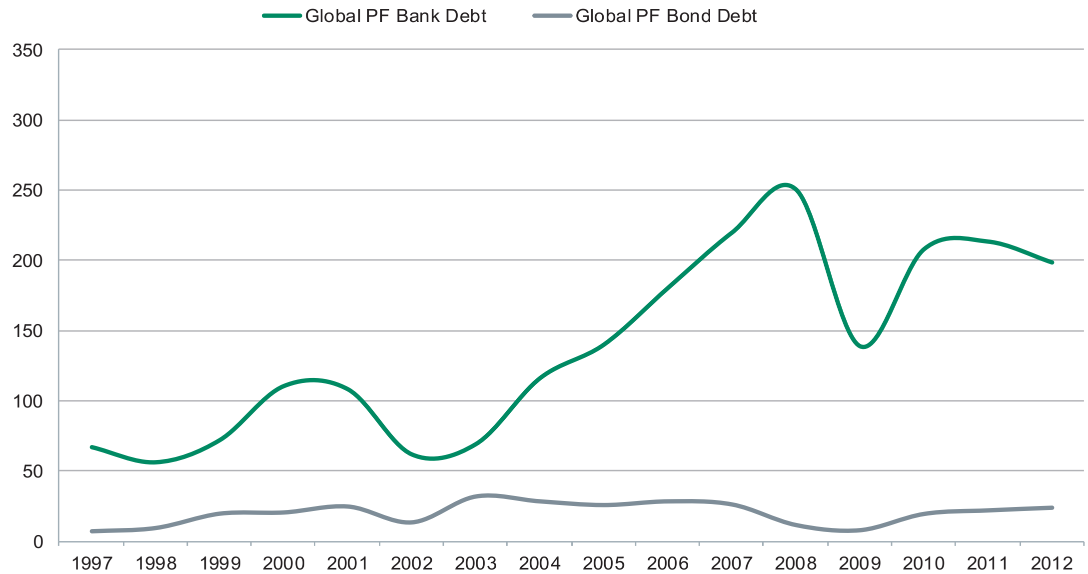

Figure 1. Global project finance volumes. (US $billion).

Source: Allianz (2015).

that global infrastructure investment needs will be around $3.3 trillion per year until 2030 (see McKinsey Global Institute, 2016).[1] In the wake of the global financial crisis of 2007–2009 and the growing urgency of climate change mitigation, the world is at a similar crossroad as 30 years, when the Washington Consensus (Williamson, 1990) emerged as a possible new template for development following the collapse of the central planning development model of previous decades. As then, institutional innovations that can unlock the flow of capital towards infrastructure investment must be envisioned.

Although the challenges are daunting, there are new opportunities for infrastructure development, as the size of the savings of long-term investors [Pension Funds, Insurance Companies, Sovereign Wealth Funds (SWFs)] has never been higher—it is currently estimated to exceed $100 trillion worldwide (City UK, 2013). Moreover, the bulk of these savings is invested in lower and lower yielding fixed income assets (Çelik and Isaksson, 2013). Long-term investors are searching harder than ever for relatively safe, long-term assets that offer a better return than government bonds. Their money would be better invested in longer term global infrastructure assets, where they are likely to face less competition from more short-term oriented investors, and where remarkably, there is also a huge demand for funding. At a time when the world recovery from the financial crisis is still timid and public debt levels remain elevated, the provision of private-sector financing to help replace aging infrastructures in advanced economies and build brand

1 Other studies by the OECD (2012), the World Bank, the International Finance Corporation (IFC), and World Economic Forum (2013) have estimated similar aggregate infrastructure expenditure needs.

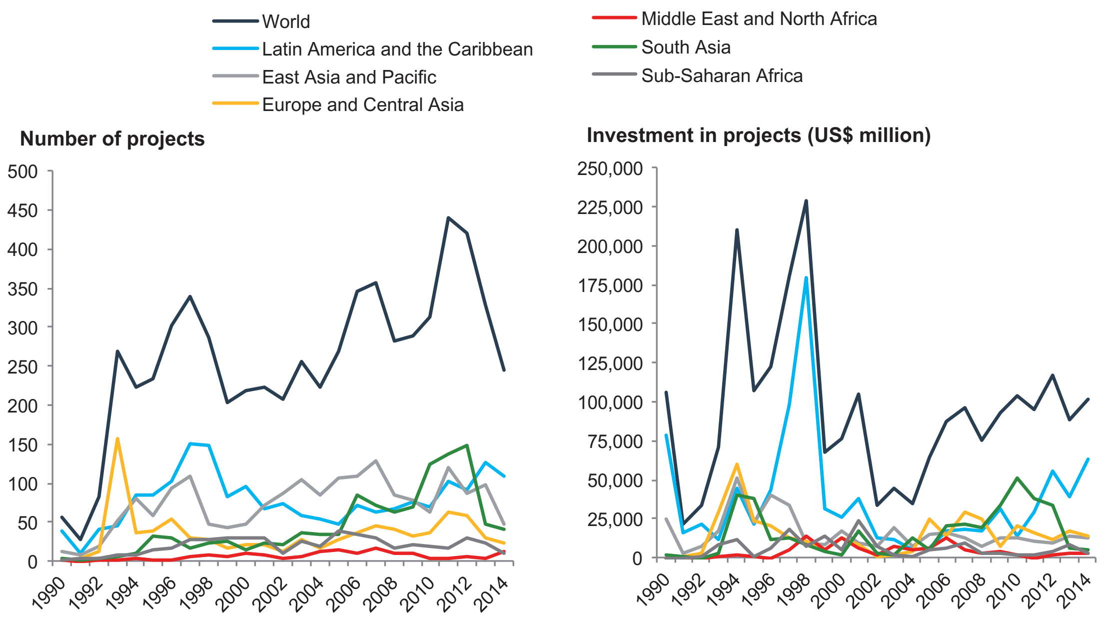

Figure 2. **Evolution of the number of public private partnership projects.**

Source: World Bank Group.

new ones in emerging markets could significantly contribute to reignite economic growth and accelerate the necessary transition to renewable energy.

However, to be able to exploit these funding opportunities, important institutional bottlenecks relating to financing and origination of infrastructure projects must be removed. In this paper, we argue that the institutional innovations of some development banks around infrastructure investment platforms are a promising way forward to circumvent these bottlenecks. Our proposition to reconfigure the MDB model around an originate-and-distribute model of PPP infrastructure investments is the key link between the global macroeconomic opportunities and the micro challenges in developing infrastructure.

There is accumulating evidence that the social rate of return from infrastructure investments amply justifies these investments. For example, Fernald (1999) has found that transportation infrastructure—roads—substantially increases the productivity of industries that make heavy use of road transport, and Donaldson (2016) and Donaldson and Hornbeck (2016) have found substantial social and economic benefits from the creation or expansion of nationwide rail transport networks. There is, of course, the occasional "bridge to nowhere" to be found in every country, but for many observers it is stating the obvious that electrification, sanitation, and transport infrastructure are a *sine qua non* for development. Yet, the risk-adjusted rate of return for investors appears to be so low that far too many valuable infrastructure facilities are not provided.

The matching of demand and supply of funds for infrastructure is hindered by both market and government failures, some of which are well understood, and others, somewhat less so: i) the public good nature of infrastructure projects, with non-excludability and non-rivalry in consumption; ii) the market power of the operator of the infrastructure facilities, and iii) the externalities (positive and negative) through trade, growth, and network spillovers associated with infrastructure investments. Considering that infrastructure projects involve the participation of many agents (construction companies, operators, insurers, government, owners, citizens), a complex chain of tasks (building, maintenance, service delivery), and, inevitably, multiple informational asymmetries regarding quality, costs of service, and ultimate benefits, it is not surprising that major obstacles often lie in their way. Informational asymmetries, in particular, lead to market failures that call for a delicate balancing of public and private interests to ensure incentive compatibility and appropriate risk sharing at the various stages of the infrastructure project, as the vast economics literature on PPPs emphasizes. For instance, a central insight of the economics literature on PPPs is that it is generally incentive-efficient to bundle construction and service-provision together with a single private operator.

Multilateral (and regional) development banks play a fundamental role in reducing both market and government failures. As we shall argue, MDBs play a critical role in helping governments identify and structure infrastructure projects. Given their international governance structure, MDBs are ideally placed to help mitigate political risk. The impact studies MDBs undertake and the strict due diligence standards they impose in the origination of new infrastructure projects are the best guarantees of the sustainability of these projects. In short, MDBs play a critical "gate keeping" role. There is only one problem: MDBs have very limited funds available for infrastructure investment (see Figure 3). This is why, the solution is for MDBs to fundamentally transform their model into an originate-and-distribute model of PPP infrastructure projects that maximize value capture. As such, they can conserve their scarce capital and leverage their gate-keeping capabilities to give access to the vast pools of long-term institutional savings to PPP infrastructure projects.

The remainder of the paper is organized as follows. Section 2 provides the state of play of long-term investment in infrastructure. Section 3 offers a critical review of the experience with and the literature on PPPs. Section 4 discusses the advent of infrastructure investment platforms. Section 5 provides concluding remarks and observations.

2. STATE OF PLAY

This section advances key stylized facts about the current size of savings of long-term investors, their asset allocation, and the global demand for infrastructure investment.

2.1. Investment patterns of long-terms investors

Institutional investors such as pension funds, insurance companies, and mutual funds, and other investors such as SWFs hold around \$100 trillion in assets under management. In 2013, CityUK estimated that pension funds, insurance companies, and mutual funds, respectively, held \$33.9, \$26.5, and \$26.1 trillion in assets under management (see Figure 4). In addition, SWFs and central banks have accumulated savings

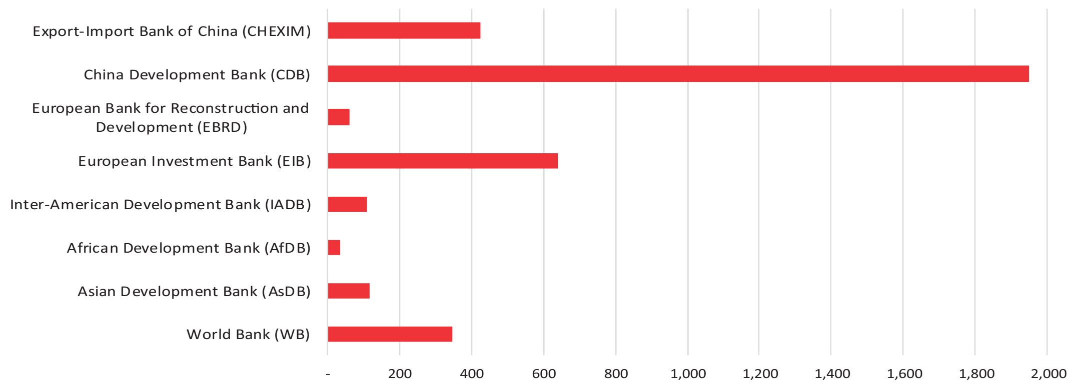

Figure 3. China's national development banks in context. Total asset (US $billion).

Notes: 1. All statements are as of December 31, 2015.

2. Total asset of World Bank is represented by total assets of IBRD. As for exchange rates, 1 AfDB Unit of Account (UA) is equivalent to 1.385730 USD, and for CDB, RMB/USD = 6.4812, as of December 31, 2015.

Sources: Bank annual (financial) reports; and IMF staff calculations. Direct links to the data sources: China CHEXIM: http://english.eximbank.gov.cn/upload/accessory/20168/201682417629732745.zip; China CDB: http://www.cdb.com.cn/English/bgxz/ndbg/ndbg2015/201608/P020160831675498298329.zip; EBRD: http://www.ebrd.com/documents/comms-and-bis/print-financial-report-2015-english-pdf.pdf; EIB: http://www.eib.org/attachments/general/reports/fr2015en.pdf; IADB: https://publications.iadb.org/bitstream/handle/11319/7555/Inter-American-Development-Bank-Annual-Report-2015-Financial-Statements.pdf?sequence=7; AfDB: https://www.afdb.org/fileadmin/uploads/afdb/Documents/Generic-Documents/Annual_Report_2015_EN_-_Full.pdf; AsDB: https://www.adb.org/sites/default/files/institutional-document/182852/adb-financial-report-2015.pdf; WB: https://openknowledge.worldbank.org/bitstream/handle/10986/22550/WBAR2015FinancialStatements.pdf.

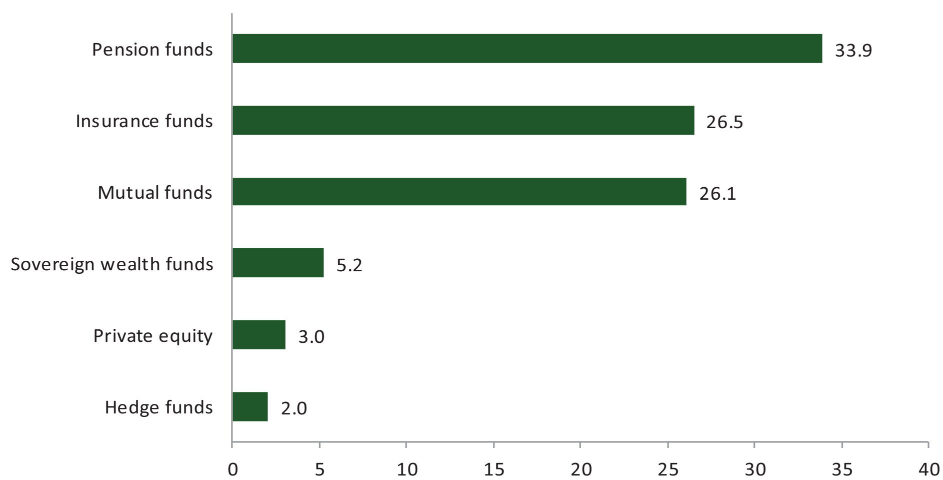

Figure 4. Global assets under management. ($trillion, end-2012).

Source: City UK (2013).

approaching $15 trillion (City UK, 2013). One gets a clearer grasp of the enormous size of this global wealth by, for example, comparing it with US nominal GDP ($18 trillion in 2015:Q3), or to the IMF's new arrangements to borrow ($0.576 trillion in 2013), or even to the total market capitalization of US listed companies ($18.7 trillion in 2012).

According to a recent OECD report (Çelik and Isaksson, 2013), out of $85 trillion held by all institutional investors covered in the report, 38% ($32 trillion) was held

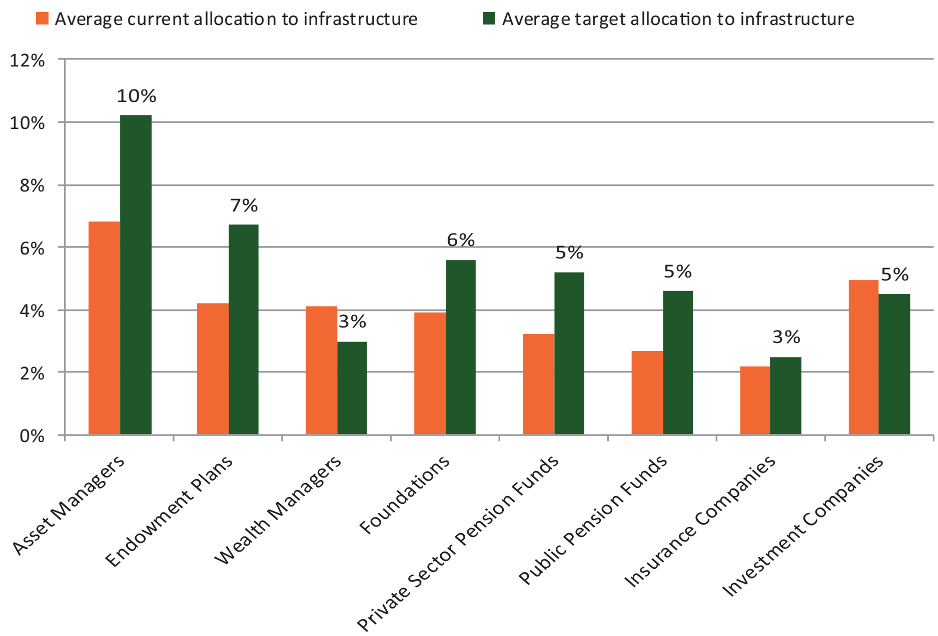

Figure 5. **Breakdown of average current/target allocation to infrastructures by investor type.**

Source: Preqin (2013).

in the form of publicly traded equity, with the remainder held mainly in fixed-income securities. Traditional institutions such as pension funds and insurance companies held $28 trillion (38%) in publicly traded equity, and alternative institutions, while mainly SWFs, private equity, and hedge funds held $4.6 trillion (40%) in publicly traded equity. The report however warns that investment allocations for each category of institutional investors are complex to pin down, largely due to cross-investments among institutional investors, increased complexity in equity market structure, and an increase in the outsourcing of ownership and asset management functions. That being said, the main lesson from these studies is that a large fraction of traditional and non-traditional investors appear to be investing primarily in government bonds and other fixed income securities.

There are however important differences across regions and individual investors, and it is encouraging to note that the targeted shares of investments in infrastructure are growing across the board, reflecting the growing realization among long-term investors that infrastructure assets are a natural habitat for their investments (see Figures 5 and 6). Long-term investors are indeed well placed to invest in more long-term global infrastructure assets. These assets match their long-term horizon. There is less competition for these assets from other investors, and there is a huge global demand for funding of these assets.

Most infrastructure investments generate cash flows only after many years and are associated with high risks during the construction phase. Financing in the form of

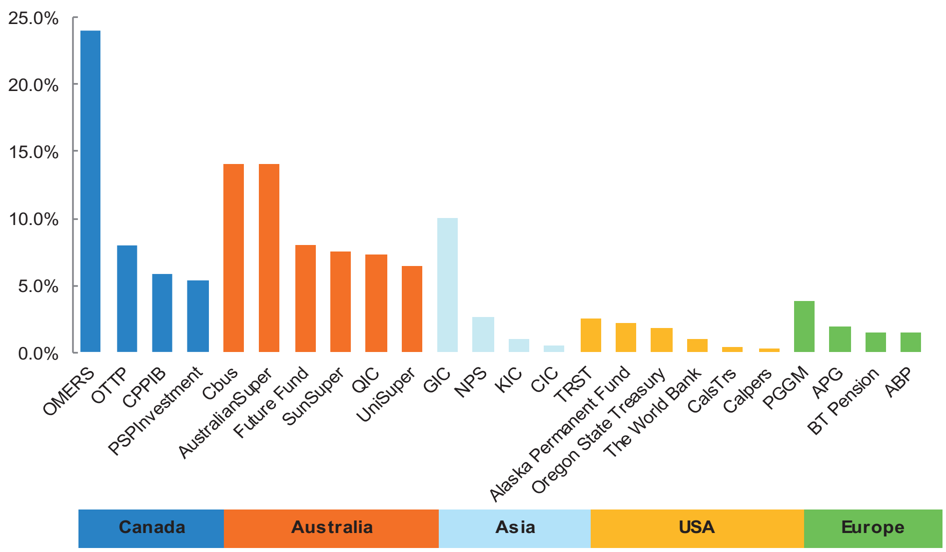

Figure 6. Asset allocation of long-term investors toward infrastructure. Infrastructure allocation (in percent of total).

Notes: Figure provided by Hermes GPE regarding OMERS, it is adjusted by Amundi according to Preqin (2014), Amundi analysis includes QIC, TRST, PGGM, APG.

Source: Milken Institute (2013).

syndicated bank loans has been an important traditional source of funds for such risky long-term projects, but the financial crisis of 2007–09, the tighter bank regulations under Basel III that have followed, and the flatter yield-curve environment, have pushed banks to significantly retrench from this risky and less profitable asset class. Nowadays, banks tend to limit loan maturity to 5 or 8 years, while infrastructure projects typically require amortization of debt over 15–20 years. As a result refinancing is necessary after the initial loan period, exposing borrowers to additional refinancing risk. In turn, the lesser role of banks in long-term investment has paved the way for a greater role of long-term investors such as pension funds, insurance companies, and SWFs. Insurance companies, in particular, have expressed strong interest in matching their long-term liabilities with such long-term assets. Industry surveys (see LP Perspective, 2014 and Preqin, 2011) provide evidence for this interest. A few statistics from these surveys are worth mentioning: i) 38% of investors surveyed by Preqin mention the lack of deal flow as an impediment to their investment in infrastructure; ii) 48% of surveyed investors expect to invest more capital in infrastructure over 2016 than in 2015. This context explains why the G20, the group of 20 major economies, has recently endorsed high level principles intended to help governments facilitate and promote long-term investment by institutional investors including in infrastructure.

The unique nature of infrastructure projects also makes them particularly illiquid investments. The global financial crisis and the subsequent multiple episodes of excess volatility in supposedly very liquid markets have also exposed the fact that the liquidity of a whole asset class can suddenly and dramatically evaporate. This new reality, if anything, strengthens the relative value of illiquid asset classes that offer an illiquidity premium, such as infrastructure investments.[2] Interestingly, in the current low-yield environment, harvesting this illiquidity premium has become increasingly important for many long-term investors.[3]

2.2. Infrastructure financing needs

Against this backdrop of a largely untapped pool of global savings, estimates suggest that the world needs to increase its investment in infrastructure by nearly 60% through 2030 (see McKinsey Global Institute, 2013). To attain those aggregate needs, investment in infrastructure will have to increase from an accumulated total of $36 trillion over the past 18 years to $57 trillion over the next 18 years. Figure 7 provides several estimates, using different approaches, all pointing to massive global infrastructure needs. These estimates can be seen as somewhat conservative considering that they correspond to a scenario where current levels of infrastructure capacity and service relative to GDP are maintained under projected economic growth.

There is a huge infrastructure investment gap in a large number of countries. The average infrastructure investment gap amounts to between $1 and 1.5 trillion per year (see Figure 8). Infrastructure investment needs range from a low 3% of GDP in advanced economies to 9% of GDP in emerging economies, and more than 15% of GDP in some low income economies (see World Economic Forum, 2013). Infrastructure investment needs are mostly earmarked for upgrading depreciating brownfield infrastructure projects in the EU and in the USA, and for greenfield investments in low-income and emerging markets.

Available estimates for Europe indicate that infrastructure investment needs up to 2020 are within the range of €1.5–2 trillion, or an annual amount of €150–200 billion on average (see European Commission, 2011). Within the infrastructure domain, energy is identified as the largest sector for investment, ahead of transport and communication. More recently, the European Commission (2013) estimated that for the EU, "overall investment needs for transport, energy, and telecom infrastructure networks, amount to €1 trillion for the period up to 2020." Those estimates cover a limited set of sectors and should thus be treated as a lower bound. It is worth noting that the European Investment Bank (EIB) has an annual volume

2 A recent report by Allianz (2015) provides some evidence of the economic significance of such premium in the case of infrastructure debt using a basket of known securities with similar ratings and duration. Figure A1 in the above mentioned report highlights listed Private Finance Initiative (PFI) bonds versus a listed A-rated utility and versus the 10-year swap rate. It indicates that over a 5-year period investors would have received a premium of ca. 100 bps for purchasing an A-rated utility and a spread of 150–200 bps for private PFI placements.

3 Investing in infrastructure is different from investing in Treasuries. The latter is a financial asset that exposes investors to aggregate risk. Instead, investments in infrastructure exposes investors to more idiosyncratic risk tied to a specific project. Existing evidence suggests that the risk-return profile of infrastructure investments appears to be quite different from other long-term assets such as equities and treasuries (e.g., Blackrock, 201557; Morgan Stanley, 200757). Average returns on infrastructure assets are somewhat higher than for bonds and equities. The volatility of returns to infrastructure investments is also higher than for bonds but smaller than for equities.

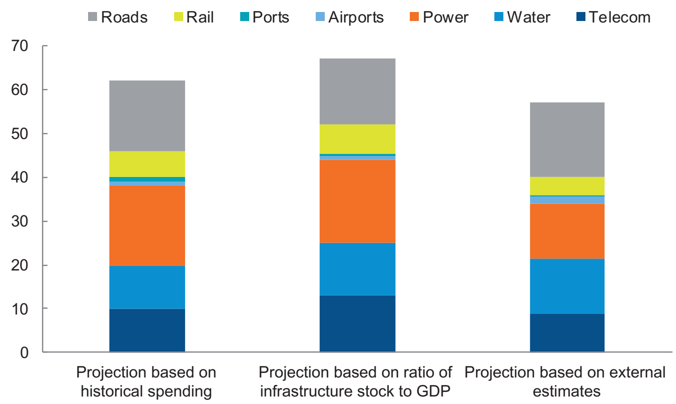

Figure 7. Estimates of needed infrastructure investments, 2013–2030. ($trillion, constant 2010 dollars).

Source: McKinsey Global Institute (2013).

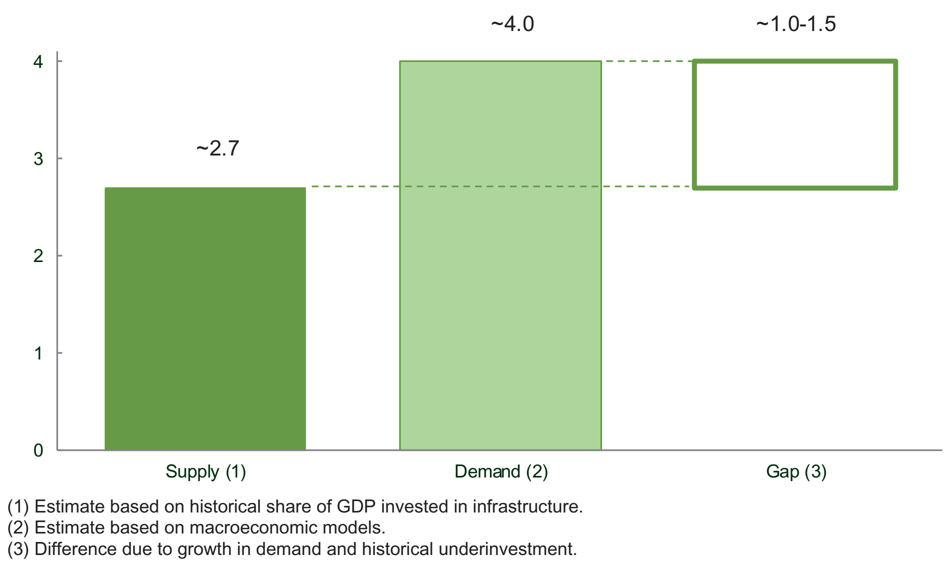

Figure 8. Gap between infrastructure supply and demand. Investment (2010 constant $trillions).

Source: Boston Consulting Group (2013).

of financing in the €50–70 billion range, and the Junker investment plan is around €315 billion over 3 years, thus significantly falling short of estimated infrastructure investment needs.

In the USA infrastructure needs are estimated to be over $2.75 trillion by 2020 to be able to adequately serve the growing US population and increased economic activity, as well as maintain or rebuild infrastructure in need of repair, or replacement (see American Society of Civil Engineers, ASCE Report Card, 2016). However, only $6 billion of Recovery Act funding was available to spend on infrastructure in the 2012 Fiscal Year. Overwhelmingly, the most pressing need for infrastructure is in surface transportation, including highways, bridges, railroads, and other transit systems.

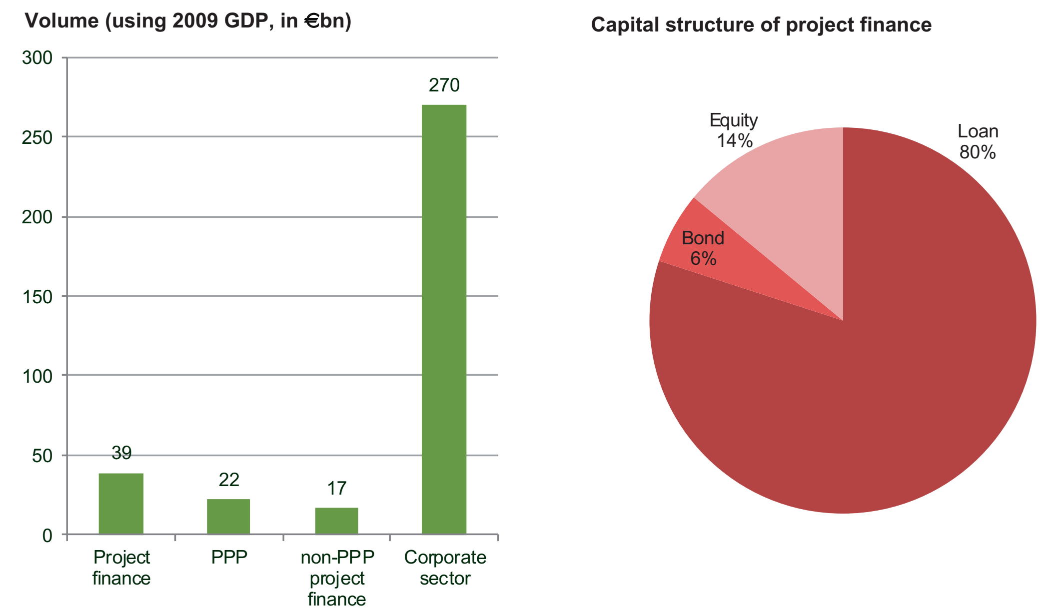

Figure 9. **Private infrastructure spending in Europe.**

Notes: It is important to note that in this analysis, private finance is defined as a residual of total infrastructure investment (minus government investment (Eurostat figures)), corporate finance as a residual within private finance (minus project finance (Dealogic figures)), and, finally, non-PPP as a residual within project finance (minus PPP (EPEC figures)).

Source: European Investment Bank (2013).

Overall, however, the future growth in the demand for infrastructure will come increasingly from emerging economies. Over the past 18 years, more than 70% of global infrastructure investment originated in advanced economies (see McKinsey Global Institute, 2013). But over the next 18 years emerging economies are likely to account for 40–50% of all infrastructure spending. Around 70% of the current pipeline available to equity investors consists of green field projects, which are viewed as much riskier than brown field investments, particularly in emerging economies.[4] Even though a growing number of investors are rethinking their investment strategies in light of these developments, they will continue to demand higher returns and will be more selective considering the riskier nature of green field investments.

Available estimates suggest that if institutional investors, excluding SWFs, were to increase their allocations for infrastructure financing to their target levels, it would result in an additional \$2.5 trillion in infrastructure investment capital through 2030 (e.g., McKinsey Global Institute, 2013). This study however highlights that while “This is a sizeable amount, [it is] still only a fraction of global infrastructure investment needs. We therefore need to look elsewhere for a complete solution. . .” As mentioned earlier, assets

4 To the extent that greenfield investments involve a higher time to maturity and greater regulatory and enforcement risks they are fundamentally riskier for investors than proven brownfield investments that are already in operation.

under management by long-term investors have reached $85 trillion. Even if a small portion of assets under management of long-term investors were to be earmarked for infrastructure development on a global scale, the impact on the global economy, as well as commercial returns, could be bigger than any other source of large-scale private investments.

3. INVESTING IN INFRASTRUCTURE THROUGH PPPs

In this section, we highlight how the economics literature on PPPs has almost entirely been framed around incentive issues that were prominent at the time when the first privatizations were initiated. This literature is mostly silent on the origination, financing, and contract enforcement issues that have since hindered and plagued PPPs in many countries. We also discuss the critical law, finance, and economics aspects of PPP origination, financing, and enforcement.

3.1. The microeconomics of PPPs: the gap between theory and reality

Most of the economics literature on PPPs is cast in a dynamic bilateral Principal–Agent framework (see Iossa and Martimort, 2015, for an overview).[5] The Principal is the government and the Agent is the infrastructure provider. The early contributions to this literature are motivated by the privatization experience in the UK in the 1980s and the subsequent proliferation of infrastructure service provision under PPP arrangements. The record of publicly provided infrastructure services in the UK prior to the privatization wave of the 1980s was rife with inefficiencies and underinvestment in maintenance and technological upgrades. In light of this evidence, economists not surprisingly, pointed to the lack of incentives for the public infrastructure service providers to minimize cost, increase quality, and maintain the infrastructure facility. A basic observation of incentive theory (Holmstrom, 1979; Mirrlees, 1999) is that the agent providing a service will have stronger incentives to perform if his/her compensation is tied to performance. Given that public infrastructure service providers were not compensated based on performance, it was not surprising that public infrastructure service provision, whether in transport, energy, water, health, education, or telecommunication, was deficient.

A major advantage of privatization, and of the private provision of infrastructure services, is that the provider is compensated based on performance, as measured by profit. However, a major "inconvenience," well recognized by the early proponents of privatization, is that maximization of profit by a monopoly infrastructure service provider exploiting its market pricing power is generally not a desirable social objective. If private

5 For a more complete list of theoretical and empirical papers on PPPs and infrastructure finance we refer the reader to: http://www.people.hbs.edu/besty/projfinportal/index.htm.

provision of infrastructure services can deliver desirable incentives for cost and quality performance, it also introduces undesirable monopoly distortions. Generally, private provision of infrastructure services must be subject to rate and standards regulation to avoid abuse of market power by the concession operator. The private service provider and the public regulator are therefore inextricably tied together through such regulatory intervention.

Moreover, as Donahue (1989) has noted, the benefits of privatization are highest when private providers are also subjected to competition. When horizontal competition is not feasible because the service provider is a natural monopoly, some discipline may be introduced through vertical competition and by periodically organizing an auction for the license to provide the service. Accordingly, the UK and many other countries have introduced fixed-term concession contracts that are up for competitive bidding or contract renegotiation when the private service-provision contract expires.

An important policy question is then, how broad a scope and how long a term to specify in the concession contract. A central insight of the economics literature on PPPs regarding this question is that it is generally incentive-efficient to structure the concession contract by bundling construction and service-provision together with a single private operator. In practice PPPs can take several different forms: there are PPPs that combine building, owning and operating (BOO); building, owning and transferring (BOT); building, rehabilitating, owning and transferring (BROT); rehabilitate, operate and transfer (ROT); and build, lease, own (BLO). According to Hammami et al. (2006), from 1990 to 2003 a total of 690 BOO, 317 BOT, 234 BROT, 108 ROT, and 5 BLO PPPs were initiated. A striking result in the economics literature on PPPs is that whenever there are positive spillovers between construction and operation of an infrastructure facility, it is optimal to design the PPP in the form of a BOO or BLO (see Hart, 2003; Bennett and Iossa, 2006; Martimort and Pouyet, 2008; Iossa and Martimort, 2012, 2015). In simple and general terms, the reason why bundling is efficient is that by assigning construction and operation to the same provider, the latter has strong incentives to construct the facility so as to minimize future operating costs.[6]

One drawback of structuring the PPP by bundling construction and operation, however, is that this generally involves a very long-term contract, lasting over 25–40 years. Moreover, under such a contract the operator faces significant risk, both during the construction phase and in the operating phase.[7] It is generally not efficient to

6 A survey by Standard and Poor's (2007) suggests that the successful delivery of PPPs remains dependent on a number of critical prerequisites. The survey indicates that, absent these prerequisites, the construction-phase performance differential between PPPs and conventional procurement methods can narrow considerably.

7 During the operating phase some PPP concession-holders may be subject to significant volume risk such as toll road operators. On the other hand, hospitals, prisons, and other such PPP operations are less subject to such demand risk during the operating phase.

expose the operator to the entire risk of the project. Again, a central lesson from agency theory (Holmstrom, 1979; Mirrlees, 1999) is that the optimal contract between a Principal and an Agent involves trading off risk-sharing and incentives. To the extent that the government is better able to absorb risk it makes sense to provide some insurance to the PPP operator, even if this comes at the expense of incentives to deliver services.

How much insurance should be offered, and what types of risk should be insured is not clear from the existing economics literature on PPPs. With the exception of a few studies (in particular Engel et al., 2008) this topic has not been studied systematically. The main argument in the economics literature against any form of insurance is that investors in PPPs are diversified investors, and as such, are best able to hold the risk, provided of course that it is properly priced. The argument in favor of insurance is that the government has a greater ability to raise funds through taxation (see Holmstrom and Tirole, 1998) and therefore should take on as much of the funding cost as is compatible with maintaining incentives for service provision by the PPP operator. Neither of these arguments is are fully compelling nor are they always relevant to the constraints faced on the ground by the contracting parties in specific PPPs. It is striking how little attention the economics literature has devoted to the fundamental question of how to structure financing of investments under PPPs, how much should come from private sources and in what form and how much should come from public sources. An equally striking observation is that almost all the economics literature on PPPs frames the contract as a bilateral contract between a private provider and a government agency. One important exception is Dewatripont and Legros (2005), who emphasize the important role a third party can play as a monitor to improve the efficiency of contract enforcement. In most developing countries the obvious third party is a MDB, which can play not only a key monitoring role of both the service provider and the government agency, but also a fundamental role in structuring financing efficiently and providing optimal insurance or guarantees to private investors in PPPs.

3.2. Origination, financing, and enforcement: the new economics and finance of PPPs

As little as the economics literature has explored the issue of financing PPPs, the most important concern of private operators and investors in practice is how to structure financing and minimize the cost of capital for PPP projects. Structuring financing of PPPs is not just a technical question; it is what supports the delicate balance between the interests and comparative advantages of the different partners in the PPP. It is not just a question of optimally allocating the different risks involved in an infrastructure project, as illustrated in Figure 10, but also a question of setting up the right governance structure to ensure the sustainability of the project. Given the public goods nature of most PPP projects a fundamental difficulty is to find a way to internalize the positive

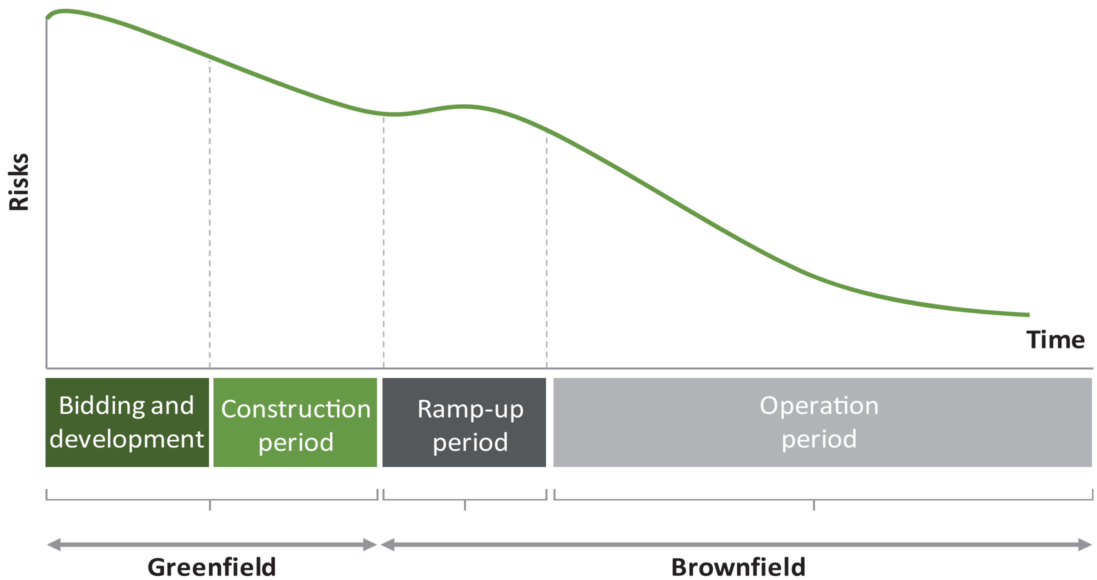

Figure 10. Risk profile development of an infrastructure asset.

Notes: The figure demonstrates conceptually the relative level of risk between the greenfield and brownfield stages of a project, assuming a stable regulatory and political environment. Political and regulatory risks can change the dynamics and lead to a higher relative risk level than shown, especially in the brownfiled stage.

Source: World Economic Forum, for illustrative purposes only.

externalities produced by the project without excessively excluding all the potential beneficiaries of the project.

This is, of course, not a new problem; what is new is the institutional context that evolves over time and technological advances. Before we discuss the new institutional context and how it shapes new approaches to the financing of PPPs, it is worth mentioning a particularly instructive old model of PPPs from the Middle-Ages in Europe in contrast with a successful modern equivalent:

"The Bridges were always the weakest links in the road network and the most difficult for occasional labour to maintain. In the course of the twelfth century local efforts began to be supplanted by a more powerful organization of resources, often of a charitable nature." [pp. 176] "It was an extremely expensive enterprise to maintain . . . It was normal for a toll to be levied from those using such a bridge, and sometimes as at the Pont St Esprit, from those using the river under it, to help pay for its upkeep and repair. However, tolls by themselves were not adequate to maintain a bridge. Those who planned to build one did not simply have to look for enough funds to build it in the first place, but for an adequate permanent endowment in land. The first years' rents from the bridge's lands paid for the initial building. The fact that the Pont St Esprit and its associated works took forty years to complete was not because medieval masons could not work any faster, but because it needed forty years' income to pay them. The endowment was then intended to pay for the maintenance of the fabric, of the brotherhood and of their chapel." [From "Power and Profit: The Merchant in Medieval Europe" (2002), Peter Spufford, Thames & Hudson, New York, pp 177–178.]

A modern equivalent of the medieval "bridge financing" model is the striking example of "value capture" implemented by Hong Kong's mass transit rail (MTR) corporation, a private operator with a majority stake held by the Hong Kong government. Just as medieval bridge operators had endowments of land to establish a sustainable revenue source, the MTR owns properties in Hong Kong whose value appreciates as a result of the extension of the transit network (see Cervero and Murakami, 2009). As a result MTR is hugely profitable unlike most mass transit systems in the world even though ticket prices are relatively low. In 2013, for example, MTR realized an operating profit of HK $16.3 billion (or $2.10 billion) of which revenues from property development, rental, and management, and station commercial businesses represented over 50% of the profit (MTR Corporation Limited Annual Report, 2013). This example illustrates how a well-designed PPP can better exploit the comparative advantages of the different partners in capturing revenue to finance infrastructure construction and operation. In MTR's case, it was better placed to combine property development with transit extension as a private operation, than the Hong Kong government.

A well-known problem that all too many heavily indebted poor countries (HIPC) have faced is that their public finances are just too stretched to be able to support large infrastructure investments that are nevertheless sorely needed. Often, the only way for these countries to be able to build an infrastructure facility is to rely on private financing through a PPP. It is most likely the reason why Hammami et al. (2006) have found that PPPs are most prevalent in HIPC. In these countries, what drives the way the financing of the PPP is structured is basically a very tight government financial constraint. The private funding of an infrastructure project generally comes against a concession contract which assigns future toll revenues to the provider. But this is only the beginning of the PPP financial-structure problem. Two other major issues are: First, how senior should the claims of the private investors be with. Should private investors be senior secured lenders, subordinated bond-holders, or common equity holders? If they are debt-holders, to what extent should this debt be guaranteed and by whom? Second, what are the control rights of private investors and what are their protections against the hold-up risk by host governments?[8]

The implementation the implementation of PPP projects and the enforcement of PPP contracts can be fraught with conflicts. When an administration other than the one that has originated a PPP project comes to power it often seeks to change the terms of the contract. Similarly, private concession operators have been known to strategically default and abandon the project before construction is complete, leaving the local government with a white elephant. To minimize the costs of such contractual disputes it is important to not only structure the PPP contract so that it is ex post efficient and incentive compatible in as many states of the world as possible, but also to build effective

8 Toll revenues in developing countries are not well accepted by users, which reinforces the risk of hold-up and expropriation by the Government. In addition, toll revenues are subject to currency risk and the lack of long-term currency hedging mechanisms is a major concern for investors.

dispute resolution procedures into the contract and, of course, to be able to depend on credible and speedy contract enforcement institutions.

In many countries such enforcement institutions are, alas, not available. One country that has had a particularly bad experience with PPPs because of its weak contractual enforcement institutions is India. According to a National Institution for Transforming India (NITI AAYOG) 2015 report: "in a large number of cases, the project authorities do not discharge their contractual obligations in a timely manner which imposes additional costs on private sector participants. There is also lack of enforcement of the contractual obligations to be discharged by the Concessionaires." Moreover, "Infrastructure projects are fraught with disputes that cause inordinate delays due to slow resolution processes. Arbitration awards are almost invariably appealed against, resulting in long drawn out disputes that often last 3 to 10 years. As per available data . . . disputes involving 870 cases are pending for resolution in the Road sector alone." [NITI Aayog, NITI BRIEF No. 5, 2015, paragraphs 4.2.1 and 4.3.1, page 10]. However, it is important to note that when a country cannot effectively rely on its own legal system to enforce PPP contracts, it is possible for that country to fall back on international commercial arbitration, a tried-and-tested enforcement mechanism generally preferred by international investors (see World Bank Group, 2016).

The reality of infrastructure assets as an investment class is that most investors are only comfortable holding debt instruments, preferably guaranteed, in relatively safe infrastructure assets.[9] This generally means that private infrastructure investors crowd into the relatively safe brownfield infrastructure-asset class (i.e., projects that are already built and operating), in which yields are no longer that attractive. Far fewer investors venture into greenfield infrastructure projects (i.e., projects that are still under development), which expose them to construction, regulatory, and demand risk, and involve much longer payback periods. For routine transport and energy infrastructure the construction risk is limited, but demand and regulatory risks may not be. For more unusual infrastructure investments, such as nuclear reactors, long tunnels, or major urban redevelopment projects, construction risk is much more of a concern (see Box A).

Another consideration in the greenfield space is that most private investors only want to hold senior, secured, and if possible, guaranteed debt. Far fewer private investors venture into holdings of common equity stakes in greenfield projects because the perception of high risks, especially for investors with limited expertise in infrastructure project finance, who are most exposed to adverse selection. One notable example of a long-term investor taking equity positions in greenfield projects is the private equity firm *Meridiam* (see Meridiam, 2016). Remarkably, Meridiam imposes lock-up periods of up to 20 or 25 years on its long term limited partners, more than double the typical length for a lock-up period

9 Guarantees are rarely available and therefore seldom sought by investors (non-recourse debt remains the norm).

Box A
Hinkley nuclear power plant project

A specific, cutting-edge, example of one of the largest PPP projects ever to be envisaged, currently in the final pre-construction stage in the UK, the *Hinkley Point* C nuclear power EPR plants project involving the French electric utility company EDF as the private provider, a strategic partnership with China's General Power Corporation (GPC), and the UK government.

Early consultations on the project began in October 2008 and the project is now reaching the point when construction is about to begin. Currently, the estimated time for construction of the new EPR plant is 8 years, the expected operational lifetime is 60 years, and the total capital commitment for the two reactors is expected to be around €43 billion.

EDF and GPC will, respectively, own 66.6% and 33.5% of the capital, and the UK government will provide a £20 billion loan guarantee. Under this structure most of the construction risk is taken on by the equity owners in the PPP, and credit risk is transferred to the UK government, who is a stronger counterparty than any private default protection seller. Moreover, a particularly innovative feature of the PPP is the so-called contract for difference provision that locks in and front-loads the future prices for the Hinkley Point C electricity sold by EDF to the national grid. This provision, in effect, allows the private provider and the UK Government to share operating risk, and thus lowers the cost of financing of the project.

It is worth mentioning that the guarantee fee has been significantly raised by the European Commission in order to "reduce the subsidy" by the UK Government, although the subsidy had been authorized by the Commission on the grounds that the "UK authorities demonstrated that the support would address a genuine market failure." The impact of the project on EDF's balance sheet and risk profile is so large that EDF has decided for risk management purposes to increase its liquidity holdings by selling ?10 billion of assets over the next 5 years.

This example is remarkable not just for the sophistication of its financial structure and risk allocation, but also for its sheer size and the particularly long-term commitments that may be involved in infrastructure projects: more than 7 years from the first consultations to the beginning of construction, 8 years of construction, and 60 years of operating income. Such an investment asset is obviously only well suited for long-term investors, which besides the operating companies include pension funds, insurance, and re-insurance companies, and sovereign wealth funds. The example is also noteworthy for its reliance on guarantees to lower the cost of debt financing. The UK Government is, of course, in a position of being able to extend such a guarantee, and thus to significantly lower the cost of capital for such projects. A simple back-of-the-envelope calculation gives the following ball-park number: assuming that the required interest payment on a 30-year AAA bond is 3%, and the required interest payment of a 30-year bond without the guarantee is 5%, the yearly interest savings to service the AAA bond versus the non-guaranteed bond for a total issue of 17 billion pounds is approximately (850 – 510) = 340 million pounds. It should be noted, however, that extending a guarantee is not costless, and the present value costs of such government guarantees is generally underestimated, as Lucas (2014) has shown, since these guarantees are typically not priced under private sector, fair-value, accounting rules, which take into account compensation for risk and therefore yield cost estimates that are significantly higher. Obviously, proper risk management should identify the limits beyond which governments or MDBs can no longer efficiently extend guarantees.

in private equity funds. Also noteworthy is the fact that on a risk-adjusted basis the returns offered by Meridiam are actually higher than the average return for brownfield investments. Meridiam typically engages in greenfield projects that have delivered double digit returns for their investors, while pure brownfield long term investments yielded only single digit returns. The reason behind the superior performance of Meridiam has to do, essentially, with the different business model it has adopted from the typical leveraged buy-out model in the private equity industry. Under the dominant business model in the industry, most of the attention is devoted to privatization of existing infrastructure assets, instead of the origination of long-term investments in infrastructure projects.[10]

4. MDBS AND INFRASTRUCTURE PLATFORMS

As Dewatripont and Legros (2005) argue, monitoring by a third party generally improves the efficiency of PPPs. We maintain that MDBs are evidently the best placed third parties to play that role for several reasons. First, in most countries, MDBs are obligatory entities with which government sponsors of infrastructure projects must contend. They are often the first to be approached for financing, for guarantees, and for advice in structuring a PPP. Second, MDBs are repositories of technical expertise and the specialized human capital needed for the development of highly idiosyncratic and complex infrastructure projects. Third, as multilateral agencies with strong professional cultures and international governance structures, they are ideally placed to enforce credible anti-corruption standards in the selection and enforcement of PPPs. This is especially true when, when their continuous, long-term, unavoidable presence on the ground, puts them in a position to withhold future projects from governments and private operators

10 To sustain its rather uncommon business model, Meridiam has invested time and resources in building an in-house multi-disciplinary team with public sector, industrial, and finance expertise.

that have been found to engage in corruption. In short, MDBs play a critical gatekeeping and technical assistance role in infrastructure investment.

MDBs also provide much of the financing for the infrastructure projects they originate. But public funding capacity and the size of MDB balance sheets more than ever fall woefully short of the global demand for infrastructure investment. This is why the new model for MDBs is an origination-and-distribution model, where MDBs help structure new PPP deals that will be increasingly financed by the large pool of global savings seeking long-term investments with higher yields than government bonds.

4.1. MDBs: from funders of public sector projects to originators and distributors of PPPs

Traditionally, the role of public development banks, and later that of MDBs, has been seen as a public response to a failure by private banks and securities markets to finance valuable, large-scale, long-term, (infrastructure) investments. With the backing of the State, development banks could afford to make longer term commitments than private banks, and through their long-term infrastructure investments, could serve as catalysts to coordinate the financing of industrialization by private banks (Diamond, 1957; Gerschenkron, 1962; Armendáriz de Aghion, 1999; Da Rin and Hellman, 2002). The model of development banks in 19th century Europe was based on the idea that they could be profitable if they sufficiently internalized the positive spillovers from industrialization, a form of value capture.

The model of MDBs post-WWII was further seen as palliating the underdevelopment of banking and financial markets in developing countries post-decolonization (Levy-Yeyati et al., 2004; de Luna-Martínez and Vicente, 2012). In the early years of economic development post-decolonization, the role of the state in coordinating investment was paramount. Accordingly, most of the early investments of MDBs went to funding public sector projects. But as the central role of the state in the economy was reassessed and more and more developing economies have transitioned away from large public sectors towards more market-based models, the mandate of MDBs also evolved.[11] Yet, MDBs remain fundamentally different from ordinary commercial banks in several respects. First, the mandate of MDBs is to stay away from commercially viable investments to avoid inefficient crowding out of private lenders. Second, the criteria MDBs apply for investment involves the important assessment of the social and economic development impact of the project. Third, MDB debt is senior to other commercial creditors according to existing conventions.

With the shift towards privatization of infrastructure, MDBs increasingly participate as co-investors along with other private sector investors, but the full potential of the new

11 The European Bank for Reconstruction and Development and the International Finance Corporation, in particular, have reoriented their loans mostly to the private sector.

role for MDBs as co-investors has only recently become fully apparent. The exceptional track record of profitable co-investments of the European Bank for Reconstruction and Development (EBRD) in the former Eastern Bloc countries under two decades of economic transition, and, most importantly, the spectacular growth impact of another development bank over the last decade and a half—the China Development Bank (CDB)—have revealed how far a development bank model, built around a modernized value capture concept and a co-investment formula with private lenders, can accelerate economic development while generating more than adequate financial returns (see Box B). As can be seen in Figure 3, by 2015 CDB assembled a balance sheet with assets exceeding $1.8 trillion, which is more than the sum of all assets on the balance sheets of all MDBs combined in 2015 [World Bank, EBRD, Asia Development Bank (ADB), IADM, African Development Bank, and EIB]. CDB was founded in 1994 and built its balance sheet in record time, mostly in the last decade. Admittedly, CDB benefited from a unique environment in China and a privileged position in China's financial system. But the development formula it perfected can be adapted and is replicable elsewhere.

To fully play their role as originators and distributors of infrastructure projects, however, MDBs must venture further in the direction of playing more of an investment banking role, coordinating deals between government agencies, private concession operators, and long-term private investors, offering when necessary, guarantees and credit enhancements that protect private investors from risks they are not prepared to carry. In addition, MDBs must further explore the bundling of multiple PPP projects towards infrastructure asset-backed securitization to be able to reach sufficient scale in bond financing to attract institutional investors. Indeed, most PPPs are too small in scale for large, long-term institutional investors, such as pension funds, reserve funds, and SWFs who do not always have dedicated infrastructure experts in their management teams.

4.2. Infrastructure platforms

Based on the more recent experience of some MDBs with co-investments with private investors, there is growing appreciation globally that MDBs can indeed play a much bigger role in the preparation, structuring, and financing of infrastructure projects along with private long-term investors. Not coincidentally, a number of infrastructure platform initiatives have been launched very recently by several MDBs, most of them still at a prototype development stage, with the aim of scaling up the distribution of investments in PPP projects to private investors and thereby increase the flow of origination of new infrastructure facilities.

In the following section, we discuss four different models that are currently at various stages of development. These platforms are all different attempts to tap into the vast pool of global long-term savings by better meeting long-term investor needs and attracting them to infrastructure assets by relaxing the operating and governance

Box B
China development bank model of investment

The investment model perfected by CDB arose out of a unique Chinese local economic development context. Strapped for funding and with a highly restricted tax base, Chinese municipalities increasingly relied on capital gains realized from urban development to fund themselves. An early notorious example of such successful urban development, financed by CDB, is known as the Wuhu model (see Sanderson and Forsythe, 2013).

Under this model a municipality would set up a special purpose vehicle charged with developing a designated zone. This entity could borrow from CDB as a senior long-term lender as well as from other commercial banks on a subordinated basis to finance the infrastructure and real estate towards urban development of the dedicated zone. Crucially, as development proceeded and land values appreciated the special purpose vehicle could sell land and development rights to real estate developers and thus realize the capital gains that would serve to repay the loans of CDB and the other commercial banks and fund municipal expenditures. Equally important is the arrangement that CDB strikes with the special purpose vehicle, collateralizing its loans with the proceeds from future land sales. In other words, the CDB lending model is built on an urban development formula that enables value capture through land and development-right sales akin to the value capture that Hong Kong's MTR relied on to finance the expansion and operation of its mass transit network, although CDB also successfully invested in many other areas and other infrastructure projects beyond mass transit networks.

To fund its investments, CDB also benefits from a unique position similar to that of the government-sponsored enterprises (GSEs) Fannie Mae, Sallie Mae, and Freddie Mac in the United States. Just as the GSEs, CDB can finance itself by issuing long-term bonds that financial markets perceive as indistinguishable from straight government bonds once CDB has secured the endorsement of the Ministry of Finance. As these bonds typically offer yields that are slightly higher than interbank rates, and significantly higher than the rate paid on excess reserve accounts by the central bank, they are very attractive to commercial banks with excess liquidity holdings. A key advantage of this funding structure is that CDB could build a massive balance sheet with a lean organization—although its balance sheet is six times larger than that of the World Bank it has only 3,500 employees as of 2015.

Although CDB like the GSEs was ideally placed to exploit some unique structural advantages, it also built a sustainable lending model for a development bank by implementing strict and sophisticated protocol for approval of new projects, so much so that it stands out relative to commercial banks in terms of its low fraction of non-performing loans (see again Sanderson and Forsythe, 2013). That is obviously not a given for a development bank, yet it is an essential condition for the success of any MDB. Much of the credit for implementing this rigorous lending protocol goes to the founding chairman of CDB, Chen Yuan.

constraints traditional development banks have faced. One specific example of constraints that development banks have been subject to is their governance structure centered exclusively around governmental actors, which de facto make it impossible for private investors to be actively involved in the orientation given to infrastructure investments both on the origination and financing fronts. We begin with a brief description of these four platforms, which will help give context to the subsequent critical assessment of the existing trade-offs and potential limitations of the models currently being proposed.[12]

4.2.1. The EIB model. With subscribed capital of over €240 billion, total assets just exceeding $600 billion in 2015, and funded projects in over 160 countries, the EIB is currently the world's largest multilateral investment bank.[13] The EIB was set up by the European Union with a very conservative business model under which the EIB is only allowed to borrow 2.5 times its subscribed capital. This constraint ensures that it can always issue AAA-rated bonds. Not all of EIB investments are in infrastructure. The EIB also plays a major role in the funding of innovation, climate change mitigation, and small and medium enterprise loans.

The EIB's most innovative infrastructure investment activities are in project finance. Project finance activities are where the EIB provides an interesting new infrastructure platform model for development banks that can support PPP infrastructure projects. The EIB's involvement can reinforce PPP projects at several levels, whether it is in project preparation, as a co-investor, a lender, or a servicer. A typical PPP in which the EIB is involved will have about 70% of the investment funded initially either through a bank loan, that may subsequently be refinanced in the bond market, or through a long-term project bond, with the EIB providing support either through a credit enhancement scheme to remove exposure of creditors to construction and early operating risks (a line

12 There are several other important global infrastructure investment initiatives that are at various early stages of development. They include: the Junker Plan, November 2014, the G20 Global Infrastructure Initiative, November, 2014, the establishment by the European Commission of infrastructure investments as a new asset class, October 2015, and the launch by the International Finance Corporation (IFC) of a new accounting platform earmarked for infrastructure projects in emerging markets, November, 2015 (see Winrow, 2015).

13 The China Development Bank is not a multilateral institution.

of credit, a subordinated debt tranche), or through an equity co-investment with a private long-term infrastructure investor such as Meridiam or DIF among others.[14]

Participation by the EIB in a project has two main advantages. A first obvious benefit is that the EIB offers more loss absorbency protection to private investors who buy the project bond. As a result, these investors are prepared to both extend the maturity of the bonds and lower their required rate of return, thus reducing the overall cost of capital of the project.[15] The second related benefit is that when the EIB is involved as an investor and in the servicing of the PPP debt, the government partner in the PPP is more likely to honor the terms of the concession contract. The EIB is a key long-term agent in the infrastructure investment space, with essential expertise in project preparation and servicing, with whom the government entity will be expecting to have to interact on future projects. This entity will therefore think twice before reneging on contractual promises or before deciding to hold up the PPP operator. A third important benefit of EIB involvement, even with a relatively small stake in the form of a project bond credit enhancement, it will apply its due diligence expertise and rigorous standards for investment, thus further reducing the credit risk for project bond investors.

Another interesting recent EIB securitization initiative is the creation of a renewable energy platform for institutional investors (REPIN) that offers repackaged renewable energy assets in standardized, liquid forms to institutional investors.[16] Although interest from institutional investors in this initiative has been limited so far, the new carbon footprint disclosures and regulations for institutional investors that are expected to be implemented after the Paris COP 21 climate agreement, could nudge more pension and SWFs to take on these securities.

4.2.2. The world bank's global infrastructure facility. The World Bank Group launched a major new initiative with the global infrastructure facility (GIF), officially established at its October 2014 Annual Meeting. The World Bank's involvement in infrastructure investment is, of course, not new. It has been engaged in infrastructure financing ever since its creation in 1945, and has thus accumulated a deep expertise in this area. In recent years, the World Bank has progressively recognized that there is a new reality for global infrastructure investment and that there are untapped funding opportunities from private investors, which could help the World Bank respond to the huge demand it receives from member countries. For this reason, The World Bank has launched this major new initiative. The World Bank has two important objectives for the GIF. First, make better use of its exceptional talent pool to accelerate origination of new projects, and second, relax its current tight funding constraints driven by its limited capital base, which no-one expects will increase substantially in the near future, by co-

14 For information on DIF, see http://www.dif.eu/.
15 Without proper monitoring, loss absorbency could lead to over-provisioning and under monitoring.
16 See http://climatefinancelab.org/idea/renewable-energy-platform-for-institutional-investors-repin/.

investing more with private investors. As prompted by the G20, the World Bank hopes to leverage its global infrastructure expertise by bringing in private funding from long-term investors through the GIF facility which was set up specially to co-invest along with private investors. Originally, the GIF was set up as an entity outside the World Bank with a total capital of $200 million. That capital was destined to be leveraged with A+ rated debt held by private investors so as to finance potentially much larger projects.

The initial contours of the GIF, however, appeared uncertain to the World Bank membership. Two main issues, in particular, have arisen. First, there is the concern that building a sound "infrastructure balance sheet" could take a long time. Second, the participation of new actors would imply a change in the governance structure which appeared unlikely at the time. In that context, the current design of the GIF with a more limited scope was deemed more realistic. One of the important unresolved logistical issues is when to bring in private investors: at an early project preparation stage or much later as a residual investor when all the parameters of the project have been set. Issues regarding oversight of social and environmental protection in large-scale infrastructure projects in developing countries by the World Bank's GIF have also been raised, particularly with respect to some fossil fuel investments in Africa and a coal mining project in Kosovo, expected to displace approximately 7,000 people (Bretton Woods Project, 2014).

Currently, the GIF platform is designed to help identify, prepare, and also supervise projects. In addition, since there are also issues on a project by project basis in every country that require policy amendments or policy interventions, and considering that the World Bank Group is present all over the world, it is better positioned to enhance the overall policy framework. Building on the World Bank's expertise in infrastructure financing, the GIF offers services in terms of identifying and preparing projects. The GIF will start with a few pilot projects amounting to up to $2 billion. A total of $80 million is being budgeted for preparation of those projects (World Bank Group, 2015). On the downstream side, GIF is budgeting $200 million (World Bank Group, 2014). The modalities on how to integrate the upstream and downstream sides are yet to be decided upon.

4.2.3. EBRD Equity Participation Fund. The EBRD fund envisions that private long-term investors be admitted as equity co-investors to the new Equity Participation Fund it set up. A fixed allocation ratio will be followed for eligible investments in equity with 30% of investment risk allocated to the fund. The EBRD retains 70% of the investment risk and private investors in the fund are passive and follow the EBRD investment protocol.

The target size of the fund is between €750 million and 1 billion. The expected investment size is between €10 and 100 million. The expected portfolio return is a 15% internal return rate. The fund term is 12 years (European Bank for Reconstruction and Development, 2014). Hence, one of the biggest limitations to EBRD's Equity Participant Fund is that the time horizon for return on investments in infrastructure is far too short, bearing closer resemblance to private equity investment patterns than to long-term investors in global infrastructure, with a minimum period of 25–30 year time horizons. In North Africa, for example, the EBRD's Equity Participation Fund is the largest limited partner in infrastructure initiatives, by serving as co-investor in more than 170 private equity funds. To date, the EBRD has made €10 billion cumulative equity investments in infrastructure across 36 countries.

The main advantage of the fund is to provide an opportunity to invest in the growth potential across the EBRD countries of operation, which are not accessible via public markets or traditional private equity funds. Indeed, global institutional investors who participate in the EBRD's direct equity investment portfolio and strategy will benefit from geographic and sector diversification, as well as the long-term capital growth and return opportunity in line with market benchmarks. In addition, fund investors also benefit from the EBRD adherence to the highest environment, social, and governance standards and unique access to a universe of both public (pre-privatization) and private companies. In terms of risk mitigation, the EBRD has stringent internal processes as well as very low-cost intermediation (cost sharing management fee, no carried interest).

4.2.4. The Asia infrastructure investment bank. The latest MDB to be created is the Asia Infrastructure Investment Bank (AIIB) expected to start operations this year. Unlike other development banks it is entirely dedicated to infrastructure investment, as its name indicates. It has a start-up committed capital of $50 billion with another $50 billion in future capital commitments. While the total committed capital of the AIIB is lower than the EIBs, its maximum leverage ratio is much higher (borrowing may be as high as 20 times capital) so that total assets of the AIIB could be double those of the EIB when it reaches full capacity.

The launch of the AIIB has been held back by US opposition to Asian countries joining the AIIB. However, the recent announcement that the UK, France, Germany, and Italy are joining the AIIB is a turning point. The AIIB now has more than 30 member countries, including India and Indonesia, with each member's voting rights on the governing board benchmarked to be proportional to the member country's share of GDP.

The creation of the AIIB is a significant step towards meeting the $8 trillion of Asian infrastructure investment needs over the next decade, estimated by the ADB. That being said, it is highly unlikely that the AIIB will be crowding out investment efforts by existing MDBs given that these institutions do not have the balance sheets to be able to meet these enormous infrastructure investment needs. The ADB has a committed capital base of about $160 billion and the World Bank about $220 billion, but much of that capital is already deployed in existing projects and their mandates are much broader than infrastructure. A MDB entirely dedicated to infrastructure and with significantly larger potential leverage than existing development banks is much closer to the future infrastructure platform model that can unlock the bottleneck preventing the flow of long-term savings towards long-term infrastructure assets. With a higher projected leverage it is likely that the AIIB will not just be issuing AAA rated bonds to long-term investors, but also lower rated bonds with a higher yield, which should make these particularly attractive to long-term investors in the current global low yield environment. Another advantage of a large development bank, fully dedicated to infrastructure, is that it can fund much larger projects and coordinate investment for entire infrastructure networks, thus increasing the profitability of individual projects. This is particularly relevant for transport, water, and electricity infrastructure projects.

4.3. Tradeoffs and next challenges

Several lessons can be drawn from this brief description of the four infrastructure investment platforms. A first obvious lesson is that the ability of development banks to leverage public money—committed capital from government contributions—by attracting private investors as co-investors in infrastructure projects, is increasing the efficiency of development banks around the world. It is not just the fact that development banks are able to invest in larger-scale infrastructure projects and thus obtain a greater bang for the public buck, but also that these private investors, together with development banks, can achieve more efficient PPP concession contracts. Development banks are not just lead investors providing some loss absorbing capital to private investors. They also give access to their expertise and unique human capital to private investors who would otherwise not have the capabilities to do the highly technical, time-consuming, due diligence to identify and prepare infrastructure projects. In addition, they offer a valuable taming influence on opportunistic government administrations that might be tempted to hold up a private PPP concession operator. Private investors in turn, keep development banks in check and ensure that infrastructure projects are economically sound and not principally politically motivated. No wonder this platform model is increasingly being embraced by development banks around the world.

At the same time these platforms look more like green shoots next to the enormous global challenge of originating an aggregate flow of infrastructure projects of the order of one trillion dollars per year for the next two decades. As promising as this platform model is, it needs to be scalable to deliver on the promise of channeling under-used, long-term, savings towards more sustainable investments. To achieve greater scale, a number of aspects of the infrastructure platform model could be further refined and other avenues for infrastructure platforms should be pursued.

A first area that merits rethinking is the process of project preparation and the protocols for allocating human capital resources inside development banks to specific infrastructure projects. A related issue is how development banks can ensure that reliance on human capital resources is adequately compensated, given that only a fraction of the projects that are being considered will turn out to be "bankable" and worth bringing to completion.[17] The current model is essentially one where a host government approaches

17 According to the EIB a PPP project is considered to be bankable if "lenders are willing to finance it. The majority of PPPs are funded on a project finance basis where a special purpose vehicle is established to ring fence the project revenues and debt liabilities." http://www.eib.org/epec/g2g/i-project-identification/12/123/index.htm.

a development bank to initiate the investigation and preparation of an infrastructure project. It is only after a first round of screening that the development bank undertakes more thorough due diligence and project preparation. Private investors are brought into the picture fairly late in this process, if at all. They are often the last parties to be brought into the picture, at a point when the main contours of the project are already set. Institutional investors have become so accustomed to being spoon-fed nearly completed deals that they currently show little interest in getting involved in earlier stages. However, if the deal flow is to be significantly ramped up, the current model has to be revamped to incentivize institutional investors to work with development banks at earlier stages of the preparation of bankable projects.

There are a number of potential obstacles created by this process. First, if there are no clear rules for allocating the right infrastructure experts to new projects as they come along, there could be substantial inefficiencies and unnecessary bureaucracy involved in the project preparation phase. Development banks are not yet all fully set up to fulfill their role in providing expertise optimally to the right projects. Ideally development banks should have an internal labor market for infrastructure experts with sufficiently widely available information on who is expert on what and who is available to work on a new project. There should be a form of a bidding process in place so that experts get matched to the right projects and are adequately incentivized to work on the right projects. Equally, there should be a shadow price for this expertise that is included in the overall cost of infrastructure projects. One difficult pricing problem is how to charge for this expertise on projects that are not undertaken. If the cost of project preparation and due diligence is only imputed on those projects that end up being developed, then there will be a number of distortions. Development banks could end up being flooded by requests; too many to handle. And they may have to devote a significant fraction of their income to pay their experts. This distortion, in turn, could give rise to understaffing and the creation of too small infrastructure teams. Development banks could, of course, relax this staffing constraint by outsourcing project preparation to external consultants, but without the long-term commitment of institutional investors to participate in the origination of new projects and, possibly, in sharing project preparation costs, development banks will not have sufficient financial resources to bring in such outside consultants.

But possibly the most important shortcoming with the current process of project preparation is that private investors are largely thought of as passive players, with perhaps the exception of the handful of private infrastructure investment funds that actively cooperate with development banks in the preparation of projects they co-invest in as long-term equity investors. But, if the infrastructure platforms are to be scaled to an adequate size then the overwhelming source of private capital will come from long-term asset managers such as pension funds, insurance companies, and SWFs. These investors are currently mostly thought of as passive players that will only be approached when the project preparation work is complete and additional sources of funding are sought.

However, the largest private investors, who after all could hold a large bundle of infrastructure assets, should be brought in much earlier and be allowed to play a much more active role. These investors will have a more global view of which infrastructure projects are bankable as opposed to the development banks that are currently geographically restricted. They should also be able to initiate or propose projects to be studied and prepared. Global institutional investors could have a better sense of what a whole infrastructure network should look like—a network of waterways, canals, sewage systems, electric grids, roads, railways, etc.—to make each individual project in the network bankable.[18] This is all the more likely if the efficient growth of the network is transnational and involves coordination of neighboring host governments, who are not necessarily used to cooperate with each other on infrastructure development. In sum, an infrastructure project initiative could also come from investors, with development banks providing investors access to host governments and playing the role of project preparation facilitators.

Furthermore, another important role of development banks in supporting infrastructure investment platforms is to undertake more comprehensive planning of infrastructure investments and how each individual project may fit into a broader infrastructure network development plan. An obvious risk in considering each project on an ad-hoc and isolated basis is that the project is more likely to be assessed as non-bankable. Building and operating a new highway may be seen as generating too few immediate development benefits and toll revenues if the subsequent development of an entire road system and other infrastructure projects is not taken into account. The same is true for investments in electrification, water, railways, and other transport networks. To the extent possible infrastructure investments should also be structured to allow the developer and operator to capture the external value created by the investment. As the Hong Kong MTR example strikingly illustrates, value capture especially for urban infrastructures is an effective way of ensuring the bankability of infrastructure investments.

Finally, the EBRD experience illustrates that many of the investments currently made by development banks are either not in infrastructure at all or not sufficiently in greenfield infrastructure projects. The reason is that a 10 or 12 year payback horizon for a project is just too short. A recent example that illustrates the risk of development banks creeping away from greenfield and more into brownfield is the EBRD's investment in the modernization of railways in Moldova in November 2014. The investment no doubt enhances the efficiency of the railway and its revenue generating capacity. It is also an important contribution to the economic development of Moldova. Nevertheless, this is not a true greenfield investment in a new railway, which the EBRD is not set up to do given its somewhat short investment horizon.

18 So far, most PPP projects have been envisioned at a national level, even in the EU. The coordination of PPP projects at a transnational level is complex and involves significantly longer preparation, which makes them less attractive to private sector investors.

5. CONCLUSION

This paper is a first attempt to conceptualize and put into perspective the dramatic evolution of the global architecture of infrastructure finance, which so far has only received the attention of development finance policy circles and has not been the subject of academic study. The infrastructure platforms we discussed will certainly help on two important fronts, namely the financing and origination of infrastructure projects. Our paper is only a first introduction to the institutional design of infrastructure platforms and much more systematic and formal research is needed to identify the optimal contract features of infrastructure platforms and multilateral PPPs.

On the more immediate economic policy front, our paper is a call for governments and MDBs to ramp up the early prototypes of infrastructure platforms and to improve the technical capabilities of host governments to be able to better cooperate with MDBs in the preparation and financing of new PPPs, so that the flow of origination of infrastructure assets reaches a critical mass large enough to be a material alternative for most large, long-term, institutional investors. Two important sets of policies are needed to further this agenda. First, the promotion of standardization of underlying infrastructure projects is essential to help scale up investment into infrastructure-based assets. Large physical infrastructure projects are indeed complex and can differ widely from one country to the next. In that respect, governments and MDBs should help provide the institutional environment to encourage the use of securitization techniques such as collateralized bond obligations or collateralized loan obligations, which will enhance the efficiency of the market and allow for a more effective pooling of risk. Securitization would also be a way to increase the size of infrastructure-backed bond offerings and thereby attract the interest of larger long-term investors. Overall, securitization can provide many advantages such as diversification for investors, lower cost of capital by allowing senior tranches to be issued with higher credit ratings, as well as higher liquidity. At the same time, securitization also creates debt instruments of variable credit risks to match the different risk appetites of investors. Second, governments and MDBs should promote the important complementarities between actors participating in the "value chain" created by platforms that include host countries, financial investors, guarantors, and financial intermediaries.

Finally, many host countries have viable long-term infrastructure projects waiting to be developed, but without the provision of guarantees to address construction, demand, and exchange rate risks, these projects currently will not be funded. A basic economic principle is that risks should be assumed by those best placed to hold them. Governments are the natural holders of political, regulatory, and governance risks. The private sector developers and operators of the infrastructure facilities for obvious incentive reasons should take on most of the construction risk, but demand risk should probably be shared, depending on the sector and type of project. Accordingly, an important complement to the development of infrastructure platforms around MDBs is the creation of multilateral guarantee funds that can take on political, regulatory, and exchange rate risk, and thus make infrastructure investments more attractive to private long-term investors.

Discussion

Nicolas Coeurdacier

SciencesPo

The paper deals with two crucial policy questions regarding the needs to launch large infrastructure projects globally. The first question addressed in the paper, more macro, asks whether policies should be targeted towards large investments in infrastructure. The second question, more micro, deals with the way such infrastructure projects should be financed. To the first question, the paper answers unambiguously yes: savings are high globally, yields are low, and there is a lack of necessary infrastructure globally. To second question, the paper argues in the favour of the use of public–private partnerships (PPPs) involving long-term institutional investors as well as multilateral and regional development banks—the latter to mitigate political risks of expropriation of private partners.

Let me discuss sequentially the two questions addressed in the paper.

I. Should we increase infrastructure investments?

While it is hardly disputable that savings are high, at least in some parts of the world, and real interest rates are currently low, one might wonder whether investments infrastructure are indeed deeply needed and whether this is the right time to launch such projects.

The paper suggests that demand for infrastructure is very high at the moment, or equivalently returns on such investments are high. If this is the case, why are infrastructure investments not currently already on the rise? The paper suggests that governments might be restricted in their ability to run this projects as many are currently consolidating their budget. Tax capacity can also be lacking in many developing/emerging countries. However, if returns were so high, wouldn't we expect the private sector to step in and provide the necessary funding? Indeed, one might wonder why private banks, which have expertise in project finance, are not willing to finance such infrastructure projects.

High returns?

One answer could be that private returns are not that high, at least risk-adjusted ones, even though, arguably social returns could well be very high. While empirical evidence on the private returns of infrastructure projects is quite scarce in the economics and finance literature, the management literature is more developed on the matter and most studies and case studies point in the same direction: private returns are quite low and risks are particularly high. Infrastructure finance suffers frequently high cost overruns and construction delays. Studies usually point towards low equity returns and high default rates [see Esty (2004) for references]. However, arguably, empirical evidence remains scarce and more research is definitely needed to assess the expected private returns and the corresponding risks of such projects.

This being said, even with low private returns, such projects can still be worth launching as social returns might be significantly higher—due to the potentially strong positive externalities of infrastructure on the aggregate economy. On this matter, there is a relative consensus in the large literature in macro and economic geography. Most studies, using various identification strategies, do find large positive output aggregate effects of the financing of infrastructure. A seminal paper by Fernald (1999) finds remarkably large rate of return of the construction of the US interstate highway system in the 1950s–1960s. Pereira (2000) estimates high long-run output multipliers for public infrastructure in the United States over 1956–1997—also corresponding to relatively large rate of returns. More recent work by Leduc and Wilson (2012) provide similar findings but they find also large shorter term output multipliers [see also, among others, Donaldson (2016) for roads in colonial India, Bloningen and Cristea (2015) for air transports in the United States].[19]

Moreover, in the current economic environment with sluggish growth and low investment rates in many advanced economies, one might expect the social returns of infrastructure projects to be even larger. With low aggregate demand, slack in labour markets and low factor costs, one might expect indeed the output multipliers of such investments to be particularly high. There is quite a consensus, theoretically, and empirically, that output (fiscal) multipliers are higher in period of low growth and/or when economies are at the zero-lower bound [see, among others, Auerbach and Gorodnichenko (2012) for empirical evidence, and Eggertsson (2011) for theoretical insights and references]. Leduc and Wilson (2012) confirm this evidence in the specific context of infrastructure investment—finding larger multipliers of US highway grants during the last 2008–2009 recession.

In summary, while risk-adjusted private returns might be low, partly explaining the insufficient involvement of the private sector in launching the necessary infrastructure investments, social returns are likely to remain high, particularly so given the current economic environment—justifying the need for increasing such investments.

Let me now turn to the second question addressed in the paper regarding the contractual arrangements to finance these large infrastructure projects.

19 As a cautious note, one should add that existing evidence finds high social returns for previous (and early) infrastructure projects. Decreasing returns might be an important concern for this type of investments.

II. How should we finance these infrastructure investments?

If, as suggested above, social returns are significantly higher than the private ones, some involvement of the public sector seems a natural outcome. Assuming that the government cannot do it alone (or is not willing to), the paper argues, in favour of PPPs. This could still help "internalizing the externalities" due to the presence of the public sector, and could, due to private incentives, generate some efficiency gains. Another argument in the favour of PPPs developed in the paper are the potential benefits from risk-sharing—due to a better allocation of risks between private and public entities. Let me focus on this latter point, which is less studied and might deserve some comments.

How to allocate risks?

Infrastructure investment is notoriously very risky. On the top of standard country-specific aggregate risks (exchange rate risk, demand risk, etc.) and standard credit risks, these projects face very large idiosyncratic risks (construction risk, technological risk, etc.) and more acute political risks (expropriation and regulatory risks). How these risks should be allocated and mitigated?

For incentives reasons, one could argue that the large idiosyncratic risks of these projects should be put in the hands of the private sector. However, the mere presence of these large risks could well be the main reason of the lack of involvement of the private sector in the first place. Because monitoring seems essential for infrastructure investments, these risks cannot be so easily diversified and reallocated to diversified private investors (long-term institutional investors for instance). Their reallocation to diversified investors would also raise many issues in case of debt restructuring—which is very common for infrastructure projects where default rates are fairly high. Increasing the number of private partners might increase coordination costs.

Credit risks would be arguably allocated to the public sector as it faces lower borrowing costs. But this would not go without potential moral hazard and excessive risk taking by the private entities—similarly to what has been found in the literature on bank risk-taking and government's guarantees [see Gropp et al. (2013) for recent evidence and references]. While this might be more of second-order in the context of infrastructure projects, this remains to be debated.

Finally, PPPs face a potentially more acute political risk of expropriation. On this latter point, the additional involvement of development banks is arguably crucial but its effectiveness remains to be proven. Empirical evidence on this matter is still rather scarce.

In conclusion, the paper is definitely thought-provoking and deals with a question that should be very high on the policy agenda. While this might indeed be a good time for increasing investment in infrastructure, additional empirical evidence on the costs/benefits of such investments is deeply needed—particularly so when involving private investors. While PPPs involving development banks and long-term investors as partners is an interesting and worth pursuing idea, some further evidence explaining the lack of private involvement in those projects in the first place should help to better address the potential market failures. Further work on the optimal allocation of the (very high) risks associated with infrastructure projects is also needed—both theoretically and empirically. This would help to fully assess the form of contractual arrangements that are deemed to be the most efficient.

Evi Pappa

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Introduction

The paper is a good piece of work that tries to bring attention to the finance of infrastructure investment into academic and policy circles. It stresses the huge infrastructure financing gap: demand for infrastructure is far from matching its supply. Both developed and emerging market economies have had to deal with international long-term private debt financing options that are less supportive of infrastructure finance. Despite the unconventional monetary policies in advanced countries after the crisis that have led to the "global saving glut", traditional sources of long-term finance have been retrenching and alternatives have not been able to adequately compensate.

After presenting the global landscape for investments in infrastructure and the problems associated with its financing, the authors try to shed light into what a new model for infrastructure investment should be. The authors propose infrastructure investment platforms as an attempt to tap into the pool of both public and private long-term savings to channel the latter into much needed infrastructure projects. It then reviews four key existing investment platforms: (a) The European Investment Bank; (b) The World Bank's Global Infrastructure Facility; (c) The EBRD Equity Participation Fund; and (d) The Asian Infrastructure Investment Bank. Looking at those recent experiences they finally draw lessons for new platforms that could potentially close the rising gap in infrastructure investment.

The paper puts a lot of emphasis on the presence of a saving glut. I do not think that the saving glut is central in the argument of the paper, to me what seems central is the gap resulting from the crisis. From the public sector side, infrastructure funding has faced stringent conditions due to fiscal consolidation, while, from the private sector side, banks have been retrenching and the supply by non-bank institutions has been inadequate. According to the evidence that the authors highlight the average infrastructure investment gap amounts to between \$1 and \$1.5 trillion per year and infrastructure investment needs range from 3% of GDP in advanced economies to 9% of GDP in emerging economies, and more than 15% of GDP in some low-income economies. To me the gap is central in the analysis. As a result, if I could be the godmother of the paper, I would rather call it "Arrival of New Investment Platforms: Mind the Gap in Infrastructure!"

Apart from complaining about the title, the paper is interesting and very relevant. Scrolling through the Internet as an outsider I found several recent entries from *The Economist* and the *Financial Times* referring to the infrastructure gap needs and its association with the development of the new investment platforms. In particular, an article by Otaviano Canuto, ex-Senior Advisor on BRICS Economies in the Development

Economics Department, World Bank, now Executive Director at the IMF, dated 19 September 2014, brings attention to similar issues raised in the current paper. Quoting Canuto word for word, The world economy faces huge needs of infrastructure finance, but the financing gap is yawning. Emerging market economies have faced a cross-border infrastructure finance drought amidst a liquidity glut and EMEs need to tap new sources for long-term funding. What Development Banks Can Bring to the Table: The key word here is "additionality." According to Canuto, investment platforms can provide some value-added relative to what markets and institutions are already able and willing to do.

Development banks can play a key role as a catalyst, for drawing private capital into long-term projects in countries and sectors where significant development results can be expected, but the market perceives high risks so as to crowd in private investment. Moreover, such investment platforms can improve the process of project selection by governments and they reduce risk via diversification.

The clash: train in vain

Before raising my points on the paper, I would like to take a specific example to discuss some failures infrastructure investments are subject to. My example is driven from the recent experience of the big scale investment in the high-speed railway system in Spain.

Since the mid-1990s, Spain's railways have been expanding at a rapid pace, thanks to huge national investments and European grants. The motivation behind what has been a sustained investment in the rail sector has had part-economic, part-political justifications: the government's aim was to build a fast, modern, and reliable web of public transportation which would link the country's main financial centres; hence, stimulating free movement and business growth. Yet, high growth in Spain was not long-lived and the arrival of the Crisis hit Spanish internal demand quite badly. The problem with the investment in high-speed trains (AVE-Renfe) is that profitability is low and comes from the overestimation of demand for these services.

A study by Ofelia Betancor and Gerard Llobet, published as a working paper in Applied Economy Studies Foundation (FEDEA) Working Papers (in Spanish), shows that this investment has significant financial and social costs. Any singular high-speed line in Spain registers significant losses. According to their 50 years' worth of financial data observations, currently, the Madrid–Barcelona corridor comes up ?4.08 bn short, the Madrid–Andalusia corridor €4.95 bn short and the Madrid–Levante corridor €5.32 bn short, on average. In terms of social benefits, numbers are similarly disappointing. Where did the AVE fail? The planning of the AVE was central and did not take into account the specific local needs or accounted for the size of the financial or social externalities of the fast lanes at the local level. The authors do not at all touch on this issue. How would the investment platforms that the authors propose avoid such failures?

What I have learned from reading the paper

In my opinion, given the externalities that the public infrastructure entails and the public nature of infrastructure, local governments should put forward projects and be responsible for them by raising debt, taxes, or both. However, local finance is scarce, especially in emerging economies. Yet, letting local governments issue debt can be very dangerous (see Argentina). Enforceability and no bail-out closes do not work in practice (see Greece) and, moreover, the regulatory and political risks are high.

This is where investment platforms should step in. For me, world development banks should work as vehicles of turning greenfield to brownfield projects in infrastructure. From the models the authors discuss the EIB is closest to what I would find ideal. The EIB's most innovative infrastructure investment activities are in project finance. Yet, I would suggest the EIB's involvement as a way to reinforce infrastructures projects in their preparation stage and as a co-investor, a lender, or a servicer. A typical project in which the EIB will be involved should have about 70% of the cost funded initially either through a bank loan, which may subsequently be refinanced in the bond market, or through a long-term project bond, with the EIB providing support either through a credit enhancement scheme, to remove exposure of local governments to construction and early operating risks. I oppose the current possibility of equity co-investment with a private long-term infrastructure investor. The participation of private investors at the initial phase of the project can only increase the cost of raising capital. To show my point, I quote a recent article from the *Financial Times* by C. Flood that is initiated by, "The growing appetite for infrastructure debt among pension funds and insurers is fueling concerns that returns from the sector could prove disappointing as rising demand pushes infrastructure debt prices up and yields down." Private or institutional investors only greed for higher returns, the government should try to get infrastructure done by issuing bonds at a fair rate and the investment platform can help the government accomplish such a scope.

Contrary to the authors' opinion, to me for investment platforms to work and maximize the social benefits of infrastructure, it is essential to highlight that the private sector should come last in this process and will participate through buying bonds or leasing the semi-finished project for a considerable span of time varying from 20 to 99 years. To avoid problems of congestion raised at the last part of the paper, the governments can prepare a short list through democratic procedures of their top priorities in local investments and the investment platform can decide on which projects to start up after a thorough evaluation of the proposals.

The infrastructure gap is there and has been yawning for a while, growth is a long-run objective, rushing to bring in short-sighted investors does not seem like a brilliant idea.

Panel discussion

Klaus Schmidt wondered whether most of the financing issues the authors show in the paper can ultimately amount to incentive problems. Ugo Panizza observed that according to policymakers, the main constraints to financing infrastructure projects are often not financing problems per se, but difficulties related to internally or externally imposed fiscal targets. Shang-Jin Wei noted that, in his view, the only existing gap is between available bankable projects and the socially optimal amount of projects. Charles Bean asked why Australia and Canada seem to be more willing to invest in infrastructure assets when compared with other countries.

George de Menil and Thorsten Beck emphasized the problem of internalizing the different externalities and appropriating the returns of infrastructure projects. Thorsten Beck also observed that there are legal tools to help in internalizing such externalities (one of the main problems for investors in emerging countries) but that at the political level these tools may not work. He asked how the authors address this political risk in the paper.

Replying to comments, Patrick Bolton first highlighted that the importance of human capital is often neglected when discussing how to make infrastructure projects bankable. He argued that most professionals/specialists (which are in scarce supply) work for development banks and that the return these banks have is considerable. Regarding political risk, he gave the example of the EBRD that has been very successful due to strong enforcement powers. Following some of the points raised during the discussion of the paper, Frédéric Samama added that from his perspective investors are increasingly worried about social gains and the impact on society as well.

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Global Public-Private Investment-Partnerships: A Financing Innovation with Positive Social Impact

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The energy transition away from fossil fuels is already underway in some of the most advanced economies. Unfortunately, however, the most climate-virtuous countries produce only a small fraction of global carbon emissions. One of the greatest challenges in achieving the energy transition on a global scale is to wean emerging market economies from their fossil fuel dependence and so encourage their development on a sustainable, carbon-free basis.

The energy transition away from fossil fuels is already underway in some of the most advanced economies. Unfortunately, however, the most climate-virtuous countries produce only a small fraction of global carbon emissions. One of the greatest challenges in achieving the energy transition on a global scale is to wean emerging market economies from their fossil fuel dependence and so encourage their development on a sustainable, carbon-free basis.

As study after study has concluded, this will require massive sustainable infrastructure investments. Yet, the same studies point to the recurring huge gap in actual and needed investments. A McKinsey report[1] estimated that total although infrastructure investment in 2015[2] was around $2.5 trillion, an average of $3.7 trillion per year would be needed for the next 20 years—and so until 2035—to meet global needs (with an another $1trillion per year required to achieve the UN Sustainable Development Goals). Overall, emerging economies account for nearly two-thirds of anticipated global infrastructure investment needs.

Global bond markets are the main source of funding for these investments, along with banks and governments. In particular, "green" bonds that are issued to finance environmentally and climate-friendly investments are becoming the main source of funding of the global energy transition. Although such bonds are a relatively recent innovation, the green bond market has grown rapidly from its start in 2008 to reach around $800 billion in outstanding issues. Continued exponential growth in this market is to be expected in the coming years, since green bonds still represent less than 1% of global bond markets.

Green bonds to date have been issued disproportionately in developed markets by government-sponsored entities, corporations, and municipalities. In the emerging market countries where the infrastructure investments are most needed, they are essentially non-existent.

One of the biggest challenges for global financial markets today is how to channel the vast pools of savings that are now invested in low or (even negative) yield fixed-income assets—as much as $17 trillion in 2019—to the higher-return sustainable, infrastructure investments in emerging markets. Economists have long puzzled over why so little capital from advanced countries, with saturated capital markets and limited investment opportunities, is flowing to emerging market countries, with high growth potential and abundant investment opportunities. Common reasons cited are emerging market countries' greater instability and inadequate property rights protections for investors, including the possibility of capital controls in the midst of financial crises.

But another important reason is the lack of development in capital markets in emerging market economies. Stock and bond markets are small in relative terms, and most emerging market economies have financial sectors that are dominated by banks. Only a handful of banks such as JPMorgan, Citi, and HSBC

* We gratefully acknowledge the support of the Rockefeller Foundation. We are grateful to Don Chew for his comments and detailed suggestions on the paper. We thank Timothée Jaulin and Jean-Marie Dumas for excellent research assistance. The views expressed in this paper are those of the authors and do not necessarily reflect the position of the Crédit Agricole Group.

1 See Jonathan Woetzel, Nicklas Garemo, Jan Mischke, Priyanka Kamra, and Robert Palter, "Bridging Infrastructure Gaps: Has the World Made Progress?" McKinsey Global Institute, *Global Discussion Paper*, October 2017

2 Economic infrastructure can be considered as roads, railways, ports, airports, power, water and telecoms.

have a global presence. And because such banks cater mostly to the needs of multinational corporations, they are not set up to channel savings from assets owners in wealthy countries to long-term investments in emerging markets, especially since the financial crisis and the imposition of tighter prudential regulations that have the effect of penalizing investments with a long payback period. In short, there is a major institutional gap in the global financial architecture that, as we argue below, now prevents the efficient allocation of capital around the world.

The World Bank Group, Multilateral Development Banks (MDBs), and other Development Finance Institutions (DFIs) can narrow this gap to some extent, but their funding is quite limited relative to the growing investment required to move to a more sustainable global economy. The most likely solution therefore lies in tapping into the vast private savings pool in rich countries by *combining* these savings with public funding from development banks.

> The AP EGO fund breaks new ground in financial innovation by applying a securitization technique with a fund structure that has an embedded first-loss protection to a global pool of green bonds to be originated in emerging market economies. This is a first in the world of structured finance.

This is where the IFC's idea to launch an emerging market green bond fund comes in. The IFC, the financial markets affiliate of the World Bank Group, is the largest global development finance institution focused on the private sector, with a significant footprint in more than 100 countries. As such, the IFC has the capability of investing directly in the most difficult markets in the world. It is uniquely placed to initiate such a fund, given that it is at the center of a network of emerging market banks. It has a long relationship with these banks and is therefore ideally placed to channel savings from rich countries through this emerging market banking network. The main challenge facing the IFC, however, has been how to attract the savings that they can then channel into sustainable investments.

In the meantime, developed country institutional investors have long sought to diversify their portfolios into alternative investments and into emerging markets. The main obstacle they face is limited expertise and capabilities in identifying and assessing large enough investments in emerging markets. The cost structure and risk management policy of most asset managers calls for large investments (at least $100 million) that are relatively safe and liquid (investment grade or high quality sub-investment grade) and well diversified (no more than 10% of the liabilities of any issuer). These constraints have severely limited their ability to enter emerging market economies.

Putting two and two together, the IFC realized that the only way of opening up emerging market countries to foreign institutional investors and deploying savings from rich countries to sustainable investments in emerging markets is by means of a securitization-like approach. By relying on its relations with emerging market banks to catalyze green bond origination, the IFC could package these bonds into a large enough green bond asset pool to appeal to institutional investors.

To manage the credit risk in this structured fund, it could ensure that the asset pool is well diversified across emerging market economies, and it could also provide some credit enhancement by investing in a sufficiently large first-loss tranche. By so doing, the IFC estimated that it could obtain an investment-grade equivalent credit risk for the senior tranche that would be targeted to institutional investors. Provided enough institutional investors were attracted to this collateralized green bond structured-fund (offering a first-loss protection by the IFC), the senior fund shares could also be listed, thereby offering valuable secondary-market liquidity.

This at least is how the idea of the AP EGO was first conceived. But, as always, a major step remained between the concept and its implementation. This step was successfully completed by Amundi Asset Management, the firm that was selected by the IFC to implement the concept. More specifically, Amundi's mandate was to put in place the detailed structure of the fund, identify the banks in emerging markets that could originate green bonds, place the securities with institutional investors, and perform the investment management of the whole fund.

The AP EGO fund, since its inception and launch on 28 February 2018, has broken a number of records and received several awards. It provides a model that can be replicated and lead to the creation of major new asset classes, among which are emerging market green bonds. In the pages that follow, we provide a brief overview of the new four-partner PPP model that is the conceptual basis for the AP EGO fund. Then, after outlining the basic structure of the fund and its institutional underpinnings, we explore the potential development of sustainable finance in emerging markets that the AP EGO fund has opened up.

The New Model for Public-Private Partnerships

The AP EGO fund is premised on a new conceptualization of public-private partnerships (PPP).[3] The usual way of describing a public-private partnership is a concession granted by a public agency to a private operator. A classical example is toll-bridges and roads. The bridges and roads are built and maintained by a private company, who is given the right under a concession contract with a public agency to charge a toll for the use of the transport infrastructure. This example involves two partners, a public and a private one.

Many ventures structured as PPPs have failed, and the form of the PPP itself has come under intense criticism. The fundamental economic problem faced by most PPPs has often been described as a *hold-up* problem: after the bridge is built, it is efficient to maximize the utilization of the bridge, which is generally achieved by giving free access to it. Public authorities are therefore under pressure to grant free access and may be tempted to renege on the PPP contract with the private operator. They can be counted on to exploit every loophole in the contract to drive down the tolls ex post.

Private operators, of course, having learned to anticipate this behavior, have either become unwilling to enter such contracts, or have responded by cutting corners in ways that allow them to recoup their investment as quickly as possible. This basic economic problem is the main reason why so many PPPs have generated contract disputes and ended in failure. Another important source of problems with PPPs has been the tendency of the granting of concessions to private operators to involve political payoffs and other forms of corruption.

Many commentators have concluded from these weaknesses in the structure of PPPs that they should be abandoned altogether and that all infrastructure investments should be tax-payer funded and publicly operated. But publicly operated and funded infrastructure cannot be seen as a model, given all the evidence around the world of the huge inefficiencies in the operation and maintenance of public infrastructure facilities.

Accordingly, the way forward is to strengthen the PPP model. In a study involving two of the present writers that was published in 2017, we argued that the PPP model should be thought of as a partnership involving *four* rather than just two partners. Besides the public agency and the private concession operator, there should be two other partners: a development bank and private investors. The development bank is a critical partner because it has the human capital and knowhow in structuring PPPs. It also plays a critical role in coordinating and planning different PPP investments. And perhaps most important, as a repeat, long-term player and gate keeper, it also plays a disciplining role for both the public authorities and the private concession companies, ensuring that they stick to the agreed terms of the PPP contract. Finally, the limited public funds of development banks can be, and are best, used as a credit enhancement and risk mitigation mechanism, one that encourages private investors to provide the bulk of the funding for green-field investments. In sum, the four-partner PPP model allows not only for the optimal allocation of risk between development banks and private investors, but also sets up the right governance structure to ensure the sustainability of the investment.

Another fundamental dimension of most PPP infrastructure projects is the public goods nature of the investment. Nearly all studies of the return on infrastructure investments conclude that the social rate of return is much higher than the private return because the investment generates valuable externalities.[4] The main challenge in originating "bankable" projects is figuring out how to internalize as much of these externalities as possible. This can be achieved through "value capture." Again, development banks can play a fundamental role in structuring the capture of social value of infrastructure investments by requiring that land development rights, which appreciate in value as a result of the infrastructure investment (and can be used as collateral to reduce the financing cost), be granted to the investors in infrastructure projects.

Most developed-country institutional investors are comfortable holding only senior debt instruments, preferably guaranteed, in relatively safe emerging market investments. This is why development banks can play an important role as credit enhancers, providing loss absorption capacity and thereby leveraging their scarce public funds to attract institutional investors. Moreover, multilateral development banks can reduce risk and provide important diversification benefits to institutional investors by bundling multiple investments and issuing asset-backed securities. An added advantage of such securitization is its ability to reach sufficient scale to attract institutional investors.

The IFC-Amundi AP EGO Fund

3 Rabah Arezki, Patrick Bolton, Sanjay Peters, Frédéric Samama and Joseph Stiglitz, "From Global Savings Glut to Financing Infrastructures," *Economic Policy*, Volume 32, Issue 90, April 2017, Pages 221–261

4 See in particular the recent studies by Dave Donaldson (2018) "Railroads of the Raj: Estimating the Impact of Transportation Infrastructure," American Economic Review, Volume108 (Number 4-5), Pages 899-934, April 2018; and Dave Donaldson and Richard Hornbeck (2016). "Railroads and American Economic Growth: a 'Market Access' Approach," *Quarterly Journal of Economics*, Volume 131 (Issue 2), Pages 799-858, May 2016.

Figure 1
Emerging Market Green Bond Potential

Investment potential in cities by region and sector to 2030

	East Asia Pacific	South Asia	Europe and Central Asia	Middle East and North Africa	Sub-Saharan Africa	Latin America and Caribbean	Total
Waste	$82 billion	$22 billion	$17 billion	$28 billion	$13 billion	$37 billion	$200 billion
Renewables energy	$266 billion	$141 billion	$88 billion	$31 billion	$89 billion	$226 billion	$842 billion
Public transportation	$135 billion	$217 billion	$116 billion	$281 billion	$159 billion	$109 billion	$1 trillion
Climate-smart water	$461 billion	$110 billion	$64 billion	$79 billion	$101 billion	$228 billion	$1 trillion
Electric vehicles	$569 billion	$214 billion	$46 billion	$133 billion	$344 billion	$285 billion	$1.6 trillion
Green buildings	$16 trillion	$1.8 trillion	$881 billion	$1.1 trillion	$768 billion	$4.1 trillion	$24.7 trillion
Total	$17.5 trillion	$2.5 trillion	$1.2 trillion	$1.7 trillion	$1.5 trillion	$5 trillion	$29.4 trillion

INCREASING INVESTMENT

Source: IFC analysis.

The new PPP model outlined in the previous section provides the conceptual framework for the innovative emerging-market green bond fund put together by the IFC and Amundi Asset Management. It frames the solution in terms of a public-private partnership between the IFC playing the role of a development bank and credit enhancer, the network of emerging market banks it has relations with, and the institutional investors who gain access to green assets originated in emerging markets.

In one key respect, however, the AP EGO Fund is a fundamentally different partnership from other PPPs—namely, it is a special purpose vehicle holding a pool of assets originated in multiple emerging market countries against which shares in a listed fund could be issued to institutional investors. The AP EGO fund breaks new ground in financial innovation by applying a securitization technique with a fund structure that has an embedded first-loss protection to a global pool of green bonds to be originated in emerging market economies. This is a first in the world of structured finance.

It is also remarkable that this innovation took place *after* the financial crisis, at a time when the private-label residential mortgage-backed securities market had ceased to function. Securitization had acquired a bad reputation in the wake of the great financial crisis, so that it was far from obvious that there would be appetite for a new experiment in credit-tranching products of much greater complexity and in an entirely new asset class.

A first open question was whether there would be enough of a deal flow in green bonds from emerging markets to back the securities issued to institutional investors. As shown in Figure 1, the IFC has projected that by 2030 the emerging market green bond market will have grown to S29.4 trillion. By far the largest category of such bonds are expected to finance green buildings ($24.7 trillion), with electric vehicles the next largest asset class ($1.6 trillion). Given that the largest asset classes that are securitized in the U.S. are residential and commercial real estate and auto loans, it is plausible that the green counterparts of these assets in emerging markets could also be securitized.

As promising as these projections are, the IFC and Amundi faced a major challenge in identifying the supply of green bonds that were already, or soon to become, available in 2018. In which countries were banks making green loans against which they could issue green bonds to be included in the AP EGO asset pool?

The IFC contemplated the use of only emerging market green bonds that were issued by banks. Given the dominance by banks of emerging market financial systems and market economies, the "greening" of bank loan portfolios was viewed as tantamount to greening their financial systems. And the thinking was that banks in such countries should be especially receptive to making environmentally friendly loans provided they can fund these loans at favorable rates by issuing green bonds that carry a lower cost of capital.

Another challenge was developing the certification process for green loans and bonds. What qualifies as a green loan, and under what criteria can a bank issue a green bond? Here again, the IFC, as the multilateral bank with expertise in financing impact loans, played a fundamental role in setting the green bond standards.

One representative example of an asset that could be added to the AP EGO pool is a $150 million green bond issued by Davivienda, the third largest bank in Colombia, and whose proceed were earmarked to fund green buildings and housing. When issued in April 2017, it was the largest green bond by a private financial institution in Latin America.

The target size of the AP EGO pool was $2 billion. How many emerging market green bonds like the Davivienda bond had been originated that could be added to the pool? If the Davivienda bond was the largest green bond issued by a private bank in Latin America, there would likely not be a sufficient pool of existing assets to reach the $2 billion target. However, the goal was not to have all the green bond assets from the get-go, especially since the securitization of these bonds would not by itself increase the origination of green bonds.

The idea of the AP EGO fund was instead to start by putting together a mixed pool of emerging market bonds—some green, some not—and over time to replace the regular bonds in the pool by green bonds, as illustrated in Figure 3. In this fashion, a steadily rising proportion of the funds raised from institutional investors would go to finance green bonds and green loans in emerging markets.

One important advantage of the strategic focus on green bonds issued by financial institutions was that it not only takes advantage of the dominance of bank lending in emerging markets, but it significantly reduces the counterparty risk faced by institutional and other investors. Thanks to their reliance on locally informed due diligence and their ability to diversify risk through their loan pool, the counterparty risk of overseas financial institutions is significantly lower than when buying bonds directly issued by non-financial entities to fund their green projects. Providing additional comfort, when local banks issue a green bond, they effectively put their entire balance sheets on the line, not just the projects they finance.

Given that the origination of green bonds was to be gradual, a critical backbone of the fund structure was to set up an IFC-led technical assistance program that would give emerging market banks the capabilities to originate green bonds. Here again the IFC played a critical role in identifying participating banks and training loan officers and analysts at these banks to originate green loans and green bonds. Indeed, an important part of the program is to set up executive education courses for bankers in emerging markets to train them in the underwriting of green bonds.[5]

During the course of 2018 and the first half of 2019, the IFC organized three in-country training sessions in Singapore and Bangkok, which were oversubscribed, with participants coming from South-East Asian countries that included Thailand, Singapore and the Philippines. These in-country courses provided an in-depth, operational training into all the steps involved in originating a green bond, with a special focus on financing the construction of green buildings.

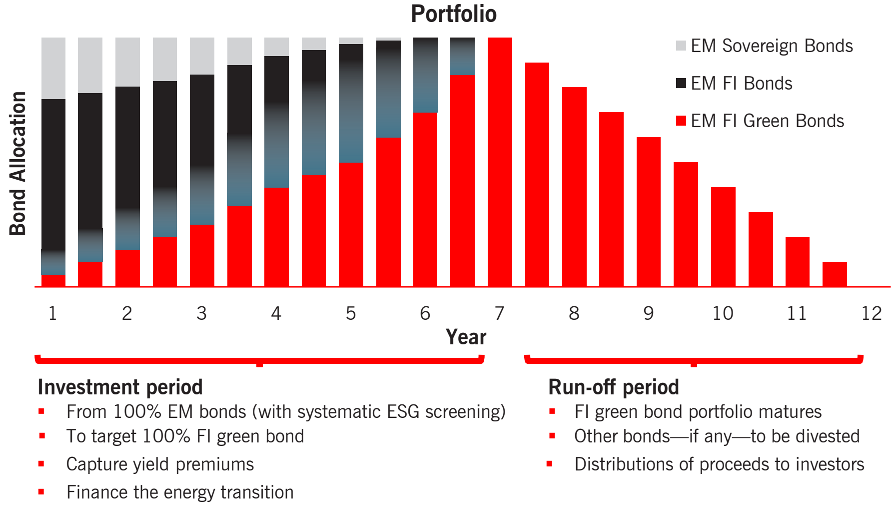
The IFC also entered into a partnership with the Stockholm School of Economics to provide executive education courses on green bonds and sustainable finance more generally, with participants coming from financial institutions in emerging markets around the world. This executive training program gives participants both the conceptual framework and the operational tools needed to allow their respective institutions to start building their green bond issuance capability and so catalyze the growth in underlying green loans. The feedback from the first participants was extremely positive. Not only that, but some emerging market banks that have participated in the program have already successfully issued their first green bond.

The IFC's technical training on green bonds is aligned with international standards, notably the Green Bond Principles, and comprises three broad pillars. First, it provides training to emerging market bankers on the issuance of green bonds and the servicing (disclosure, coupon servicing, and other engagement with investors) of the green bond throughout the asset's lifetime. Second, it provides training on third party certification and impact reporting of the green bonds. Third, the program organizes global and regional events to gather local bankers, investors, analysts, and policy makers. In so doing, the AP EGO fund has introduced the first comprehensive program focusing on both the supply and the demand of green bonds in emerging markets.

Overall, the AP EGO fund has projected that the origination of green bonds and the replacement rate of other assets by green bonds will take place at an annual rate of 15%, with the "investment period" spread out over seven years (see Figure 2). In the first few years of the fund, the bulk of the assets are expected to be "plain" bonds issued by emerging market banks, together with a small fraction of sovereign bonds. By

5 The technical assistance program received seed funding of $7.5 million through a SECO grant (Swiss Secretariat for Economic Affairs) and additional financial support from SIDA (Swedish International Development Cooperation Agency) as well as the Grand Duchy of Luxembourg.)

Figure 2
Gradual shift towards Green Bonds



Source: Amundi.

year seven of the fund, the asset pool is expected to be 100% green bonds, which will be amortized over the remaining five year period of the fund.

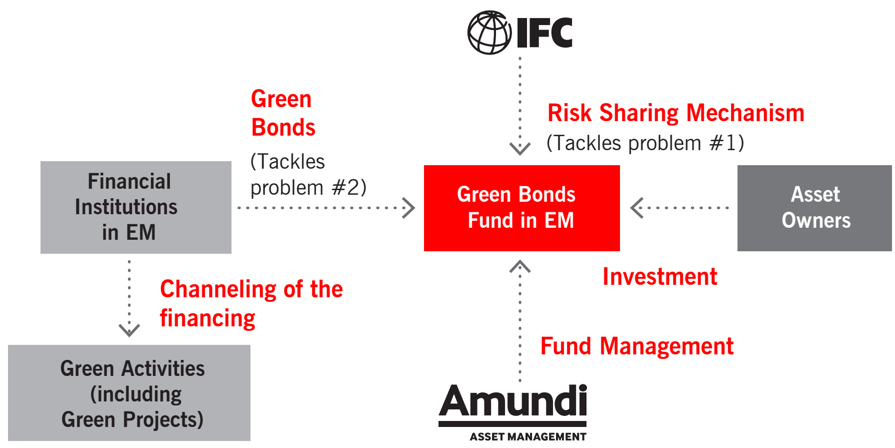
Without any further changes, the fund would be liquidated after twelve years. But once the origination infrastructure is in place, and assuming that institutional investors' appetite for these assets remains sufficiently strong, this fund could easily be turned into a master fund structure in which assets that mature are replaced by newly originated assets, and investors in the fund can continuously reinvest their dividends in the fund, thereby ensuring its perpetuation.

Although this is less apparent from the structure of the fund, much new ground was covered when exploring the potential interest of institutional investors. The usual process in launching a new fund is to begin by determining the scope of the fund, preparing all the required documentation for investors, and then to enter a fundraising phase, en route to eventually completing the launch of the fund. In the case of the AP EGO fund, however, the awareness campaign began substantially before the scope and final documentation of the fund were put together. Indeed, an intense awareness campaign to convince investors of the urgency of the climate change threat and of the timeliness and substantial value added of the creation of a green bond market in developing countries was necessary. Multiple teams were dispatched simultaneously around the world to pitch the concept and round up investors. Given the novelty of the fund, the new GPPIP structure, the prospective new asset class, the new role of the IFC, much explaining and convincing was necessary.

The good news, however, is that some highly respected institutional investors became champions of the fund early on. Thanks to the enthusiasm and support of those investors, the fundraising phase was successfully completed in a very short period of time. Overall, the fundraising phase that followed the "awareness campaign" resulted in a $1.4 billion commitment from 16 institutional investors.[6] The investor base was quite diverse[7] and included prominent development banks such as the European Investment Bank,[8] the European Bank for Reconstruction and Development,[9] Proparco,[10] and other large European institutional investors such as Alecta,[11] AP3, AP4,[12] APK Pensionkasse, Crédit Agricole Assurances, ERAFP, Local Tapiola, and MP Pension—a group that collectively represents 77% of the subscriptions outside the IFC seed commitment. In this sense, the development of the AP EGO fund is both a landmark innovation in terms of its scope and structure, and a strong signal from

6 https://int.media.amundi.com/news/ifc-amundi-successfully-close-world-s-largest-green-bond-fund-3df5-b6afb.html
7 https://ifcextapps.ifc.org/ifcext/pressroom/IFCPressRoom.nsf/0/F4D6285A3177879A85258252005DE769
8 https://www.eib.org/en/press/all/2018-066-eib-backs-worlds-first-emerging-market-green-bond-fund-with-usd-100-million-investment.htm
9 https://www.ebrd.com/news/2018/ebrd-ifc-and-eib-commit-us-425-million-to-fund-for-green-bonds-in-emerging-markets.html
10 https://www.proparco.fr/en/actualites/proparco-invests-us100m-boost-green-financing-emerging-and-developing-countries
11 https://www.ipe.com/alecta-a-swedish-investors-green-bond-learning-curve/10029273.article
12 https://www.ipe.com/alecta-erafp-among-backers-of-14bn-em-green-bond-fund/10023735.article

Figure 3
Overview of the two main mechanisms



Source: Amundi.

institutional investors of their commitment and interest in pursuing novel forms of impact investment.

To summarize, the overall concept of the AP EGO fund, and how it addresses the two fundamental problems of concern to investors—namely, how to reduce the risk tied to investments in emerging markets, and how to originate green bonds in emerging markets—is illustrated in Figure 3. The underlying contractual architecture of the fund is a GPPIP, with the IFC playing the role of a development bank that provides credit enhancement, monitoring, and technical support in the origination of green bonds. The other key partners are the network of emerging market banks that fund green projects and issue green bonds, and the asset manager, Amundi, which is charged with structuring and managing the pool of assets, and distributing the cash flows to institutional investors.

The aim of the AP EGO fund is not only to accomplish a successful investment, but also to initiate a new asset class, and thereby help break down existing institutional barriers that prevent the flow of savings from developed markets into sustainable assets in emerging markets. The fund is structured so that all the money raised can be invested straight away from the closing date in a well-diversified pool of emerging market assets, and as part of a process that will dynamically replace existing assets with green bonds. This fully-funded structure sends a very simple but strong message to the market: there is a significant pool of cash available for and committed to investments into green bonds.

Early Days

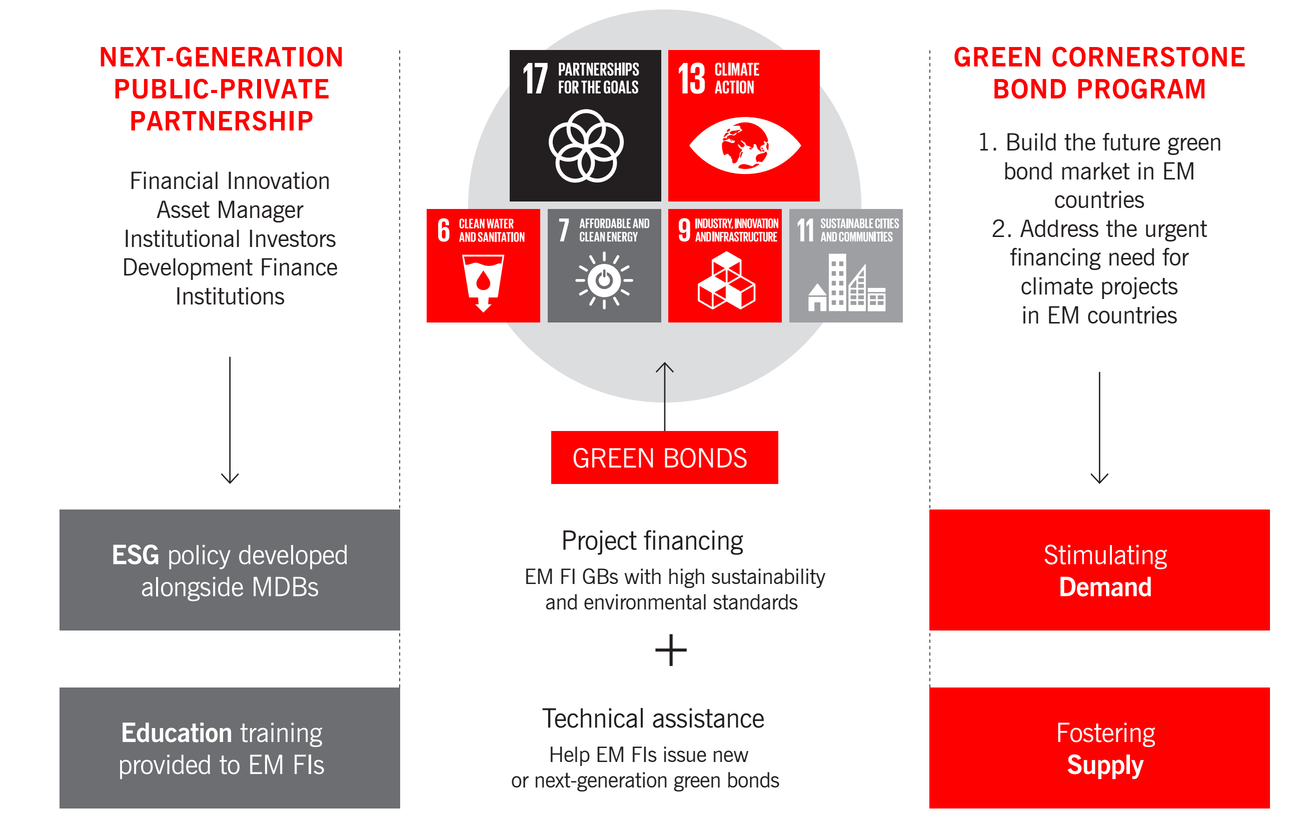
The AP EGO fund was launched by Amundi and the IFC in February 2018. As of this writing (March 2020), it is the largest green bond fund in the world, having raised more than $1.4 billion from institutional investors at closing and declared its intent to deploy up to $2 billion by 2025. The IFC's plan was to launch the largest existing green bond fund in such a way as to send a clear message to market participants about the untapped sustainable investment opportunities in emerging markets. The risk mitigation mechanisms of the fund and the focus on financial institutions gave institutional investors confidence to engage with a new asset class in emerging markets, thereby supporting the (indirect) financing of sustainable infrastructure at scale in emerging markets, both areas that had been long deemed as "too risky" for these investors.

As can be seen in Figure 4, the AP EGO fund aims to support progress in meeting the United Nations (UN) Sustainable Development Goals (SDGs), a set of 17 goals for sustainable development adopted by the UN in 2015. By the end of 2018, the two most relevant SDGs were 17 (Partnerships for the Goals) and 13 (Climate Action). But there were others as well:

SDG 6 (Clean Water and Sanitation): 0.22%[13] of the green bond portfolio is invested in water management projects.

13 As at the end of 2018.

Figure 4
AP EGO is aligned with multiple SDGs at once



Source: Amundi.

SDG 7 (Affordable and Clean Energy): 45%[14] of the green bond portfolio is invested in renewable energy, and 5%[15] of the portfolio is tied to energy efficiency projects.

SDG 11 (Sustainable Cities and Communities): 12%[16] of the green bond portfolio is tied to green transport, and 3%[17] of the portfolio to green building projects.

SDG 13 (Climate Action): AP EGO contributes to global climate action through investments in green bonds that support the development of sustainable infrastructure.

SDG 17 (Partnerships for the Goals): AP EGO mobilized additional financial resources for developing countries by originating most of the capital deployed from private sector sources in developed countries. Fully 77% of the capital invested in the fund (outside IFC initial commitment) comes from private sector sources.

14 Ibid.
15 Ibid.
16 Ibid.
17 Ibid.

It's important to keep in mind that this impact has been achieved with minimal reliance on public funding, thanks to the GPPIP structure that allows for the "crowding in" of private funding from institutional investors. Instead of directly financing projects on their balance sheet (which by definition is limited), public development finance institutions can use their balance sheet to unlock private sector investor capabilities, leveraging their capital, and creating markets with impact. In this case, for example, an equity investment of only $125 million by a multilateral development bank (the IFC) has been sufficient to launch a target fund of $2 billion, achieving a 16x multiplication factor aimed at financing green bonds. And given that the AP EGO fund subscribes to only 5% of any given green bond issue, that $2 billion is capable of providing the funding base for as much as $40 billion of investments. This is a promising and effective way of developing capital markets in developing countries and achieving maximum impact from the first world savings channeled to those countries. Since its launch in 2018, the AP EGO fund's financial performance has exceeded expectations. It has a diversified portfolio of 98 issuers

Figure 5
Risk Profile

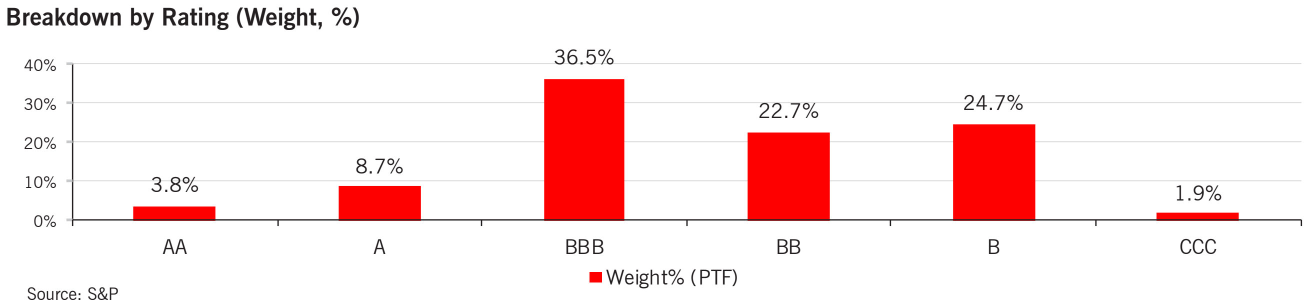
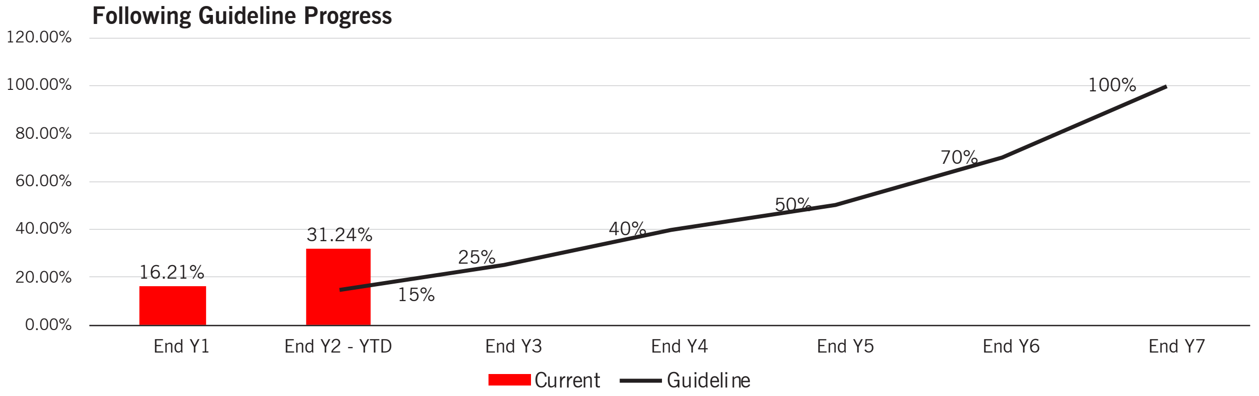


Figure 6
Deployment into Green Bonds*



*Green Bonds valued based on Amundi Planet statutory valuation principles Guideline: Amundi Planet / Investment Ratio into Green bonds – IFC Contract.
Source: Amundi, Fund Accounting Data as at 31st December 2019 Provided for illustrative purposes only. Investment views are valid as at the date stated and are presented to illustrate the team process. They are subject to change and do not necessarily represent the current or future views of the Amundi team

from 46 countries with an average BB+ rating. In addition, it benefits from an IFC credit enhancement. These two elements together contribute to a substantially reduction of the risk faced by investors in the fund.

And more central to the fund's mission, the growth in the green bond composition of the asset pool has been faster than expected (as can be seen in Figure 6), with 23 green bonds today representing over 30% of the value of the fund.

What's more, this shift has been achieved along with a satisfactory level of diversification among the countries represented by the issuers. Such diversification is expected to be maintained throughout the life of the fund; and for this to happen, the green bond market in EM must continue to grow, presumably with the help of the technical assistance facility.

Thanks in part to these early signs of promise, the AP EGO fund has already received considerable attention and recognition, as reflected by the six awards it received since its launch—including the prestigious 2019 PRI Real World Impact Initiative of the Year[18] and the Environmental Finance Initiative of the Year Award 2019.[19]

New Initiatives in Sustainable Capital Market Development

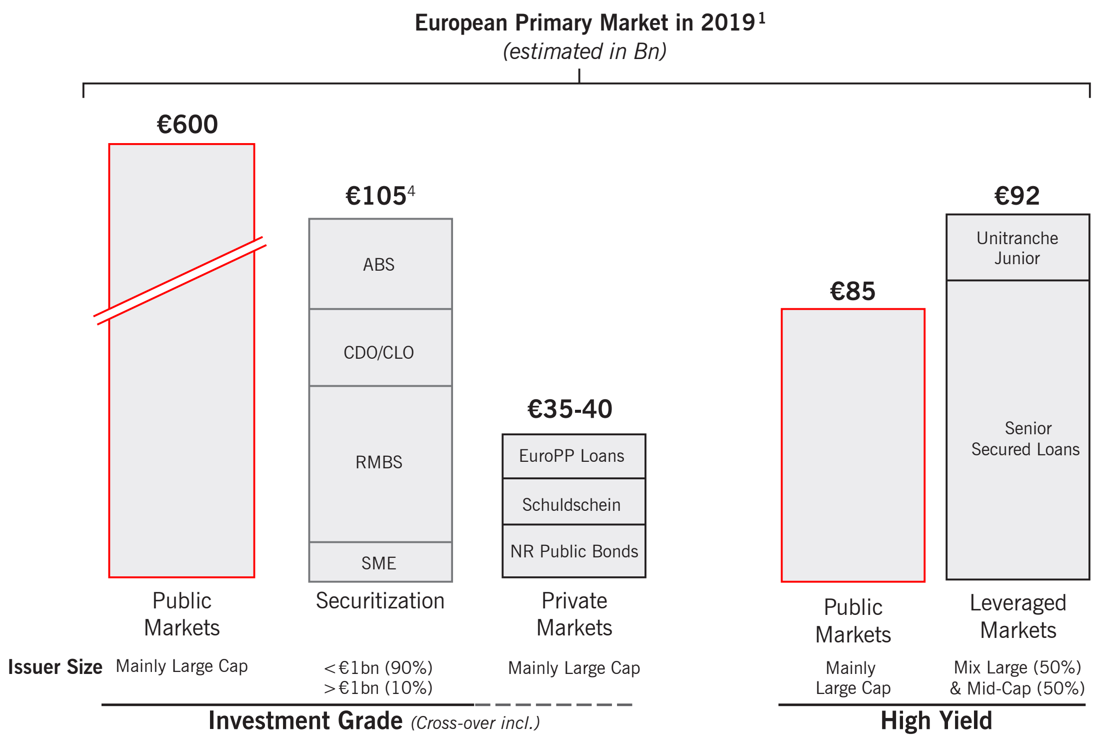
Not long after the launch of the AP EGO Fund, the European Investment Bank (EIB), which is the EU's main multilateral development bank, and its Asian counterpart, the Asian Infrastructure Investment Bank (AIB), both decided to undertake similar initiatives to further develop the green and climate bond market. The European green bond market had matured over the past decade, with increasing issuance volumes and recognized

18 https://www.unpri.org/pri-awards-2019-case-study-planet-emerging-green-one-fund/4826.article

19 https://www.environmental-finance.com/content/awards/green-social-and-sustainability-bond-awards-2019/winners/green-bond-fund-of-the-year-initiative-of-the-year-amundi-and-ifcs-emerging-green-one.html

Figure 7

European Fixed Income Primary Market Issuances



Note: European primary market defined as corporate issuances in Euro.

(1) Sources: Amundi, Morgan Stanley, Société Générale CIB, AFME. (2) Source: Climate Bonds Initiative. (3) Source: Estimates from European Commission. (4) €190Bn taking into account issuers retained primary market

standards. One important shortcoming, however, was that green bonds had been issued by mostly investment-grade entities in the form of listed senior unsecured debt. Adding a green label to such debt did not improve the financing terms per se for the issuer, although it may have helped enhance the issuer's overall reputation and increased its stock price.[20] And because the European green bond market comprises only a small subset of European issuers—namely, large corporates and sovereign and quasi-sovereign entities—the EIB reasoned that the growth of that market could be stunted unless more issuers, including many with weaker balance sheets, were encouraged to enter the market. In fact, to this point only a handful of green securities had been issued in the lower-rated segments of the fixed income market; and that was believed to be well below the level of potential development of these green markets, where both volume and suitable standards were still lacking.

Hence, the decision by the EIB to collaborate with Amundi in developing a comprehensive program similar to the AP EGO fund for these other fixed-income market segments.[21] The program targets green bond issuance by small and medium size enterprises, along with larger companies with smaller projects, and bond issues to finance clean energy infrastructure ABS, green real estate debt, and other green projects. The EIB would play a critical role in designing and encouraging the adoption of consistent, though flexible and tailored, green standards for each of these asset classes and, in so doing, promote the grow these market segments.

The fund was established in July 2019, and a first tranche of EUR 253 million was successfully placed six months later, with the overall objective being a EUR 1 billion size fund in the near future. The attraction, again, for fixed-income investors especially in the current negative interest rate environment, is access to a potentially much larger green asset pool, with appealing yields and lower risk achieved through diversification and credit enhancement. Such a program fits naturally into

20 Caroline Flammer, Boston University, "Corporate Green Bonds," July 2018. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3125518

21 https://int.media.amundi.com/news/amundi-and-the-european-investment-bank-launch-the-green-credit-continuum-programme-which-aims-to-provide-eur-1bn-for-the-development-of-green-debt-in-europe-7154-b6afb.html

the broader objectives of the European Union to accelerate the renewable energy transition by ramping up green investments far beyond the universe of listed, investment-grade issuers, and extending the development of green standards to all asset classes, particularly those originated by financial intermediaries. As in the case of the AP EGO fund, this program is likely to achieve its full potential only if supported by the four key public and private partners of a GPPIP.

Needless to say, the EIB, as the European Union's main multilateral development bank and a leader in green finance in Europe, is a key partner in this GPPIP. It has been committed for some time to developing sustainable finance in Europe. As with the IFC's role in the AP EGO fund, the EIB's role as an anchor investor (and credit enhancer), including its expertise in green bond origination, is critical in attracting other institutional investors to reach sufficient scale. And like the IFC, the EIB is uniquely positioned to set green standards and support their dissemination.

The Asian Infrastructure Investment Bank (AIIB)[22] has similar sustainable development goals and also seeks to enlist the help of capital markets in funding sustainable infrastructure investments in Asia. Accordingly, it is proposing to develop an innovative program that aims to identify and support future climate champions in the region. Specifically, on September 10, 2019, the AIIB announced the creation of a $500 million portfolio dedicated to Asia Climate Bonds. Using this initial managed fixed income portfolio of $500 million, the program is expected to attract another $500 million from climate change-focused institutional investors. As in the case of the AP EGO fund, a portion of the investment proceeds is dedicated to market education, engagement, and issuer support.

The launch of this portfolio of Asia Climate Bonds is part of the AIIB's Sustainable Capital Market Initiative, which rests on four pillars:[23] (1) proof of concept—to show that investment with an ESG strategy can generate positive returns, with the ultimate goal of attracting and encouraging investors to invest more in emerging markets; (2) ESG research—to catalyze the development of ESG strategies for debt capital markets; (3) transparency and disclosure—working with stakeholders to promote effective disclosure and transparency in the markets; and (4) capacity building—bringing together a range of market participants (corporates, industry, associations, investors, ratings agencies, regulators, etc.) with the aim of developing deeper green bond markets in Asia.

22 https://www.aiib.org/en/news-events/news/2019/20190910_001.html
23 https://www.aiib.org/en/news-events/media-center/blog/2019/20190712_004.html

Conclusion: A New Role for Public Money

Much as commercial banks have been important catalysts for "big push" industrialization in the past,[24] public development banks and governments today are in a position to act as catalysts for the energy transition by marshalling capital markets to finance sustainable development. Although the risks of climate change have been known for several decades, it is only around the time of the COP21 and the Paris agreement of 2015 that investors began to understand that climate change was not only a longer-run threat to the planet, but a much more immediate risk to their investments.[25] The resulting mobilization of institutional investors around the issue of climate change made many realize the impressive potential for organizing capital, as illustrated by the Action 100+ initiative.[26] Such developments are a clear indication that many of the world's largest and most influential institutional investors are prepared to combine forces with governments and public development banks in combatting climate change.

But even as investor awareness, financial market capabilities, and carbon footprint disclosures continue to grow, the financial instruments that allow investors to align their investments with the goal of carbon neutrality, or to finance green projects, remain quite limited. Financial innovation in support of sustainable capital market growth is needed. Global public-private investment partnerships, as illustrated by the AP EGO fund and its follow-on initiatives are well suited and stand ready to play a central role in meeting this new demand.

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24 Marco Da Rin and Thomas Hellmann, "Banks as catalysts for industrialization," *Journal of Financial Intermediation*, Volume 11, Issue 4, October 2002.
25 See Mats Andersson, Patrick Bolton, and Frederic Samama, "Governance and Climate Change: A Success Story in Mobilizing Investor Support for Corporate Responses to Climate Change," *Journal of Applied Corporate Finance*, Volume 28, Number 2, Spring 2016.
26 http://www.climateaction100.org

Financial Analysts Journal
Volume 72 • Number 3

PERSPECTIVES

Hedging Climate Risk

Mats Andersson, Patrick Bolton, and Frédéric Samama

We present a simple dynamic investment strategy that allows long-term passive investors to hedge climate risk without sacrificing financial returns. We illustrate how the tracking error can be virtually eliminated even for a low-carbon index with 50% less carbon footprint than its benchmark. By investing in such a decarbonized index, investors in effect are holding a "free option on carbon." As long as climate change mitigation actions are pending, the low-carbon index obtains the same return as the benchmark index; but once carbon dioxide emissions are priced, or expected to be priced, the low-carbon index should start to outperform the benchmark.

Whether or not one agrees with the scientific consensus on climate change, both climate risk and climate change mitigation policy risk are worth hedging. The evidence on rising global average temperatures has been the subject of recent debates, especially in light of the apparent slowdown in global warming over 1998–2014.[1] The perceived slowdown has confirmed the beliefs of climate change doubters and fueled a debate on climate science widely covered by the media. This ongoing debate is stimulated by three important considerations.

The first and most obvious consideration is that not all countries and industries are equally affected by climate change. As in other policy areas, the introduction of a new regulation naturally gives rise to policy debates between the losers, who exaggerate the costs, and the winners, who emphasize the urgency of the new policy. The second consideration is that climate mitigation has typically not been a "front burner" political issue. Politicians often tend to "kick the can down the road" rather than introduce policies that are costly in the short run and risk alienating their constituencies—all the more so if there is a perception that the climate change debate is not yet fully settled and that climate change mitigation may not require urgent attention. The third consideration is that although the scientific evidence on the link between carbon dioxide (CO_2) emissions and the greenhouse effect is overwhelming, there is considerable uncertainty regarding the rate of increase in average temperatures over the next 20 or 30 years and the effects on climate change. There is also considerable uncertainty regarding the "tipping point" beyond which catastrophic climate dynamics are set in motion.[2] As with financial crises, the observation of growing imbalances can alert analysts to the inevitability of a crash but still leave them in the dark as to when the crisis is likely to occur.

This uncertainty should be understood as an increasingly important risk factor for investors, particularly long-term investors. At a minimum, the climate science consensus tells us that the risks of a climate disaster are substantial and rising. Moreover, as further evidence of climate events linked to human-caused emissions of CO_2 accumulates and global temperatures keep rising, there is an increased likelihood of policy intervention to limit these emissions.[3] The prospect of such interventions has increased significantly following the Paris Climate Change Conference and the unanimous adoption of a new universal agreement on climate change.[4] Of course, other plausible scenarios can be envisioned whereby the Paris agreement is not followed by meaningful policies. From an investor's perspective, there is therefore a risk with respect to both climate change and the timing of climate mitigation policies. Still, overall, investors should—and some are beginning to—factor carbon risk into their investment policies. It is fair to say, however, that there is still little awareness of this risk factor among (institutional)

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Editor's note: The views expressed in this article are those of the authors and do not necessarily reflect the views of the Amundi Group, AP4, or MSCI.

Editor's note: This article was reviewed and accepted by Robert Litterman, executive editor at the time the article was submitted.

investors.[5] Few investors are aware of the carbon footprint and climate impact of the companies in their portfolios. Among investors holding oil and gas stocks, few are aware of the risks they face with respect to those companies' stranded assets.[6]

In this article, we revisit and analyze a simple, dynamic investment strategy that allows long-term passive investors—a huge institutional investor clientele that includes pension funds, insurance and re-insurance companies, central banks, and sovereign wealth funds—to significantly hedge climate risk while essentially sacrificing no financial returns. One of the main challenges for long-term investors is the uncertainty with respect to the timing of climate mitigation policies. To use another helpful analogy with financial crises, it is extremely risky for a fund manager to exit (or short) an asset class that is perceived to be overvalued and subject to a speculative bubble because the fund could be forced to close as a result of massive redemptions before the bubble has burst. Similarly, an asset manager looking to hedge climate risk by divesting from stocks with high carbon footprints bears the risk of underperforming his benchmark for as long as climate mitigation policies are postponed and market expectations about their introduction are low. Such a fund manager may well be wiped out long before serious limits on CO_2 emissions are introduced.

A number of "green" financial indexes have existed for many years. These indexes fall into two broad groups: (1) pure-play indexes that focus on renewable energy, clean technology, and/or environmental services and (2) "decarbonized" indexes (or "green beta" indexes), whose basic construction principle is to take a standard benchmark, such as the S&P 500 or NASDAQ 100, and remove or underweight the companies with relatively high carbon footprints.[7] The "first family" of green indexes offers no protection against the timing risk of climate change mitigation policies. But the "second family" of decarbonized indexes does: An investor holding such a decarbonized index is hedged against the timing risk of climate mitigation policies (which are expected to disproportionately hit high-carbon-footprint companies) because the decarbonized indexes are structured to maintain a low tracking error with respect to the benchmark indexes.

Thus far, the success of pure-play indexes has been limited. One important reason, highlighted in **Table 1**, is that since the onset of the financial crisis in 2007–2008, these index funds have significantly underperformed market benchmarks.

Besides the fact that clean tech has been overhyped,[8] one of the reasons why these indexes have underperformed is that some of the climate mitigation policies in place before the financial crisis have been scaled back (e.g., in Spain). In addition, financial markets may have rationally anticipated that one of the consequences of the financial crisis would be the likely postponement of the introduction of limits on CO_2 emissions. These changed expectations benefited the carbon-intensive utilities and energy companies more than other companies and may explain the relative underperformance of the green pure-play indexes. More importantly, the reach of the pure-play green funds is very limited because they concentrate investments in a couple of subsectors and, in any case, cannot serve as a basis for building a core equity portfolio for institutional investors.

The basic point underlying a climate risk–hedging strategy that uses decarbonized indexes is to go beyond a simple divestment policy or investments in only pure-play indexes and instead keep an aggregate risk exposure similar to that of standard market benchmarks. Indeed, divestment of high-carbon-footprint stocks is just the first step. The second key step is to optimize the composition and weighting of the decarbonized index in order to minimize the tracking error (TE) with the reference benchmark index. It turns out that TE can be virtually eliminated, with the overall carbon footprint of the decarbonized index remaining substantially lower than that of the reference index (close to 50% in terms of both carbon intensities and absolute carbon emissions). Decarbonized indexes have thus far essentially matched or even outperformed the benchmark index.[9] In other words, investors holding a decarbonized index have been able to significantly

Table 1. Pure-Play Clean Energy Indexes vs. Global Indexes

	S&P 500	NASDAQ 100	PP 1	PP 2	PP 3	PP 4	PP 5
Annualized return	4.79%	11.40%	5.02%	–8.72%	2.26%	–8.03%	–1.89%
Annualized volatility	22.3	23.6	24.1	39.3	30.2	33.8	37.3

Notes: Table 1 gives the financial returns of several ETFs that track leading clean energy pure-play indexes. Pure Play 1 refers to Market Vectors Environmental Services ETF, Pure Play 2 to Market Vectors Global Alternative Energy ETF, Pure Play 3 to PowerShares Cleantech Portfolio, Pure Play 4 to PowerShares Global Clean Energy Portfolio, and Pure Play 5 to First Trust NASDAQ Clean Edge Green Energy Index Fund. Annualized return and volatility were calculated using daily data from 5 January 2007 to the liquidation of Pure Play 1 on 12 November 2014.
Sources: Amundi and Bloomberg (1 September 2015).

reduce their carbon footprint exposure without sacrificing any financial returns. In effect, these investors are holding a "free option on carbon": So long as the introduction of significant limits on CO_2 emissions is postponed, they can obtain the same returns as on a benchmark index. But from the day CO_2 emissions are priced meaningfully and consistently and limits on CO_2 emissions are introduced, the decarbonized index should outperform the benchmark.[10] A climate risk–hedging policy around decarbonized indexes is essentially an unlevered minimum risk arbitrage policy that takes advantage of a currently mispriced risk factor (carbon risk) in financial markets. Although larger arbitrage gains are obtainable by taking larger risks (and this climate risk–hedging strategy errs on the side of caution), the strategy is particularly well suited for long-term passive investors who seek to maximize long-term returns while limiting active stock trading over time.

A Green Index without Relative Market Risk: The Basic Concept

Investor perceptions of lower financial returns from green index funds could explain why green indexes have thus far remained a niche market. Another reason might be the design of most green indexes, which lend themselves more to a bet on clean energy than a hedge against carbon risk. In contrast, the design we support allows passive long-term investors to hedge carbon risk. Thus, the goal is not just to minimize exposure to carbon risk by completely divesting from any company with a carbon footprint exceeding a given threshold, but also to minimize the tracking error of the decarbonized index with the benchmark index. We support this design because it implements a true dynamic hedging strategy for passive investors and can easily be scaled to significantly affect not only portfolios' footprints but also (eventually) the real economy.[11]

The basic idea behind index decarbonization is to construct a portfolio with fewer composite stocks than the benchmark index but with similar aggregate risk exposure to all priced risk factors. This approach is possible because, as Koch and Bassen (2013) showed, carbon risk is asymmetrically concentrated in a few firms.[12] Ideally, the only major difference in aggregate risk exposure between the two indexes would be with respect to the carbon risk factor, which would be significantly lower for the decarbonized index. So long as carbon risk remains unpriced by the market, the two indexes will generate similar returns (i.e., offer the same compensation for risk demanded by the representative investor), thus achieving no or minimal TE. But once carbon risk is priced or is expected to be priced by the market, the decarbonized index should start outperforming the benchmark.

The central underlying premise of this strategy is that financial markets currently underprice carbon risk. Moreover, our fundamental belief is that eventually, if not in the near future, financial markets will begin to price carbon risk. Our premise leads inevitably to the conclusion that a decarbonized index is bound to provide higher financial returns than the benchmark index. We believe that the evidence in support of our premise is overwhelming. Currently, virtually all financial analysts overlook carbon risk. Only in 2014 did a discussion about stranded assets make it into a report from a leading oil company for the first time, and the report mostly denied any concern that a fraction of proven reserves might ever become stranded assets.[13] Only a few specialized financial analysts[14] factor stranded assets into their valuation models of oil company stocks. Nor, apart from a few exceptions,[15] do financial analysts ever evoke carbon-pricing risk in their reports to investors. In sum, current analysts' forecasts assume by default that there is no carbon risk. Under these circumstances, it takes a stretch of the imagination to explain that financial markets somehow currently price carbon risk correctly. Even more implausible is the notion that financial markets currently price carbon risk excessively. Only in this latter scenario would investors in a decarbonized index face lower financial returns than in the benchmark index.

Some might object that our fundamental belief that financial markets will price carbon risk in the future is not particularly plausible. After all, the evidence from many climate talks' failures following Kyoto suggests, if anything, that global carbon pricing in the near future is extremely unlikely. If that should be the case, our investor in the decarbonized index would simply match the returns of the benchmark index—a worst-case scenario. Any concrete progress in international negotiations—and the implementation of nationally determined independent contributions agreed to in Paris—will change financial market expectations about carbon risk and likely result in higher financial returns on the low-TE index relative to the benchmark index.

The Decarbonized Index Optimization Problem. Given our basic premise and fundamental belief, the next question is how to go about constructing the green index. There are several possible formulations of the problem in practice. One formulation is to eliminate high-carbon-footprint composite stocks, with the objective of meeting a target carbon footprint reduction for the green index, and then to reweight the remaining stocks in order to minimize tracking error with the benchmark index. The dual formulation is to begin by imposing a constraint on maximum allowable tracking error with the benchmark index and then, subject to this constraint, exclude and reweight composite stocks in the benchmark index to maximize the green index's carbon footprint reduction. Although there is no compelling reason to choose one formulation over the other, we favor the second formulation, which seeks to minimize tracking error subject to meeting a carbon footprint reduction target.

Another relevant variation in the design of the constrained optimization problem is whether to (1) require at the outset the complete exclusion of composite stocks of the worst performers in terms of carbon footprint or (2) allow the green index to simply underweight high-carbon-footprint stocks without completely excluding them. Although the latter formulation is more flexible, it has drawbacks, which we discuss later in the article.

We confine our analysis to essentially two alternatives among the many possible formulations of the constrained optimization problem for the construction of a decarbonized index that trades off exposure to carbon, tracking error, and expected returns. We describe both formulations formally, under the simplifying assumption that only one sector is represented in the benchmark index.

The two portfolio optimization problems can be simply and easily represented. Suppose that there are N constituent stocks in the benchmark index and that the weight of each stock in the index is given by $w_i^b = \left[\frac{\text{Mkt cap}(i)}{\text{Total mkt cap}}\right]$. Suppose next that each constituent company is ranked in decreasing order of carbon intensity, q_l^i, with company $l = 1$ having the highest carbon intensity and company $l = N$ the lowest (each company is thus identified by two numbers $[i,l]$, with the first number referring to the company's identity and the second to its ranking in carbon intensity).

In the first problem, the green portfolio can be constructed by choosing new weights, w_i^g, for the constituent stocks to solve the following minimization problem:

$$\text{Min}\,\text{TE} = sd\left(R^g - R^b\right),$$

where

$$w_j^g = 0 \text{ for all } j = 1,\ldots,k$$

$$0 \le w_i^g \text{ for all } i = k+1,\ldots,N$$

sd = standard deviation

That is, the decarbonized index is constructed by first excluding the k worst performers in terms of carbon intensity and reweighting the remaining stocks in the green portfolio to minimize TE.[16] This decarbonization method follows transparent rules of exclusion, whatever the threshold k.

In the second problem formulation, the first set of constraints $(w_j^g = 0 \text{ for all } j = 1,\ldots,k)$ is replaced by the constraint that the green portfolio's carbon intensity must be smaller than a given threshold: $\sum_{l=1\ldots N} q_l w_l^g \le Q$. In other words, the second problem is a design, which potentially does not exclude any constituent stocks from the benchmark index and seeks only to reduce the carbon intensity of the index by reweighting the stocks in the green portfolio. Although the second problem formulation (pure optimization) dominates the first (transparent rules) for the same target aggregate carbon intensity, Q, because it has fewer constraints, it has a significant drawback in terms of the methodology's opacity and the lack of a clear signal for which constituent stocks to exclude on the basis of their relatively high carbon intensity.

Optimization Procedure. For both problem formulations, the *ex ante* TE—given by the estimated standard deviation of returns of the decarbonized portfolio from the benchmark—is estimated by using a multifactor model of aggregate risk (see Appendix D for more detailed information). This multifactor model significantly reduces computations, and the decomposition of individual stock returns into a weighted sum of common factor returns and specific returns provides a good approximation of individual stocks' expected returns. More formally, under the multifactor model the TE minimization problem has the following structure:

$$\text{Min}\left[\sqrt{\left(W^p - W^b\right)'\left(\boldsymbol{\beta}\boldsymbol{\Omega}_f\boldsymbol{\beta}' + \boldsymbol{\Delta}^{AR}\right)\left(W^p - W^b\right)}\right],$$

where

$$w_l^g = 0 \text{ for all } l = 1,\ldots,k$$

$$0 \le w_l^g \text{ for all } l = k+1,\ldots,N$$

$\left(W^p - W^b\right)$ = the vector of the difference in portfolio weights of the decarbonized portfolio and the benchmark

$\boldsymbol{\Omega}_f$ = the variance–covariance matrix of factors

$\boldsymbol{\beta}$ = the matrix of factor exposures

$\boldsymbol{\Delta}^{AR}$ = the diagonal matrix of specific risk variances

Risk Mitigation Benefits of Low Tracking Error. To explore more systematically the potential benefits of achieving a bounded tracking error, we ran a number of simulations with the pure optimization methodology and determined a

TE–carbon efficiency frontier for a decarbonized index constructed from the MSCI Europe Index. As illustrated in **Figure 1**, achieving a nearly 100% reduction in the MSCI Europe carbon footprint would come at the price of a huge tracking error of more than 3.5%.[17]

Such a large TE would expose investors in the decarbonized index to significant financial risk relative to the benchmark—even in a good scenario whereby the decarbonized index is expected to outperform the benchmark as a result of climate mitigation policies. **Figure 2** depicts the risk that a large TE might expose investors to and how that risk can be mitigated by lowering the TE. We first posit a scenario whereby the expected yearly return of the green index is 2.5% higher than that of the benchmark[18] and show (with a confidence interval of two standard deviations) that a 3.5% TE could expose investors to losses relative to the benchmark in the negative scenario.

As Figure 2 illustrates, if we lower the TE of the decarbonized index from 3.5% to 1.2%, the decarbonized index generates returns at least as high as those of the benchmark *even in the worst-case scenario*.

Illustrative Example. A simple example can illustrate in greater detail how a low-carbon, low-TE index might be constructed and how its financial returns—relative to the benchmark—would vary with (expectations of) the introduction of carbon taxes. Let us consider a portfolio of four stocks (A, B, C, D), each priced at 100. The first two stocks (A, B) are, say, oil company stocks; stock C is outside the oil industry, but its price is perfectly correlated with the oil industry stock price; and stock D is a company whose stock price is uncorrelated with the oil industry. The pre–carbon taxation returns on these stocks are 20%, 20%, 20%, and 30%, respectively. On the one hand, we assume that stocks A and B have a relatively high carbon footprint, which would expose them to relatively high implied carbon taxation—40% and 10% of earnings, respectively. On the other hand, we assume that stocks C and D have no carbon tax exposure. We then construct the low-carbon, low-TE index as follows: (1) We filter out entirely stocks A and B, (2) we treble the weighting of stock C to maintain the same overall exposure to the oil sector as the benchmark portfolio, and (3) we leave the weighting of stock D unchanged. If the introduction of carbon taxes is expected, the price of stock A will drop to 72 and the price of stock B will increase to 108, whereas the price of stock C will increase to 120 and the price of stock D will rise to 130. What are the implications for returns on the low-carbon, low-TE index relative to the benchmark? In this scenario, the low-TE index would outperform the benchmark by 14%.

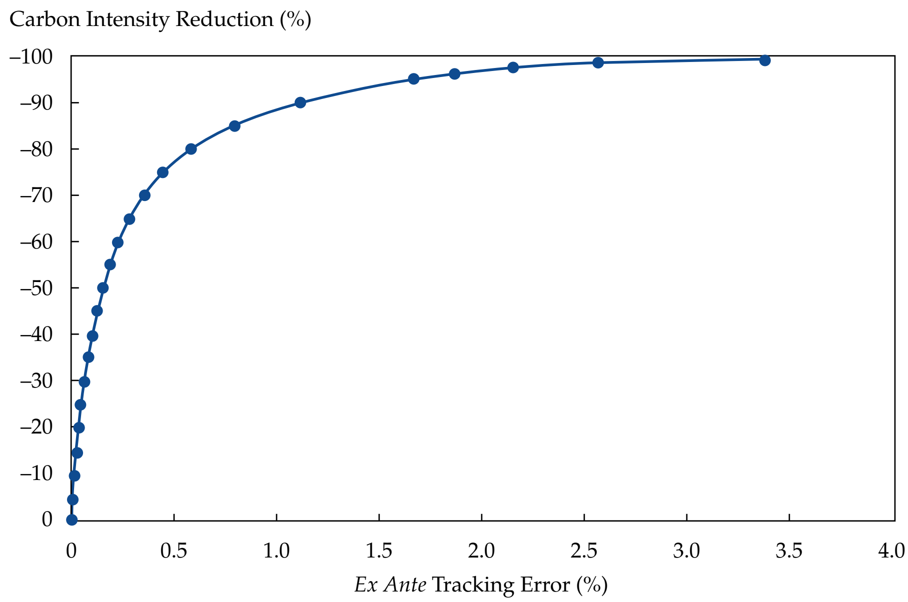
Tracking Error Management and Carbon Risk Repricing. Index managers seek to limit *ex ante* TE. However, some enhanced indexes, such as decarbonized indexes, also seek to increase returns relative to the benchmark. Although the two goals may seem in conflict, we note that the optimization procedure focuses on *ex ante* TE and excess returns are necessarily measured *ex post*. Therefore, if the risk model used to limit *ex ante* TE does not take into account carbon risk (or any factor responsible for a divergence of returns), a small *ex ante* TE can be compatible with active returns *ex post*. Two polar carbon-repricing scenarios can be considered: (1) a smooth repricing with moderate regulatory and technological changes that progressively impair the profitability of carbon-intensive companies and (2) a sharp repricing caused by unanticipated disruptive technologies or regulations. In the first scenario, investors could experience active positive returns with *ex post* TE in line with *ex ante* TE. In the second scenario, investors in a decarbonized index could experience a peak in *ex post* TE with active positive returns.

Beyond Optimization: Methodological Considerations and Caveats

In this section, we consider other issues besides portfolio optimization, including the benefits of clear signaling via transparent rules, trade-offs involved in different designs of decarbonized indexes and different normalizations of carbon footprints, how to deal with anticipated changes in companies' carbon footprints, and a few caveats.

Benefits of Clear Signaling through Transparent Rules. As all issuers well understand, inclusion in or exclusion from an index matters and is a newsworthy event. We believe that inclusion in a decarbonized index ought to have similar value. Clearly communicating which constituent stocks are in the decarbonized index would not only reward the included companies for their efforts in reducing their carbon footprint but also help discipline the excluded companies. This pressure might induce excluded companies to take steps to reduce their carbon footprint and to reward their CEOs for any carbon footprint reductions.[19] Because companies' exclusion from the index would be reevaluated yearly, it would also induce healthy competition to perform well with respect to carbon footprints, with the goal of rejoining the index.[20] Finally, clear communications concerning exclusion criteria based on carbon footprints would inspire a debate on whether greenhouse gas (GHG) emissions are properly measured and would lead to improvements in the

Figure 1. Carbon Frontier on the MSCI Europe Index



Source: Amundi (30 June 2015).

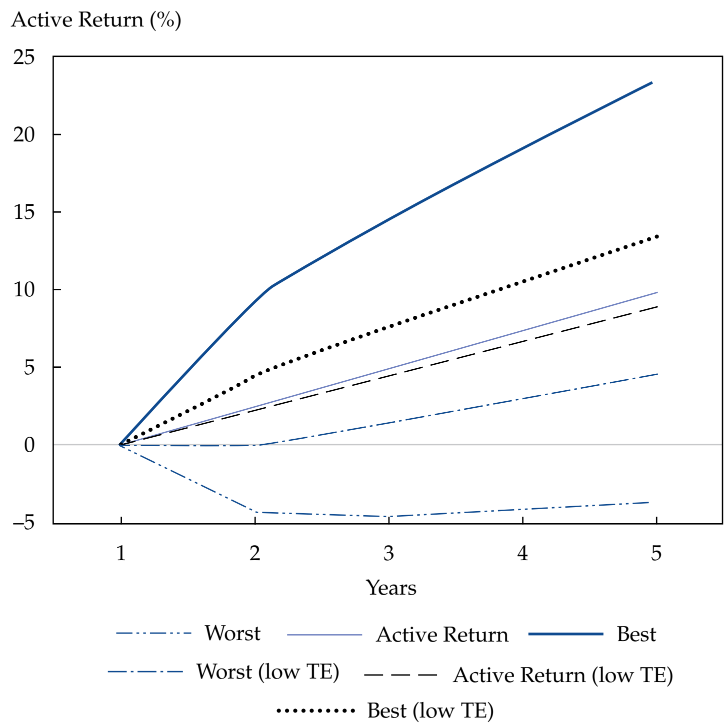
methodology for determining companies' carbon footprints.

Design Trade-Offs. A number of trade-offs are involved in the design of a decarbonized index. For example, an obvious question about balancing concerns the sector composition of the benchmark index. To what extent should the decarbonized index seek to preserve the sector balance of the benchmark? While seeking to preserve sector composition, should the filtering out of high-carbon-footprint stocks be performed sector by sector or across the entire benchmark index portfolio? Some believe that a sector-blind filtering out of companies by the size of their carbon footprint would result in an unbalanced decarbonized index that essentially excludes most of the fossil energy sector, electric utilities, and mining and materials companies. Obviously, such an unbalanced decarbonized index would have a very high tracking error and would be undesirable. Interestingly, however, a study of the world's 100 largest companies has shown that more than 90% of the world's GHG emissions are attributable to sectors other than oil and gas (see Climate Counts 2013). Hence, a sector-by-sector filtering approach could result in a significantly reduced carbon footprint while still maintaining a sector composition roughly similar to that of the benchmark. Later in the article, we show more concretely how much carbon footprint reduction can be achieved by decarbonizing the S&P 500 and MSCI Europe indexes.

One simple way to address this issue is to look at the decarbonized portfolio's TE for the different optimization problems and pick the procedure that yields the decarbonized index with the lowest TE. But there may be other relevant considerations besides TE minimization. For example, one advantage of a sector-by-sector filtering approach with transparent rules (subject to the constraint of maintaining roughly the same sector balance as that of the benchmark index) is that excluded companies can more easily determine their carbon footprint ranking in their industry and how much carbon footprint reduction it would take for their stock to be included in the decarbonized index. In other words, a sector-by-sector filtering approach would foster greater competition within each sector for companies to lower their carbon footprint. Another related benefit is that the exclusion of the worst GHG performers in the sector would also reduce exposure to companies that fare poorly on other material sustainability factors (given that carbon footprint reduction is a good proxy for investments in other material sustainability factors).[21]

Normalization of the Carbon Footprint. Because the largest companies in the benchmark index are likely to be the companies with the highest GHG emission levels, a filtering rule that excludes the stocks of companies with the highest absolute emission levels will tend to be biased against the largest companies, which could result in a high TE for the decarbonized index. Accordingly, some normalization of companies' carbon footprints is appropriate. Another reason to normalize the absolute carbon footprint measure is that a filter based on a normalized measure would be better at selecting the least wasteful companies in terms of GHG emissions. That

Figure 2. Returns and Risk with Low Tracking Error



Source: Amundi.

is, a normalized carbon footprint measure would better select companies on the basis of their energy efficiency. A simple and comprehensive, if somewhat rudimentary, normalization would be to divide each company's carbon footprint by sales. Normalizations adapted to each sector are preferable and could take the form of dividing CO_2 emissions by (1) tons of output in the oil and gas sector, (2) revenue from transporting one tonne over a certain distance in the transport sector, (3) total GWh (gigawatt-hour) electricity production in the electric utility sector, (4) square footage of floor space in the housing sector, or (5) total sales in the retail sector.

Changes in Companies' Carbon Footprints. Ideally, the green filter should take into account expected future carbon footprint reductions resulting from current investments in energy efficiency and reduced reliance on fossil fuels. Similarly, the green filter should penalize oil and gas companies that invest heavily in exploration with the goal of increasing their proven reserves, which raises the risk of stranded assets for such companies. This "threat" would provide an immediate incentive to any company with an exceptionally high carbon footprint to make investments to reduce it and would boost the financial returns of the decarbonized index relative to the benchmark.

Caveats. Whenever an investment strategy that is expected to outperform a market benchmark is pitched, a natural reaction is to ask, what's the catch? As explained earlier, the outperformance of the decarbonized index is premised on the fact that financial markets currently do not price carbon risk. Thus, an obvious potential flaw in our proposed climate risk–hedging strategy is the possibility that financial markets currently *overprice* carbon risk. While this overpricing is being corrected, the decarbonized index would underperform the benchmark index. We strongly believe this argument to be implausible because the current level of awareness of carbon risk remains very low outside a few circles of asset owners, a handful of brokers, and asset managers. Another highly implausible scenario is that somehow today's high-carbon-footprint sectors and companies will be tomorrow's low-carbon-footprint sectors and companies. One story to back such a scenario could be that the high-GHG emitters have the most to gain from carbon sequestration and will thus be the first to invest in that technology. Under this scenario, the decarbonized index would underperform the benchmark precisely when carbon taxes are introduced. This scenario is not in itself a crushing objection because the green filter can easily take into account investments in carbon sequestration as a criterion for inclusion in the index. In the end, this scenario simply suggests a reason for the carbon filter to take into account measures of companies' predicted carbon footprints.

A more valid concern is whether companies' carbon footprints are correctly measured and whether the filtering based on carbon intensity fits its purpose. Is there a built-in bias in the way carbon footprints are measured, or is the measure so noisy that investors could be exposed to many carbon measurement risks? A number of organizations—Trucost, CDP (formerly Carbon Disclosure Project), South Pole Group, and MSCI ESG Research—provide carbon footprint measures of the largest publicly traded companies, measures that can sometimes differ from one organization to another.[22] For example, it has been observed that GHG emissions associated with hydraulic fracturing for shale gas are significantly underestimated because the high methane emissions involved in the hydraulic fracturing process are not counted. Thus, what would appear to be—according to current carbon footprint measurements—a welcome reduction in carbon footprints following the shift from coal to shale gas could be just an illusion. Consequently, a green filter that relies on this biased carbon footprint measure risks exposing investors to more rather than less carbon risk.

As described in greater detail in Appendix C, GHG emissions are divided into three scopes: Scope 1, which measures direct GHG emissions; Scope 2, which concerns indirect emissions resulting from the company's purchases of energy; and Scope 3, which covers third-party emissions (suppliers and consumers) tied to the company's sales. Although Scope 3 emissions may represent the largest fraction of GHG emissions for some companies (e.g., consumer electronics companies and car manufacturers),[23] there is currently no systematic, standardized reporting of these emissions. This lack is clearly a major limitation and reduces the effectiveness of all existing decarbonization methodologies. For example, excluding the most-polluting companies in the automobile industry and the auto components industry on the basis of current emission measures would lead mostly to the exclusion of auto components companies. Automobile manufacturers would largely be preserved because most of the carbon emissions for a car maker are Scope 3 emissions. As reliance on decarbonized indexes grows in scale, however, more resources will likely be devoted to improving the quality of Scope 3 and the other categories of GHG emissions. The inclusion of Scope 3 emissions would also better account for green product innovations by materials companies that bolster the transition toward a low-carbon economy. For instance, aluminum producers might be excluded under the current GHG measures owing to their high carbon intensity even though aluminum will fare better than other materials in the transition to renewable energy.

There are three evident responses to these existing measurement limitations. First, drawing an analogy with credit markets, we know that a biased or noisy measure of credit risk by credit-rating agencies has never been a decisive reason for abolishing credit ratings altogether. Credit ratings have provided an essential reinforcement of credit markets for decades despite important imprecisions in their measurements of credit risk, which have been pointed out by researchers of credit markets over time. Second, as with credit ratings, methodologies for measuring carbon footprints will be improved, especially when the stakes involved in measuring carbon footprints correctly increase because of the role of these measures in any green filtering process. Third, the design of the decarbonized index itself offers protection against carbon footprint measurement risk; if there is virtually no tracking error with the benchmark, investors in the decarbonized index are partly hedged against this risk.

Finally, a somewhat more technical worry is that the stocks excluded from the decarbonized index could also be the most volatile stocks in the benchmark index because these stocks are the most sensitive to speculation about climate change and climate policy. If that is the case, tracking error cannot be eliminated entirely, but that should not be a reason for deciding not to invest in the decarbonized index. On the contrary, the decarbonized index will then have a higher Sharpe ratio than the benchmark, commensurate with a higher TE.[24]

To summarize, our proposed strategy for hedging climate risk is especially suitable for passive long-term investors. Rather than a risky bet on clean energy (at least in the short run), we have described a decarbonized index with minimal tracking error that offers passive investors a significantly reduced exposure to carbon risk, allowing them to "buy time" and limit their exposure with respect to the timing of the implementation of climate policy and a carbon tax. Thus, a key difference between this approach and existing green indexes is switching the focus from the inevitable transition to renewable energy to the timing risk with respect to climate policy. As we show later in the article, carbon exposure can be reduced significantly—with maximum insurance against the timing of climate policy—by minimizing tracking error with the benchmark index. We believe that this approach is essentially a win-win strategy for all passive asset owners and managers. Moreover, should this strategy be adopted by a large fraction of passive index investors—a market representing close to $11 trillion in assets, according to a recent study[25] (Boston Consulting Group 2015)—companies will feel the pressure to improve their performance on GHG emissions and debates about carbon emissions will surely be featured prominently in the financial press.[26] It constitutes, therefore, an easy entry point for a wide clientele of investors and could trigger the mobilization of a much broader ecosystem dedicated to the analysis and understanding of climate-related transition risks.

Decarbonized Indexes in Practice: How Small Are Their Carbon Footprints?

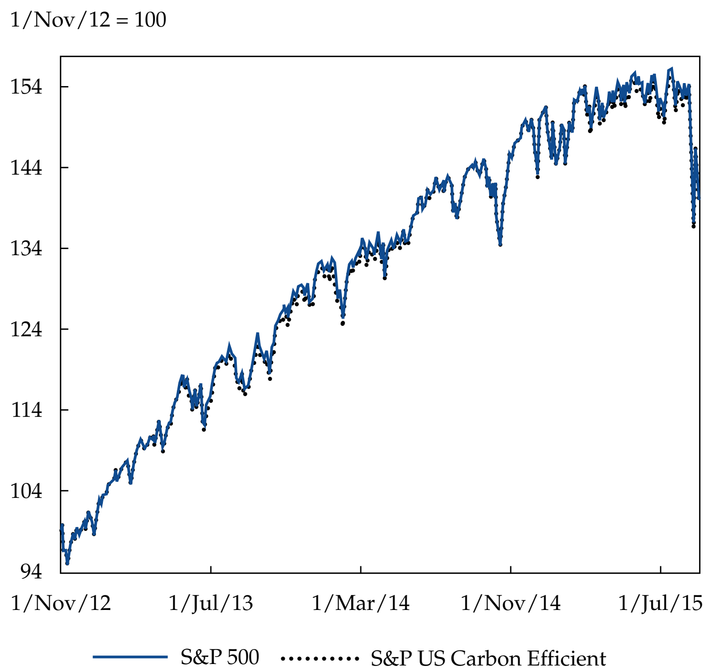
There are several examples of decarbonized indexes. AP4, the Fourth Swedish National Pension Fund (Fjärde AP-fonden), is, to our knowledge, the first institutional investor to adopt a systematic approach that uses some of these decarbonized indexes to significantly hedge the carbon exposure of its global equity portfolio. In 2012, AP4 decided to hedge the carbon exposure of its US equity holdings in the S&P 500 by switching to a decarbonized portfolio with a low TE relative to the S&P 500 through the replication of the S&P 500 Carbon Efficient Select Index. This index excludes the 20% worst performers in terms of carbon intensity (CO_2/Sales) as measured by Trucost, one of the leading companies specializing in the measurement of the environmental impacts of publicly traded companies. An initial design constraint on the decarbonized index is to ensure that stocks removed from the S&P 500 do not exceed a reduction in the Global Industry Classification Standard (GICS) sector weight of the S&P 500 by more than 50%. A second feature of the S&P 500 Carbon Efficient Select Index is the readjustment of the weighting of the remaining constituent stocks to minimize TE with the S&P 500. Remarkably, this decarbonized index reduces the overall carbon footprint of the S&P 500 by roughly 50%,[27] with a TE of no more than 0.5%. This first model of a decarbonized index strikingly illustrates that significant reductions in carbon exposure are possible without sacrificing much in the way of financial performance or TE. In fact, AP4's S&P 500 Carbon Efficient Select Index portfolio has outperformed the S&P 500 by about 24 bps annually since it first invested in the decarbonized index in November 2012, as **Figure 3** shows, which is in line with the 27 bp annual outperformance of the S&P 500 Carbon Efficient Select Index since January 2010.

AP4 has extended this approach to hedging climate risk to its equity holdings in emerging markets.[28] Relying on carbon footprint data from MSCI ESG Research, AP4 has sought to exclude from the MSCI EM Custom ESG Index not only the companies with the highest GHG emissions but also the worst companies in terms of stranded-asset risk. Turning to its Pacific-ex-Japan stock holdings, AP4 has applied a similar methodology in constructing its decarbonized portfolio, excluding the companies with the largest reserves and highest carbon emissions intensity while maintaining both sector and country weights in line with its initial index holdings in the region.

More recently, AP4, FRR (Fonds de réserve pour les retraites, or the French pensions reserve fund), and Amundi have worked with MSCI to develop another family of decarbonized indexes with a slightly different design. The result is the MSCI Global Low Carbon Leaders Index family—based on existing MSCI equity indexes (e.g., MSCI ACWI, MSCI World, and MSCI Europe)—which addresses two dimensions of carbon exposure. It excludes from the indexes the worst performers in terms of both carbon emissions intensity and fossil fuel reserves intensity while maintaining a maximum turnover constraint as well as minimum sector and country weights. The remaining constituent stocks are then rebalanced to minimize TE with the respective benchmarks.[29] **Table 2** compares the performance of the resulting decarbonized indexes, based on a backtest, with that of the MSCI Europe Index. As Table 2 shows, the Low Carbon Leaders Index delivers a remarkable 90 bp annualized outperformance over the MSCI Europe Index for November 2010–February 2016, with a similar volatility and a 0.7% tracking error.

At the end of January 2016, we conducted a performance attribution analysis, after the MSCI Europe Low Carbon Leaders Index was launched, for the period November 2014–January 2016,[30] when the outperformance was particularly strong (an overall 189 bps[31]). Our analysis shows how to distinguish which part of the performance is due to sector allocation (allocation effect[32]) and which part is due to stock selection within sectors (selection effect[33]). At the sector level (using the GICS[34] taxonomy), the allocation effect is responsible for 37 bps of outperformance, with the underweighting of the energy and materials sectors responsible for 40 bps and 20 bps, respectively. More importantly, the effect of screening out the worst GHG performers within a sector is greater than the allocation effect, with a 120 bp outperformance. Interestingly, the positive screening effect is concentrated in two sectors, Materials (127 bps) and Utilities (25 bps; see **Table E1** in Appendix E). The largest negative contributor, Consumer Staples, had an allocation effect of –37 bps and a selection effect of –8 bps.

Figure 3. S&P 500 and S&P US Carbon Efficient Indexes



Sources: Amundi and Bloomberg (31 August 2015).

We conducted a second-level analysis (industry level; see **Table E2** and **Table E3** in Appendix E) that focused on the largest contributor, the materials sector, and found that the index was strongly underweighted in the diversified metals and mining (DM&M) stocks, with a 68 bp allocation effect and a 36 bp selection effect. The reason behind this underweighting is that coal represents the major part of DM&M reserves. As for the utilities sector, the index was underweighted on multi-utilities because of their high emissions (an 11 bp selection effect and an 8 bp allocation effect). Stock performance for these two sectors was related to trends in the energy sector (mostly a fall in coal prices).

AP4, MSCI, FRR, and Amundi have further explored the robustness of these decarbonized indexes to other exclusion rules and to higher carbon footprint reductions. They found that there is not much to be gained by using more flexible criteria that permit less than 100% exclusion of high-carbon-footprint stocks. **Table 3** compares the performances of a fully "optimized" portfolio, with no strict exclusion of the worst performers, and a portfolio based on the "transparent exclusion rules" outlined earlier. Whether in terms of reduced exposure to carbon or overall tracking error, the two portfolios deliver similar results.

Interestingly, however, the two methods for constructing the decarbonized index yield substantial sector differences in TE contribution, which is concentrated in two sectors (materials and energy) for the fully optimized index. In contrast, the limit put on total sector exclusion in the Low Carbon Leaders Index (with transparent rules) spreads the effort across several sectors (see **Figure F1** in Appendix F for a detailed breakdown of the contributions to specific risks).

Conclusion

Our decarbonized index investment strategy stands on its own as a simple and effective climate risk–hedging strategy for passive long-term institutional investors, but it is also an important complement to climate change mitigation policies. Governments have thus far focused mostly on introducing policies to control or tax GHG emissions and to build broad international agreements for the global implementation of such policies (for a discussion of the pros and cons of cap-and-trade mechanisms versus a GHG emissions tax, see Guesnerie and Stern 2012).[35] Governments have also provided subsidies to the solar and wind energy sectors, thereby boosting a small-business constituency that supports climate change mitigation policies. Similarly, index decarbonization can boost support for such policies from a large fraction of the investor community. In addition, as more and more funds are allocated to decarbonized indexes, stronger market incentives will materialize, inducing the

Table 2. Financial Performance of Transparent Rules on MSCI Europe

Key Metrics	MSCI Europe Index	MSCI Europe Low Carbon Leaders Index
Total return[a]	7.8%	8.7%
Total risk[a]	13.2%	13.2%
Return/risk	0.59	0.65
Sharpe ratio	0.57	0.63
Active return[a]	0%	0.9%
Tracking error[a]	0%	0.7%
Information ratio	NA	1.16
Historical beta	1.00	1.16
Turnover[b]	1.8%	9.9%
Securities excluded	NA	93
Market cap excluded	NA	21.4%
Reduction in carbon emissions intensity (tCO_2/US$ millions)	NA	52%
Reduction in carbon reserves intensity (tCO_2/US$ millions)	NA	66%

NA = not applicable.
Notes: The index of low-carbon leaders is reviewed and updated every six months (in May and November). This table was created after the November 2015 review of the list of index constituents.
[a]Gross returns were annualized in euros for 30 November 2010–29 February 2016.
[b]Annualized one-way index turnover for 30 November 2010–29 February 2016.

Table 3. Carbon and Financial Performances of Transparent Rules on MSCI Europe

	Optimized Index (low-carbon target)	Transparent Rules (low-carbon leaders)
Reduction in carbon emissions intensity (tCO_2/US$ millions)	82%	62%
Reduction in carbon reserves intensity (tCO_2/US$ millions)	90%	81%
Tracking error[a]	0.9%	0.72%

Note: Backtests were run over a four-year period, from 30 November 2010 to 30 June 2014.
[a]Gross returns were annualized in euros for 30 November 2010–31 July 2015.
Source: MSCI.

world's largest corporations—the publicly traded companies—to invest in reducing GHG emissions. Moreover, the encouragement of climate risk hedging can have real effects on reducing GHG emissions even before climate change mitigation policies are introduced. The mere expectation that such policies will be introduced will affect the stock prices of the highest-GHG emitters and reward those investors that have hedged climate risk by holding a decarbonized index. Finally, the anticipation of the introduction of climate change mitigation policies will create immediate incentives to initiate a transition to renewable energy.

A simple, costless policy in support of climate risk hedging that governments can adopt immediately is to mandate disclosure of the carbon footprint of their state-owned investment arms (public pension funds and sovereign wealth funds). Such a disclosure policy would have several benefits.

Given that climate change is a financial risk, disclosure provides investors (and citizens) with relevant information on the nature of the risks they are exposed to. Remarkably, some pension funds have already taken this step by disclosing their portfolios' carbon footprint—in particular, ERAFP and FRR in France; KPA Pension, the Church of Sweden, and the AP funds in Sweden; APG in the Netherlands; and the Government Employees Pension Fund (GEPF) in South Africa.

Given that citizens and pensioners will ultimately bear the costs of climate change mitigation, disclosure of their carbon exposure through their pension or sovereign wealth funds helps internalize the externalities of climate change. Indeed, investment by a public pension fund in polluting companies generates a cost borne by its government and trustees and thereby lowers the overall returns on investment. The China Investment Corporation

(CIC), China's sovereign wealth fund, has already made some statements in that direction.

Disclosure of the carbon footprint of a sovereign wealth fund's portfolio can be a way for sovereign wealth funds of oil- and gas-exporting countries to bolster risk diversification and hedging of commodity and carbon risk through their portfolio holdings. The basic concept underlying a sovereign wealth fund is to diversify the nature of the country's assets by extracting the oil and gas under the ground and thereby "transforming" these assets into "above-ground" diversifiable financial assets. Thus, it makes sense to follow up this policy by diversifying investments held by the sovereign wealth fund away from energy companies and other stock holdings that have a large carbon exposure. Interestingly, the French government recently approved a law on energy transition that requires French institutional investors to disclose their climate impact and carbon risk exposure.[36]

A more direct way to support investment in low-carbon, low-TE indexes is to push public asset owners and their managers to make such investments. Governments could thus play an important role as catalysts to accelerate the mainstream adoption of such investment policies. In this respect, it is worth mentioning the interesting precedent of the recent policy of the Shinzō Abe administration in Japan to support the development of the JPX-Nikkei Index 400. What is particularly noteworthy is that the Abe administration sees this index as an integral part of its "third arrow" plan to reform Japan's companies. GPIF—by far the largest Japanese public investor, with more than $1.4 trillion of assets under management—has adopted the new index. This example illustrates how the combination of a newly designed index with a policymaking objective and the adoption of that index by a public asset owner can be a catalyst for change.

In his book *Finance and the Good Society*, Robert J. Shiller (2012, p. 7) advances a welcome and refreshing perspective on financial economics:

> Finance is not about "making money" per se. It is a "functional" science in that it exists to support other goals—those of society. The better aligned society's financial institutions are with its goals and ideals, the stronger and more successful the society will be.

It is in this spirit that we have pursued our research on how investors can protect their savings from the momentous risks associated with GHG emissions and their long-term, potentially devastating effect on climate change. Climate change has mostly and appropriately been the bailiwick of scientists, climatologists, governments, and environmental activists. There has been relatively little engagement by finance with this important issue, but investors and financial markets cannot continue to ignore climate change. The effects of rising temperatures, the increasingly extreme weather events climate change generates, and the climate change mitigation policy responses it could provoke may have dramatic consequences for the economy and thus investment returns. Therefore, financial innovation should be explored so that the power of financial markets can be used to address one of the most challenging global threats faced by humankind.

Besides offering investors a hedging tool against the rising risks associated with climate change, a decarbonized index investment strategy can mobilize financial markets to support the common good. As a larger and larger fraction of the index-investing market is devoted to decarbonized indexes, a virtuous cycle will be activated and enhanced whereby the greater awareness of carbon footprints and GHG emissions will exert a disciplining pressure to reduce CO_2 emissions and will gradually build an investor constituency that supports climate change mitigation policies. Governments, businesses, technology innovators, and society will thus be encouraged to implement changes that accelerate the transition to a renewable energy economy.

Our basic premise/working assumption is that to foster the engagement of financial markets with climate change, it is advisable to appeal to investors' rationality and self-interest. Our argument is simply that even if some investors are climate change skeptics, the uncertainty surrounding climate change cannot be used to dismiss climate change and related mitigation policies as a zero probability risk. Any rational investor with a long-term perspective should be concerned about the absence of a market for carbon and the potential market failures that could result from this incompleteness. A dynamic decarbonized index investment strategy seeks to fill this void, offering an attractive hedging tool even for climate change skeptics.

Finally, the decarbonization approach we have described for equity indexes can also be applied to corporate debt indexes. Although the focus in fixed-income markets has been on green bonds, corporate debt indexes—decarbonized along the same lines as equity indexes (screening and exclusion based on carbon intensity and fossil fuel reserves while maintaining sector neutrality and a low TE)—could be a good complement to green bonds. Similarly, low-water-use indexes and other environmental leader indexes can be constructed in the same way as our decarbonized index.

We thank the Rockefeller Foundation for its support of this research project. For their helpful comments, we are grateful to Bertrand Badré, Lorenzo Bernasconi, *Pierre-Olivier Billard, Pascal Blanqué, Jean Boissinot, Remy Briand, Pierre Cailleteau, Yves Chevalier, Catherine Crozat, Bob Eccles, Christiana Figueres, Remco Fischer, Mark Fulton, Evan Greenfield, Mickaël Hellier, Harrison Hong, Maximilian Horster, Haizhou Huang, Mikael Johansson, Tegwen Le Berthe, Linda-Eling Lee, Mark Lewis, Bob Litterman, Jun Ma, Justin Mundy, Carl Page, Fredrik Regland, Ailsa Roell, Olivier Rousseau, Alessandro Russo, Michael Sheren, Martin Skancke, Lord Nicholas Stern, Laurent Trottier, Eric Usher, and Gernot Wagner. We thank Timothée Jaulin for excellent research assistance.*

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Appendix A. Current Context of Climate Legislation

The United Nations Framework Convention on Climate Change (UNFCCC) coordinates global policy efforts toward the stabilization of GHG concentrations in the atmosphere, with a widely accepted policy target for the upcoming decades of limiting GHG emissions to keep average temperatures from rising more than 2°C by 2050. However, no concrete policies limiting GHG emissions have yet been agreed to that make this target a realistic prospect. To give an idea of what this target entails, scientists estimate that an overall limit on the concentration of CO_2 in the atmosphere between 350 parts per million (ppm) and 450 ppm should not be exceeded if we are to have a reasonable prospect of keeping temperatures from rising by more than 2°C (IPCC 2014). Maintaining CO_2 concentrations under that limit would require keeping global CO_2 emissions below roughly 35 billion tons a year, which is more or less the current rate of emissions; it was 34.5 gigatons (Gt) in 2012, according to the European Commission.

Although the process led by the UNFCCC stalled during many years following the adoption of the Kyoto Protocol, a number of countries have taken unilateral steps to limit GHG emissions in their jurisdictions. Thus, a very wide array of local regulations, as well as legislation focused on carbon emission limits and clean energy, has been introduced in the past decade—for example, 490 new regulations were put in place in 2012 as opposed to only 151 in 2004 and 46 in 1998 (UNEP FI 2013). Moreover, after promising signs of greater urgency concerning climate policies in both the United States[37] and China, the "Paris agreement" negotiated during the climate conference in Paris in December 2015 marked "an unprecedented political recognition of the risks of climate change."[38]

The Paris agreement, however, does not detail a course for action and entails many nonbinding provisions with no penalties imposed on countries unwilling or unable to reach their targets. But if the prospect of a global market for CO_2 emission permits—or even a global carbon tax—also seems far off, the establishment of a national market for CO_2 emission permits in China in the next few years could be a game changer. Indeed, in the U.S.–China Joint Announcement on Climate Change and Clean Energy Cooperation, China has pledged to cap its CO_2 emissions around 2030 and to increase the non-fossil-fuel share of its energy consumption to around 20% by 2030.[39] Moreover, following the launch of seven pilot emissions-trading schemes (ETSs), which are currently in operation, China's National Development and Reform Commission (NDRC) stated that it aimed to establish a national ETS during its five-year plan (2016–2020).[40]

Yet, despite China's impressive stated climate policy goals and the Paris agreement, substantially more reductions in CO_2 emissions need to be implemented globally to have an impact on climate change. In particular, the global price of CO_2 emissions must be significantly higher to induce economic agents to reduce their reliance on fossil fuels or to make carbon capture and storage worthwhile (current estimates indicate that a minimum carbon price of $25–$30 per ton of carbon dioxide equivalent [CO_2e] is required to cover the cost of carbon capture).[41] Therefore, with the continued rise in global temperatures and the greater and greater urgency regarding strong climate mitigation policies in the coming years, policymakers may at last realize that they have little choice but to implement radical climate policies, resulting in a steep rise in the price of carbon. On top of national governments' mobilization and international agreements, major religious authorities have recently expressed their concerns about climate change, urging both governments and civil society to act.[42]

Appendix B. Risk of Stranded Assets

The notion of stranded assets was introduced by the Carbon Tracker Initiative (2011, 2013)[43] and the Generation Foundation (2013). It refers to the possibility that not all known oil and gas reserves will be exploitable should the planet reach the peak of sustainable concentrations in the atmosphere before all oil and gas reserves have been exhausted. A plausible back-of-the-envelope calculation goes as follows: According to the Carbon Tracker Initiative (2011), Earth's proven fossil fuel reserves amount to approximately 2,800 Gt of CO_2 emissions. But to maintain the objective of no warming greater than 2°C by 2050 (with at least a 50% chance), the maximum amount of allowable emissions is roughly half, or 1,400 Gt of CO_2. In other words, oil companies' usable proven reserves are only about half of reported reserves. Responding to a shareholder resolution, ExxonMobil published in 2014, for the first time ever, a report describing how it assesses the risk of stranded assets.[44] Much of the report is an exercise in minimizing shareholders' and analysts' concerns about stranded-asset risk by pointing to the International Energy Agency's projections on growing energy demand without competitive substitutes leading to higher fossil fuel prices. Nonetheless, it cannot be entirely ruled out that investors will see a growing fraction of proven reserves as unexploitable because they are simply too costly—whether because of the emergence of cheap, clean, and reliable substitutes in the form of competitive clean energy or because climate mitigation policies become an increasingly binding reality (or, most likely, both).

Appendix C. Carbon Data

In this appendix, we offer further details on the available carbon emissions and carbon reserves data as well as the main providers of the carbon data we used.

Nature of Carbon Emissions and Carbon Reserves Data

Carbon emissions and carbon reserves relate to a wide array of greenhouse gases (GHGs) and hydrocarbon reserves. The standard unit of measurement is the metric ton of carbon dioxide equivalent ($MtCO_2e$), usually shortened to tons of carbon. Regarding GHG emissions, the most widely used international carbon-accounting tool for governments and businesses is the GHG protocol. This protocol serves as the foundation for almost every GHG standard in the world—notably, the International Organization for Standardization (ISO) and the Climate Registry. Corporate users include BP, Shell, General Motors, GE, AEG, Johnson & Johnson, Lafarge, and Tata Group. Noncorporate users include trading schemes (EU ETS, UK ETS, Chicago Climate Exchange); nongovernmental organizations (CDP, WWF, Global Reporting Initiative); and government agencies in China, the United States, US states, Canada, Australia, Mexico, and other jurisdictions.

According to the protocol, GHG emissions are divided into three scopes. Scope 1 relates to direct GHG emissions—that is, emissions that occur from sources owned or controlled by the company (e.g., emissions from fossil fuels burned on site or in leased vehicles). Scope 2 emissions are indirect GHG emissions resulting from the purchase of electricity, heating, cooling, or steam generated off-site but purchased by the entity. Scope 3 emissions encompass indirect emissions from sources not owned or directly controlled by the entity but related to its activities (e.g., employee travel and commuting, vendor supply chain). Obviously, Scope 3 emissions represent the largest GHG impact for many companies, whether in upstream activities (e.g., consumer electronics) or downstream activities (e.g., automotive industry). Scope 3 emissions reporting still lacks standardization, however, and the reporting level remains low; only 180 of the Fortune 500 companies reported on some portion of their supply chain in 2013.[45]

The estimation of the CO_2 equivalent of carbon reserves is a three-step process that involves the classification and estimation of hydrocarbon reserves that are then translated into CO_2 emissions. Most of the time, the data used for estimation of fossil fuel reserves and stranded assets concern proven reserves (a 90% probability that at least the actual reserves will exceed the estimated proven reserves). Those data are publicly available and must be disclosed in company reports. Once the proven reserves are estimated in volume or mass, two steps remain. First, the calorific value of total fossil fuel reserves must be estimated. Second, that calorific value must be translated into carbon reserves by using a carbon intensity table.

Carbon Data Providers

At the two ends of the spectrum of carbon data providers, we found entities that simply aggregate data either provided directly by companies or publicly available and those that use only their internal models to estimate carbon emissions and reserves.

Corporations themselves are the primary providers of carbon data via two main channels: (1) CSR (corporate social responsibility) reports from 37% of the world's largest companies (with a market capitalization exceeding $2 billion) completely disclose their GHG emission information; (2) CDP provides the largest global carbon-related database, in partnership with Bloomberg, MSCI ESG, Trucost, and others. Companies respond to CDP's annual information request forms for the collection of climate change–related information; the number of respondents has increased from 235 in 2003 to 2,132 in 2011. Financial data vendors, such as Bloomberg, generally provide datasets sourced from CDP, CSR reports, and other relevant reports. The heterogeneity of sources explains the discrepancies that can sometimes be found in carbon footprint measurements.

Appendix D. TE Minimization with a Multifactor Risk Model

In this appendix, we describe the multifactor risk model that we used to determine the decarbonized portfolio with minimum tracking error. We reduce *ex ante* TE by first estimating factor returns, then estimating risk, and ultimately minimizing TE.

Ex Ante and *Ex Post* Tracking Error

Index managers usually seek a very low tracking error, but some may also seek higher returns by optimizing index replication (e.g., tax optimization, management of changes in index composition, management of takeover bids). For index managers, there is a trade-off between the goals of minimizing tracking error and maximizing return. Portfolio managers use two different measures of tracking error: (1) *Ex post* TE is the measure of the volatility of the realized active return deviations from the benchmark, and (2) *ex ante* TE is an estimation (or prediction) based on an estimated multifactor model.

Ex ante TE is a function of portfolio weights, benchmark weights, the volatility of stocks, and correlations across assets. Thus, to estimate portfolio risk once portfolio weights and benchmark weights are given, we need the covariance matrix of security returns. One can estimate such a covariance matrix by using historical data of security returns, but that method is burdensome and prone to estimation error (spurious correlations).

An alternative method is to use a multifactor model. We rely on the widely used Barra multiple-factor model (MFM),[46] which decomposes the return of an individual stock into the weighted sum of common factor returns and an idiosyncratic return as follows:

$$r_i = \beta_{country\ i} f_{country\ i} + \beta_{sector\ i} f_{sector\ i} + \beta_{size\ i} f_{size\ i} + \cdots + u_i$$

$$r_i = \sum_{j=1}^{j} \beta_{ji} \tilde{f}_j + u_i$$

$$\begin{bmatrix} r_1 \\ \vdots \\ r_n \end{bmatrix} = \begin{bmatrix} \beta_{11} & \cdots & \beta_{1k} \\ \vdots & \ddots & \vdots \\ \beta_{nk} & \cdots & \beta_{nn} \end{bmatrix} \begin{bmatrix} f_1 \\ \vdots \\ f_j \end{bmatrix} + \begin{bmatrix} u_1 \\ \vdots \\ u_n \end{bmatrix}$$

$$r = \beta f + u,$$

where

β_{ji} = the factor loading for security *i* on common factor *j*

f_j = the common factor return

u_i = the part of the return that cannot be explained by common factors

Estimating Factor Returns

Common factors used by Barra include industries, styles (size, value, momentum, and volatility), and currencies; 68 factors are used for the multiple-horizon US equity model.

Common factor returns are estimated using monthly stock returns. The time series of factor returns are then used to generate factor variances and covariances in the covariance matrix:

$$\begin{bmatrix} \text{Var}(f_1) & \cdots & \text{Cov}(f_1, f_k) \\ \vdots & \ddots & \vdots \\ \text{Cov}(f_k, f_1) & \cdots & \text{Var}(f_k) \end{bmatrix}.$$

To capture variance and covariance dynamics and improve the predictive power of the model, Barra uses an exponential weighting scheme that gives more weight to recent data, and so, on average, the last two to three years of data represent 50% of the available information ("half life").

From Factor Returns to Risk Estimation

Similar to components of returns, components of risks can be divided into common factor sources and security-specific risks:

$$\text{Var}(\text{total risk}) = \text{Var}(\text{common factor risk}) + \text{Var}(\text{active specific risk}),$$

and the multifactor equation becomes

$$\text{Var}(r) = \text{Var}(\boldsymbol{\beta} f + u)$$

$$\text{Var}(r) = \boldsymbol{\beta} \boldsymbol{\Omega}_f \boldsymbol{\beta}' + \boldsymbol{\Delta},$$

where

$\boldsymbol{\beta}$ = the matrix of factor exposures

$\boldsymbol{\beta}'$ = the transposed matrix

$\boldsymbol{\Omega}$ = the variance–covariance matrix for the *k* factors

$\boldsymbol{\Delta}$ = the diagonal matrix of specific risk variances

The volatility, σ_p, of any portfolio *p*, represented by a vector of portfolio weights $\mathbf{W}_p$, is thus

$$\sigma_p = \sqrt{\mathbf{W}_p \left(\boldsymbol{\beta} \boldsymbol{\Omega}_f \boldsymbol{\beta}' + \boldsymbol{\Delta} \right) \mathbf{W}_p'}.$$

TE Minimization

In the case of tracking error minimization, the objective function is the *ex ante* tracking error; constraints can range from turnover limits to reweighting rules with or without active weight constraints, among others.

Let us consider an example of a low-carbon, low-TE, multi-utilities fund. First, we have a reference universe of 10 constituents: the multi-utilities industry group in the utilities sector in a large economic zone. We assign to each constituent an index weight equal to $\left[\text{Mkt cap}(i)/\text{Total mkt cap}\right]$ in order to obtain a market cap–weighted index, and we let $\left(w_1^b,\cdots,w_{10}^b\right)$ be the constituent stocks' weights. We rank the constituents according to their carbon intensity (e.g., CO_2e/GWh) and then adopt the following constraint (rule):

$$\begin{pmatrix} w_1^b \\ w_2^b \\ \vdots \\ w_{10}^b \end{pmatrix} => \begin{pmatrix} 0 \\ w_2 \\ \vdots \\ w_{10} \end{pmatrix}.$$

In other words, the optimal portfolio $(0, w_2, \cdots, w_{10})$ will be the result of the minimization of the following objective function:

$$\text{Min}\left[\sqrt{\left(W^p - W^b\right)'\left(\boldsymbol{\beta}\boldsymbol{\Omega}_f\boldsymbol{\beta}' + \boldsymbol{\Delta}\right)\left(W^p - W^b\right)}\right],$$

where

$$\forall i = 1,\cdots,10;\ 0 \le w_i$$
$$i = 1;\ w_1 = 0,$$

and

$\left(W^p - W^b\right)$ = the active weights of the portfolio with regard to the benchmark

$\boldsymbol{\Omega}_f$ = the variance–covariance matrix of factors

$\boldsymbol{\beta}$ = the matrix of factor exposures

$\boldsymbol{\Delta}$ = the diagonal matrix of specific risk variances

Barra uses an optimization algorithm to minimize TE under the new constraint of excluding stock 1. It selects active weights depending on the factor loading of each security and the covariance between each factor in order to create a new portfolio that closely tracks the reference portfolio.

Appendix E. Performance Attribution in the MSCI Europe Low Carbon Leaders Index vs. the MSCI Europe Index

In this appendix, **Table E1**, **Table E2**, and **Table E3** give several measures of performance attribution for various sectors in the MSCI Europe Low Carbon Leaders Index versus the MSCI Europe Index.

Appendix F. Percentage Contributions to Specific Risks by Sector

In this appendix, **Figure F1** depicts the breakdown of the percentage contributions to specific risks by sector.

Figure F1. Percentage Contributions to Specific Risks by Sector

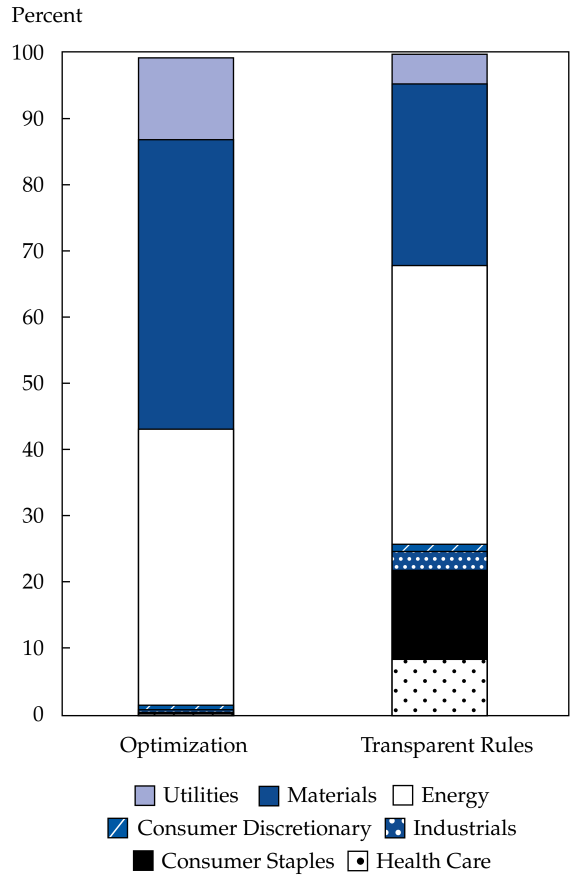

Table E1. MSCI Europe Low Carbon Leaders vs. MSCI Europe, 7 November 2014–31 January 2016

	MSCI Europe Low Carbon Leaders Index			MSCI Europe Index			Attribution Effect		
Sector	Weight	Total Return	Contribution to Return	Weight	Total Return	Contribution to Return	Allocation Effect	Selection Effect	Total Effect
Total	100.00	6.06	6.06	100.00	4.17	4.17	0.37	1.52	1.89
Materials	6.18	2.65	0.20	7.23	–17.72	–1.10	0.20	1.27	1.47
Utilities	3.87	7.55	0.30	4.00	0.83	0.04	0.02	0.25	0.27
Health care	13.48	11.16	1.29	13.84	9.28	1.12	0.00	0.21	0.21
Consumer discretionary	12.57	12.58	1.41	11.45	12.18	1.23	0.09	0.05	0.15
Industrials	12.93	7.74	0.98	11.04	7.11	0.74	0.06	0.07	0.14
Telecommunication services	5.61	17.44	0.89	4.95	16.58	0.70	0.08	0.05	0.13
Information technology	3.69	25.97	0.93	3.56	21.92	0.69	0.02	0.11	0.13
Financials	24.64	–4.18	–1.18	22.75	–4.55	–1.26	–0.15	0.11	–0.04
Energy	5.15	–26.05	–1.33	7.13	–16.82	–1.10	0.40	–0.52	–0.12
Consumer Staples	11.90	22.71	2.56	14.07	24.19	3.12	–0.37	–0.08	–0.45

Sources: Amundi; MSCI; FactSet.

Table E2. MSCI Europe Low Carbon Leaders vs. MSCI Europe—Materials Sector, 7 November 2014–31 January 2016

	MSCI Europe Low Carbon Leaders Index			MSCI Europe Index			Attribution Effect		
Sector	Weight	Total Return	Contribution to Return	Weight	Total Return	Contribution to Return	Allocation Effect	Selection Effect	Total Effect
Materials	6.18	2.65	0.20	7.23	–17.72	–1.10	0.20	1.27	1.47
Diversified metals and mining	0.75	–23.73	–0.36	1.84	–55.54	–1.15	0.68	0.36	1.04
Construction materials	0.47	28.56	0.10	0.75	–0.75	–0.01	0.01	0.11	0.12
Specialty chemicals	1.69	14.25	0.32	1.16	12.26	0.12	0.04	0.03	0.06
Steel	0.34	–23.61	–0.06	0.27	–43.40	–0.11	–0.04	0.09	0.06
Diversified chemicals	1.27	–7.61	–0.06	1.16	–9.39	–0.06	–0.02	0.02	0.00

Sources: Amundi; MSCI; FactSet.

Table E3. MSCI Europe Low Carbon Leaders vs. MSCI Europe—Utilities Sector, 7 November 2014–31 January 2016

	MSCI Europe Low Carbon Leaders Index			MSCI Europe Index			Attribution Effect		
Sector	Weight	Total Return	Contribution to Return	Weight	Total Return	Contribution to Return	Allocation Effect	Selection Effect	Total Effect
Utilities	3.87	7.55	0.30	4.00	0.83	0.04	0.02	0.25	0.27
Multi-utilities	1.43	–0.20	–0.01	1.82	–8.02	–0.13	0.08	0.11	0.19
Water utilities	0.38	21.29	0.09	0.21	21.24	0.04	0.03	0.00	0.03
Electric utilities	1.45	12.10	0.18	1.63	7.66	0.10	–0.03	0.05	0.03
Gas utilities	0.50	10.96	0.05	0.30	10.84	0.03	0.01	0.00	0.01
Renewable electricity	0.11	–3.12	0.00	0.04	–3.12	0.00	0.00	0.00	0.00

Sources: Amundi; MSCI; FactSet.

Notes

1. A recent study by a team from the National Oceanic and Atmospheric Administration found that this perceived slowdown was entirely the result of measurement errors in recorded ocean temperatures (Karl, Arguez, Huang, Lawrimore, McMahon, Menne, Peterson, Vose, and Zhang 2015).
2. For an analysis of the consequences of this deep uncertainty for the economics of carbon pricing, see Litterman (2012).
3. For a widely quoted speech on climate change and the "tragedy of horizon" and related "transition risks," see Carney (2015).
4. The United Nations Framework Convention on Climate Change (UNFCCC) coordinates global policy efforts toward the stabilization of greenhouse gas (GHG) concentrations in the atmosphere, with a widely accepted policy target for the coming decades of limiting GHG emissions to keep average temperatures from rising more than 2°C by 2050. However, no concrete policies limiting GHG emissions have yet been accepted that make this target a realistic prospect. Although the process led by the UNFCCC stalled following the adoption of the Kyoto Protocol, a number of countries have taken unilateral steps to limit GHG emissions in their own jurisdictions. The 21st Conference of the Parties to the UNFCCC, which was held in Paris in December 2015 (http://www.un.org/sustainabledevelopment/cop21/), is seen by many observers as a crucial milestone in the fight against climate change. For further details, see Appendix A.
5. A handful of organizations contribute to raising awareness of carbon risk among institutional investors. For example, the Portfolio Decarbonization Coalition (PDC)—co-founded by AP4, CDP, Amundi, and UNEP FI in September 2014—enables pioneers in the decarbonization of portfolios to share their knowledge and best practices. When it was founded, PDC set a target of $100 billion in institutional investment decarbonization to be reached by the time of the Paris conference in December 2015. It was able to significantly surpass this target, with its 25 members claiming $600 billion of decarbonized investments out of $3.2 trillion of assets under management. For more information, see http://unepfi.org/pdc/ and Top1000Funds (2015). Another example is the "Aiming for A" coalition—a group representing institutional investors—which engages carbon-intensive companies to "measure and manage their carbon emissions and move to a low-carbon economy."
6. For more information on stranded assets, see Appendix B.
7. The carbon footprint of a company refers to its annualized GHG emissions relative to a financial metric (e.g., revenue or sales) or a relevant activity metric (e.g., units produced). For further details, see the pertinent discussion later in the article as well as Appendix C.
8. See Gartner, Inc. (2016).
9. Later in the article, we report the performance results of the "decarbonized" S&P 500 and MSCI Europe indexes.
10. The mechanics that affect the relationship of carbon legislation, technological changes, and financial returns are obviously complex and not straightforward. But the purpose of decarbonized indexes is to circumvent these difficulties by focusing on an area with somewhat less uncertainty: the companies most exposed to carbon risk. Later in the article, we delve into further details.
11. To explore the links between portfolio decarbonization and the incentives it gives to companies to rechannel their investments and lower their carbon footprint, see http://unepfi.org/pdc/.
12. Koch and Bassen (2013) estimated an "equity value at risk from carbon" for European electric utilities, which is driven by their fossil fuel mix, and showed that a filter on companies with a high carbon-specific risk reduces the exposure to global carbon risk without otherwise affecting the risk–return performance of an equity portfolio.
13. See "Energy and Carbon—Managing the Risks," ExxonMobil report (March 2014).
14. These are mostly environmental, social, and governance (ESG) analysts, who until recently were largely segregated from mainstream equity analyst teams and whose audience consists predominantly of ethical investors.
15. HSBC is a notable exception, with its early integrated analysis of the materiality of carbon risk in the oil and gas as well as coal industries (HSBC 2008). Since then, the Carbon Tracker Initiative has been instrumental in raising awareness of stranded asset issues, and energy-focused analysts are increasingly and consistently integrating carbon-related risk into their analyses (see, e.g., HSBC 2012; Lewis 2014).
16. A multisector generalization of this optimization problem can break down the first set of constraints into companies that are excluded on the basis of their poor ranking in carbon intensity across all sectors, as well as companies that are excluded within each sector on the basis of either their poor carbon intensity score or high stranded assets relative to other companies in their sector.
17. Unless noted otherwise, tracking error is calculated *ex ante*.
18. This level of outperformance over such a time frame is hypothetical and for illustrative purposes only. Although we hope that a scenario of radical climate risk mitigation policy measures is possible in the near future, global climate policy implementation and its potential impact on equity valuation understandably remain a very speculative exercise.
19. In this respect, it is worth mentioning that Veolia and Danone now include carbon footprint improvement targets in their executive compensation contracts.
20. An interesting example of such a mechanism is the JPX-Nikkei Index 400, a new index based on both standard quantitative criteria (e.g., return on equity, operating profit, and market value) and more innovative qualitative criteria (e.g., a governance requirement of at least two independent outside directors). Launched with the support of the giant Japanese pension fund GPIF (Government Pension Investment Fund) to foster better corporate performance, the JPX-Nikkei 400 was quickly dubbed the "shame index." It is now carefully scrutinized by analysts, and companies are taking inclusion in the index more and more seriously.
21. For a discussion of the relationship between sustainability investments and shareholder value creation, see Khan, Serafeim, and Yoon (2015).
22. For an attempt at comparing different providers' results within a given universe, see http://www.iigcc.org/events/event/50-shades-of-green-carbon-foot-print-workshop. The differences that emerged came from different estimation models. But professionals agree that the measures are globally converging toward a much-improved harmonization.
23. For 60% of the companies in the MSCI World Index, at least 75% of emissions are from supply chains (Trucost 2013).
24. Moreover, most modern optimization techniques use factor exposures and correlations to reduce tracking error risk from such known systematic factors as volatility, small cap, and beta; they would therefore increase the weights on high-volatility/low-carbon stocks to replace high-volatility/high-carbon stocks.
25. Index and ETF investments represent a growing share of total investment products, amounting to almost 14% of total assets under management, with a year-over-year growth rate of 10% from 2013 to 2014.
26. Beyond the $11 trillion in index funds, asset owners that are members of CDP represent an asset base as high as $95 trillion (see CDP.net).
27. When AP4 started investing in 2012, a 48% reduction in carbon footprint was achieved.

28. For an early analysis of carbon-efficient indexes in emerging markets, see Banerjee (2010).
29. The criteria for excluding a stock from the index are straightforward: First, companies with the highest emissions intensity (as measured by GHG emissions/sales) are excluded, with a limit on cumulative sector weight exclusion of no more than 30%. Second, the largest owners of carbon reserves per dollar of market capitalization are excluded until the carbon reserves intensity of the index is reduced by at least 50%.
30. Our performance attribution analysis was for the MSCI Europe Low Carbon Leaders Index from 7 November 2014 to 29 January 2016.
31. During the same period, the MSCI North America Low Carbon Leaders Index outperformed the MSCI North America Index by 121 bps.
32. The allocation effect measures whether the choice of sector allocation led to a positive or negative contribution. All else being equal, overweighting outperforming sectors leads to a positive allocation effect.
33. The selection effect measures within each sector whether the portfolio manager selected the outperforming or underperforming stocks.
34. The Global Industry Classification Standard is an industry taxonomy consisting of 10 sectors, 24 industry groups, 67 industries, and 156 sub-industries.
35. Notable exceptions include the French government, which took a lead role ahead of the Paris conference in mobilizing the financial sector by requiring institutional investors to report on their climate risk exposure. A handful of central banks have also been instrumental in raising awareness of the possible hazards of climate change regulations and the potential mobilization of financial institutions. Significant contributions include the People's Bank of China and UNEP Inquiry (2015) report "Establishing China's Green Financial System" and the Bank of England's ongoing prudential review of climate-related risks to the financial sector.
36. See Article 173 of *Projet de loi relative à la transition énergétique pour la croissance verte*: "La prise en compte de l'exposition aux risques climatiques, notamment la mesure des émissions de gaz à effet de serre associées aux actifs détenus, ainsi que la contribution au respect de l'objectif international de limitation du réchauffement climatique et à l'atteinte des objectifs de la transition énergétique et écologique, figurent parmi les informations relevant de la prise en compte d'objectifs environnementaux." // "The information relative to the consideration of environmental objectives includes: the exposure to climate-related risks, including the GHG emissions associated with assets owned, and the contribution to the international goal of limiting global warming and to the achievement of the objectives of the energy and ecological transition."
37. Prominent voices in the business community have expressed their concern that the debate over climate policy has become too politicized. Also, in June 2014, the US Environmental Protection Agency unveiled an ambitious program calling for deep cuts in carbon emissions from existing power plants, with a 30% national target by 2030—which is equivalent to 730 million tons of carbon emission reductions, or about two-thirds of the nation's passenger vehicle annual emissions.
38. See "The Paris Agreement Marks an Unprecedented Political Recognition of the Risks of Climate Change," *Economist* (12 December 2015).
39. See https://www.whitehouse.gov/the-press-office/2014/11/11/fact-sheet-us-china-joint-announcement-climate-change-and-clean-energy-c.
40. The interregional ETS covering the Beijing, Tianjin, and Hebei Provinces was under discussion in February 2016, at the time of writing. In addition, the National Development and Reform Committee issued a paper in February 2016 that set up an agenda to ensure the establishment of a national ETS in 2017. We note that following China's lead, a movement is underway to move away from existing oil and gas subsidies. According to a recent IMF study by Coady, Parry, Sears, and Shang (2015), global subsidies for fossil fuels were estimated to be $333 billion in 2015.
41. The current price level is far below $30, with average carbon prices ranging from the lowest at RMB9.00/tCO_2e in Shanghai to the highest at RMB44.4/tCO_2e in Shenzhen, with others at RMB35 in Beijing, RMB23 in Tianjin, RMB22 in Hubei, RMB13 in Chongqing, and RMB14 in Guangdong (as of 4 March 2016); around EUR4.96/CO_2e (as of 7 March 2016) in Europe; and \$7.5/CO_2e under the Regional Greenhouse Gas Initiative in the United States (as of 2 February 2016).
42. Pope Francis's *Laudato Si'* encyclical (published in May 2015), Muslim scholars' *Islamic Declaration on Global Climate Change* (published in August 2015), and US rabbis' *Rabbinic Letter on the Climate Crisis* (released in May 2015) show that climate change has become a shared concern among religious authorities.
43. For a recent study on the risk of stranded assets, see Lewis (2014).
44. See ExxonMobil (2014); Shell followed with its "Open Letter on Stranded-Asset Risk" in May 2014.
45. See https://www.greenbiz.com/blog/2013/08/12/hybrid-lcas-help-companies-size-scope-3-emissions.
46. For a thorough review of Barra equity risk modeling, see MSCI Barra (2007).

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RÉSUMÉ

Cette thèse repose sur une série de papiers académiques publiés dans deux domaines. D'une part ils analysent le climat comme un risque spécifique car certain, porteur de nombreuses forces non-linéaires et interagissant entre-elles, et mettant la vie humaine en danger. D'autre part, ils présentent des solutions innovantes permettant de mobiliser les marchés financiers sur le sujet du climat. Les innovations tant pour les actions que pour la dette prennent en compte les contraintes des investisseurs institutionnels afin de permettre leur mobilisation à grande échelle.

MOTS CLÉS

Réchauffement climatique, marchés financiers, innovation, bien public

ABSTRACT

This thesis is based of a collection of scholarly papers published in two different fields. Firstly, it looks into climate change as a special risk, considering the fact that it is inevitable, composed of various non-linear and interconnected dynamics, and has the potential to endanger human life. Secondly, it presents pioneering solutions to drive the financial markets in the direction of addressing climate change. These solutions for stocks and bonds take into consideration institutional investors constraints in order to achieve their large mobilization.

KEYWORDS

Climate change, financial markets, innovation, public good