Asset-level data and the Energy Transition: Findings from ET Risk Work Package 2

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The Energy Transition Risk Project

The Energy Transition (ET) Risk consortium, funded by the European Commission, is working to develop the key analytical building blocks needed for ET risk assessment and bring them to market.

1. TRANSITION SCENARIOS: The consortium will develop and publicly release two transition risk scenarios, the first representing a limited transition extending current and planned policies and technological trends (e.g. IEA ETP RTS trajectory), and the second representing an ambitious scenario that expands on the data from the IEA ETP 2DS.

2. COMPANY & FINANCIAL DATA: Oxford Sustainable Finance Programme and 2° Investing Initiative will jointly consolidate and analyse asset-level information across six energy-relevant sectors (power, automotive, steel, cement, aircraft, shipping), including an assessment of committed emissions and the ability to potentially 'unlock' such emissions (e.g. reducing load factors).

3. VALUATION AND RISK MODELS:
    a. climateXcellence Model – The CO-Firm's scenario risk model covers physical assets and products and determines asset-, company-, country-, and sector-level climate transition risks and opportunities under a variety of climate scenarios. Effects on margins, EBITDA, and capital expenditure are illustrated under different adaptive capacity assumptions.
    b. Valuation models – Kepler Cheuvreux. The above impact on climate- and energy-related changes to company margins, cash flows, and capex can be used to feed discounted cash flow and other valuation models of financial analysts. Kepler Cheuvreux will pilot this application as part of their equity research.
    c. Credit risk rating models – S&P Global. The results of the project will be used by S&P Global to determine if there is a material impact on a company's creditworthiness.
    d. Assumptions on required sector-level technology portfolio changes are aligned with the Sustainable Energy Investment (SEI) Metrics, which developed a technology exposure-based climate performance framework and associated investment products that measure the financial portfolio alignment.

About the Oxford Sustainable Finance Programme

The Oxford Sustainable Finance Programme at the University of Oxford Smith School of Enterprise and the Environment is a multidisciplinary research centre working to be the world's best place for research and teaching on sustainable finance and investment. The Programme was established in 2012 to understand the requirements, challenges, and opportunities associated with a reallocation of capital towards investments aligned with global environmental sustainability.

We research environment-related risk and opportunity across different sectors, geographies, and asset classes; how such factors are emerging and how they positively or negatively affect asset values; how such factors might be interrelated or correlated; their materiality (in terms of scale, impact, timing, and likelihood); who will be affected; and what affected groups can do to pre-emptively manage risk. We have conducted pioneering research on stranded assets and remain the only academic institution conducting work in a significant and coordinated way on the topic.

The production of high-quality research on the materiality of environment-related factors is a necessary, though insufficient, condition for these factors to be successfully integrated into decision-making. Consequently, we develop the data, analytics, frameworks, and models required to enable the integration of this information. We have particular expertise in asset-level data, spatial analysis, scenarios, and stress tests, and also focus on how information is presented and used.

We also research barriers to the adoption of practices related to sustainable finance and investment. This includes the role of policy, regulation, governance, incentives, behaviours, and norms in shaping investment decisions and capital allocation.

The Programme is based in a world leading university with a global reach and reputation. We work with leading practitioners from across the investment chain (including actuaries, asset owners, asset managers, accountants, banks, data providers, investment consultants, lawyers, ratings agencies, stock exchanges), with firms and their management, and with experts from a wide range of related subject areas (including finance, economics, management, geography, anthropology, climate science, law, area studies, psychology) within the University of Oxford and beyond.

The Global Sustainable Finance Advisory Council that guides our work contains many of the key individuals and organisations working on sustainable finance and stranded assets-related issues. The Council also has a role in helping to informally co-ordinate and share information on sustainable finance and stranded assets work internationally. The Programme's founding Director is Dr Ben Caldecott.

About the Authors

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Disclaimers

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Executive Summary

Physical environmental change and societal responses to environmental change, particularly climate change and the transition to a net zero emissions economic system, create many risks and opportunities for financial institutions. A key barrier for financial institutions responding to these challenges are shortcomings in the availability of appropriate forms of data, information, and analysis. In particular, the failure to utilise asset-level data is a major barrier to financial institutions and financial regulators (among others) that prevents them appropriately understanding environmental risks, returns, and impacts.

Detailed and complete data on corporate assets are required in order to adequately assess risk in companies and the diffusion of that risk through the financial system. At present, data on corporate assets may only be released piecemeal, incomplete, or long after the fact, and the public is usually reliant on patchy voluntary disclosure in order to assess absolute and relative corporate risks. Not only does this put various stakeholders in a problematic position, but regulators are frequently forced to make crucial decisions against a backdrop of pervasive uncertainty. This paper outlines the potential benefits and users of asset-level data and details the construction of a demonstrator asset-level database: the Assets@Risk database. This database aggregates asset-level data across the globe for the major carbon emitting industries: Power, Steel & Iron, Cement, Automobile, Airlines, and Shipping industries, and applies robust peer-reviewed methodologies for the construction of Cumulative Committed Carbon Emissions (CCCEs) and technologies for Reducing Cumulative Committed Carbon Emissions (RCCCEs) to each individual asset. Furthermore, each industry database comprises sufficient assets to account for at least two-thirds of total global emissions within its industry. This combined database uniquely allows for the granular estimation of global climate related risks and the potential for their mitigation.

As a preliminary demonstration of the capabilities of this database, we report the Cumulative Committed Carbon Emissions (CCCEs) for each asset, and aggregate these across major emitting nations and asset status. According to the results presented in Table 14, the power industry dominates committed emissions, accounting for 88% of the 646 billion tons of committed CO_2 emissions attributable to the five industries. The Steel & Iron and Automobile industries comprise another 10% of emissions covered, and Airlines and Shipping have minor contributions.[1] The proportion of emissions attributable to the power industry is also expected to increase as 85% (293.9bt/345.2bt) of the CCCEs of active assets arise from power, compared to 90% (272.5bt/299.5bt) of pipelined CCCEs. Furthermore, across the five industries it is shown that there is roughly an equal split between the committed emissions attributable to currently active assets (53%) and those in the planning pipeline (47%). In terms of national geographies, Table 13 shows that China, India, and the US combined account for over 60% of the 646 GtCO2 expected to be emitted from existing and pipelined assets.

The total CCCEs expected to be emitted from both existing and pipelined assets compare unfavourably with common emissions targets. For instance, in order for the climate to have an equal chance of warming less than 2°C, the CO_2 budget for power as of mid-2016 (commensurate with our data) is approximately 300 GtCO2.[2] However, in Table 6 we show that the power industry alone is slated to register nearly double the required CCCEs to achieve this level of warming (566 GtCO2). Combining committed emissions from Steel, Automobiles, Aviation, and Shipping for existing and pipelined assets yields 646 GtCO2 (Table 13). Indeed, this level of emissions is commensurate with estimations for temperature rises exceeding 3°C.[3] It is therefore

[1] Cement is thought to generate about 5% of global emissions[1], due to data limitations we were not able to estimate its CCCEs or RCCCEs.
[2] The calculation is derived from 1,100 GtCO2 total CO2 budget and 15% as share attributable to power taken from; Pfeiffer, A., Millar, R., Hepburn, C., Beinhocker, E. (2016). "The '2°C capital stock' for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy." *Applied Energy*, 179: 1395-1408.
[3] Ibid.

clear that if the 2°C carbon budget is to be maintained then deep carbon emission cuts will have to be made, either in the form of premature asset retirement or through asset retrofits which reduce carbon emissions.

In order to investigate the viability of retrofitting assets in order to reduce carbon emissions, this report also compiles carbon reducing technologies (RCCCEs) from the existing climate-related literature and applies these to individual assets across the six industries according to applicable asset-specific characteristics. As many of these carbon-reducing technologies are mutually exclusive, we cannot apply all applicable technologies to each asset, but instead must choose feasible combinations. For demonstration purposes, we calculate the combination of CCCEs and costs which would result if the maximum technically feasible extent of RCCCE technologies were applied to each asset, and aggregate these within major emitting nations. We see from Table 17 that by applying technically maximum feasible RCCCEs to our databases we would reduce global CCCEs across the six industries from 646 GtCO2 (Table 13) to 504 GtCO2 (Table 17): a reduction of 22%, which would cost $84 trillion. This amounts to 107% of current global GDP ($78.28 trillion[4]). However, 91% of this cost arises from converting fuel-burning automobiles to fully electric drive-trains and would reduce emissions by only 39 GtCO2. By contrast, power and shipping RCCCE costs both account for just 4% ($3.39 trillion) of the total, but their technically feasible RCCCEs would lower emissions by 82 and 13 GtCO2, respectively.

This wide variation in costs is depicted in the RCCCE Marginal Abatement Cost curve in Figure 22, comprising only the combination of technically maximum RCCCEs. This figure shows that the primary sources of emissions reductions from this exercise are from the RCCCEs: Power_6 (Subcritical to Advanced Supercritical), Shipping_2 (HFO to Biodiesel B100), Power_1 (Geologic CCS), and Auto_12 (Diesel Electric Vehicle Conversion). It should be borne in mind that these estimations do not necessarily represent the actual extent and costs of feasible carbon emissions reducing technologies, rather they express only the emissions reduction potential which, given our data on individual asset characteristics, we are certain can be applied to each individual asset in our database. Therefore, the technically maximum RCCCEs we report represent a *minimum* level of possible carbon reductions. Although we do not analyse either CCCEs and RCCCEs at the company level, our data allows for this future extension.

Physical environmental change and societal responses to environmental change, particularly climate change and the transition to a net zero emissions economic system, create diverse and significant risks for the global economic system. A key barrier to responding to these challenges is the lack of asset-level data, which prevents market actors from appropriately understanding environmental risks, returns, and potential impacts. In response, we have developed the Assets at Risk Database (Assets@Risk), which synthesises asset-level data globally across six major carbon-emitting industries (Power, Cement, Steel and Iron, Automobiles, Airlines, Shipping). This paper has demonstrated only a fraction of the potential capabilities of asset-level data, but it is hoped that a case has been made for the potential of asset-level data to meet now deferred emissions goals and more effectively respond to economic and climate uncertainty.

Asset-level data secured from a variety of proprietary and non-proprietary sources, combined with disclosures where available, has the potential to address these challenges. Asset-level data is information about physical and non-physical assets tied to company ownership information. Asset-level data can be aggregated at the company, regional, or global level, enabling the assessment of asset, company, asset manager, asset owner, and system-wide exposure to a wide range of environmental factors in a granular, comparable, and systematic way.

Analysis using asset-level data is typically:

- **Bottom-Up:** Asset-level exposure is aggregated up to the company level rather than inferred from company-level reporting.

[4] CIA. (2014). *World Factbook*.

- **Fundamental:** Fundamental asset attributes (for example, location, technology, and age) inform analysis rather than disclosed metrics (for example, carbon intensity) enabling more sophisticated and flexible analysis.
- **Comparable:** Standardisation can ensure accurate company comparisons and avoids embedded methodological assumptions.
- **Forward-looking:** Asset attributes (such as age) can enhance analysis of company future performance and enable validation of company projections.
- **Efficient:** It can significantly reduce reporting burdens and reduce time and money spent on assuring voluntary disclosures.
- **Timely:** Asset-level data can be updated in real time as events occur (like mergers or asset commissioning) rather than according to annual reporting cycles.
- **Transparent:** Asset attributes are transparent and are based on real observational data, giving stakeholders access to the same data as company executives.
- **Scalable:** The marginal costs of data acquisition and analysis decrease with scale of the dataset.
- **Science-driven:** Unlocks scientific approaches to analysis which are repeatable and testable.
- **Unbiased:** Assessment of environmental factors informed by asset-level data do not rely on the (non-expert) opinions of corporate boards.
- **Self-improving:** Science and technology-driven risk analysis and data acquisition improve continuously with new generations of technology and research. Costs also reduce over time.

In order to demonstrate the potential of asset-level data, we have developed a demonstrator database, called the Assets at Risk Database (Assets@Risk) comprised of six major carbon-emitting industries (Power, Cement, Steel and Iron, Automobiles, Airlines, and Shipping) which covers the individual assets responsible for at least two-thirds of total global emissions within each industry. For each asset, an amount of cumulative committed carbon emissions (CCCE) has been calculated according to methods set out in this document. For each asset type, an amount of *reducible* CCCE (RCCCE) has also been calculated – the amount of CCCE which might be reduced by implementing certain retrofit technology, and the associated costs. This analysis is prepared in the RCCCE_Options database.

Going forward, a 'Principle of Asset-Level Disclosure' in existing disclosure regimes and frameworks could make good asset-level data more widely available.[5][6][7] Several members of the ET Risk consortium have formed the Asset-level Data Initiative (ADI) to drive the use of, improve access to, and enhance the quality of asset-level data.[8] The database and analysis presented in this document is indicative of the aspirations of this initiative and its potential to improve knowledge and governance of many forms of corporate risk.

Aggregate high-level findings of the Assets@Risk and RCCCE_Options databases are presented here. Figure 1 shows CCCEs of major countries by pipeline status. Figure 2 shows CCCEs of major countries by industrial sector. Figure 3 shows the marginal abatement cost curve of RCCCE mitigation options and the extent to which the options reduce CCCEs.

[5] Dupre, S. Thomae, J, Weber, C., & Caldecott, B. (2016) *Climate Disclosure: How to Make it Fly*, 2 degrees Investing Initiative & Smith School of Enterprise and the Environment, University of Oxford.
[6] Caldecott, B. (2016) 'The future of climate-related disclosure', *Economist*.
[7] Caldecott, B., & Kruitwagen, L. (2016) "Guest Opinion: How asset level data can improve the assessment of environment risk in credit analysis", *S&P Global Market Intelligence.*
[8] For more information about the Asset-level Data Initiative (ADI) see: https://assetleveldata.org/

Figure 1: CCCEs of major countries by pipeline status

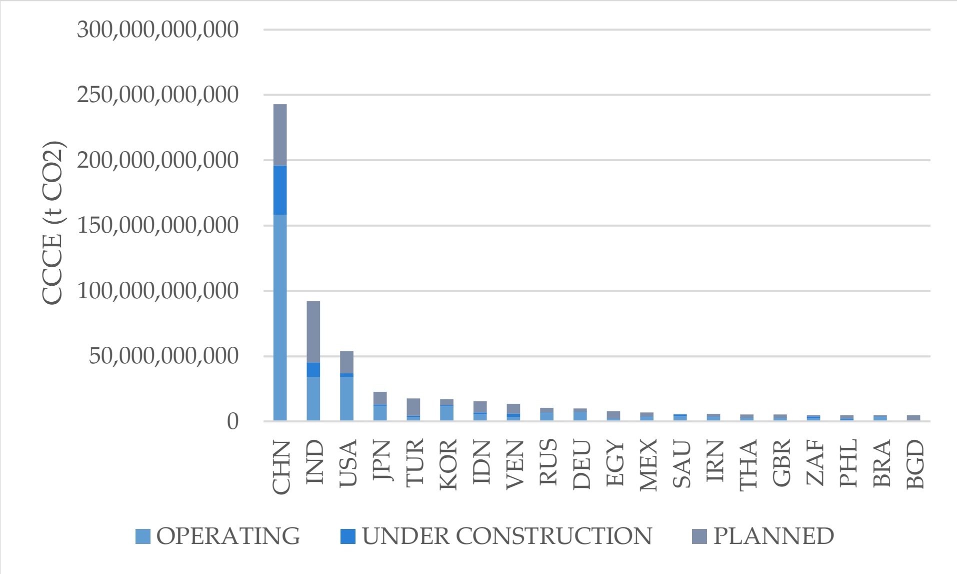


Figure 2: CCCEs by major country and industrial sector

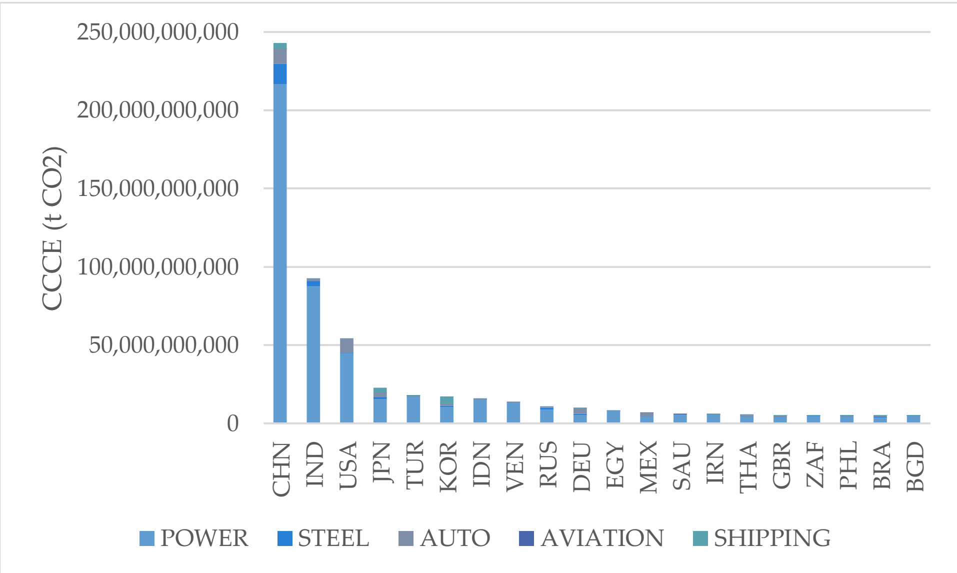
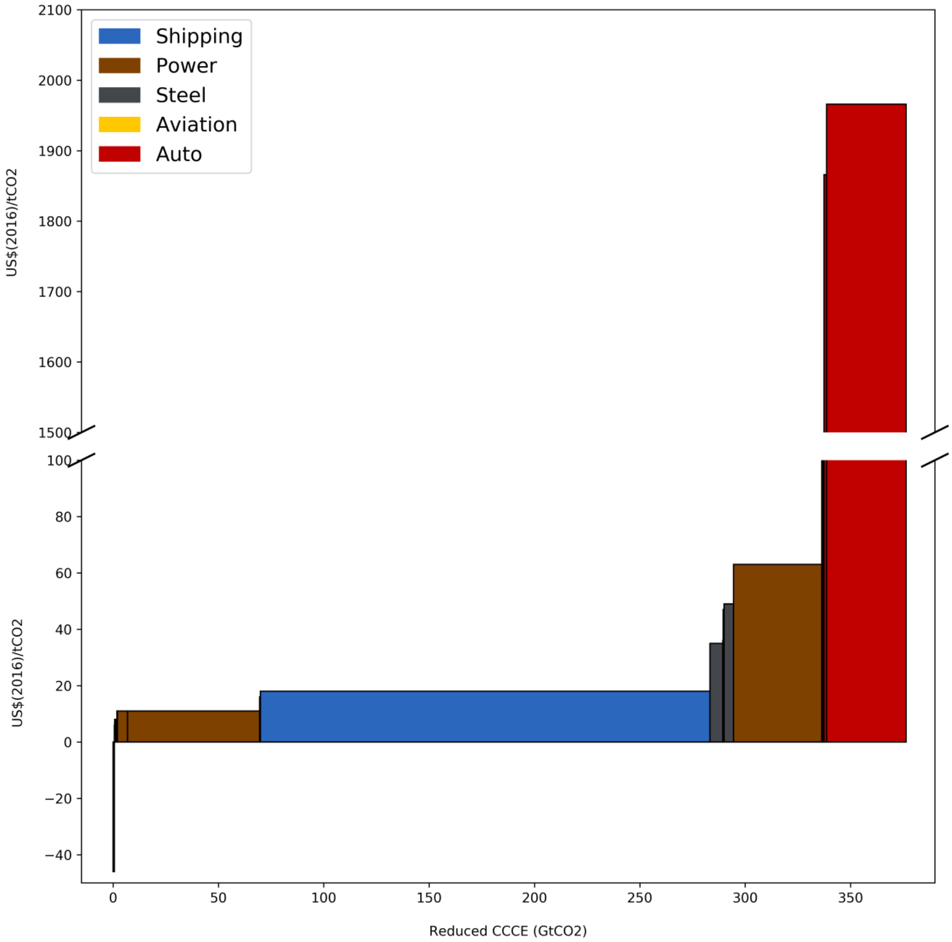


Figure 3: Marginal abatement cost curve and potential mitigating impact of RCCCEs



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It should be borne in mind that these estimations do not necessarily represent the actual extent and costs of feasible carbon emissions reducing technologies, rather they express only the emissions reduction potential which, given our data on individual asset characteristics, we are certain can be applied to each individual asset in our database.

This paper demonstrates only a small fraction of the potential capabilities of asset-level data, but it is hoped that a compelling case has been made for the potential of asset-level data to support decision-making by a wide range of different key user groups connected to the financial system. This will support the alignment of finance with sustainability, thereby helping to manage material environment-related risks and supporting investment in technologies to deliver the transition to global environmental sustainability.

Introduction

The need and potential for asset-level data

Physical environmental change and societal responses to environmental change, particularly climate change and the transition to a net zero emissions economic system, create many risks and opportunities for financial institutions. A key barrier for financial institutions responding to these challenges are shortcomings in the availability of appropriate forms of data, information, and analysis. In particular, the failure to utilise asset-level data is a major barrier to financial institutions and financial regulators (among others) that prevents them appropriately understanding environmental risks, returns, and impacts.

Over the last few years the Bank of England, the G20 Financial Stability Board (FSB), and European Systemic Risk Board, among many other respected institutions, have all highlighted how a late and abrupt transition to a low carbon economy could have implications for financial stability. They have emphasised the need to

[11] Ibid.
[12] CIA. (2014). *World Factbook.*

pre-emptively manage 'stranded asset' risk in financial institutions and throughout the financial system as a whole. They have also highlighted how without better data this transition will be extremely challenging. Correcting this major gap is now an urgent priority.

At present, data on corporate assets may only be released piecemeal, incomplete, or long after the fact, and the public is usually reliant on patchy voluntary disclosure in order to assess absolute and relative corporate risks. Not only does this put various stakeholders in a problematic position, but regulators are frequently forced to make crucial decisions against a backdrop of pervasive uncertainty.

Asset-level data secured from a variety of proprietary and non-proprietary sources, combined with disclosures where available, has the potential to address these challenges. Asset-level data is information about physical and non-physical assets tied to company ownership information. Asset-level data can be aggregated at the company, regional, or global level, enabling the assessment of asset, company, asset manager, asset owner, and system-wide exposure to a wide range of environmental factors in a granular, comparable, and systematic way.

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Subsequent sections of this paper are structured as follows. The remainder of the introduction outlines specific use cases for asset-level data, describes the methodology employed to select the individual industry databases comprising Assets@Risk, details the comprehensiveness of the databases', specifies the protocols followed in calculating CCCEs for each asset, and outlines the methodology used in the calculation of

CCCEs and RCCCEs. Section 2 provides a description of the data and details of the CCCE and RCCCE analyses applied to each industry and relevant geographies. Section 3 aggregates the results across all six industries and presents specific emissions reductions and costs for each of the RCCCE technologies. Section 4 concludes.

Use cases of asset-level data

In this section, we present use cases describing potential questions for which assets-level data could be brought to bear, and describe specific benefits that various user groups would stand to gain through its use. Table 1 below outlines a number of specific use cases, prospective users, and current projects that asset-level data could be immediately and directly applied to.

Table 1: Use Cases

Use Case	Users	Description	Current Initiatives
Top down global policy implementation tracking	UNFCCC, OECD, G20, etc.	Tracking global mitigation at sector, technology, locality, etc. levels	G20 deep decarbonisation
Top down national/regional policy implementation tracking	National/regional governments	Tracking national/regional mitigation at sector, technology, locality, etc. levels, tracking ownership of major emitters	
Bottom up policy design	National/regional governments	Mitigation policy better designed to capture low-hanging fruit, minimise side effects, and maximise co-benefits.	Green Belt and Road Initiative (BRI) Data and Analysis Platform
Target setting	Emitting entities (companies, municipalities, etc.)	Setting detailed 'science-based' mitigation targets for any entity owning GHG emitting assets	CDP Science-Based Targets initiative
Improving climate modelling	Climate researchers	Improving geospatial assessment of GHG emissions in regions lacking high quality GHG inventory data	Gurney Lab High Resolution Workshop
Physical environment-related risks	Investors, asset managers, and intermediaries	Assessing exposure of investees to physical and/or policy/market risks	Green Belt and Road Initiative (BRI) Data and Analysis Platform
Transition environment-related risks	Investors, asset managers, and intermediaries	Assessing exposure of investees to transition (e.g. economic, regulatory, technology) risks	SEI Metrics Consortium; ET Risk; Green Belt and Road Initiative (BRI) Data and Analysis Platform
Liability environment-related risks	Investors, asset managers, and intermediaries, civil society	Assessing exposure to and assigning liability for failure to mitigate/ address/ disclose climate change risks	ClientEarth[13]
Systemic risk assessment	Investors, financial regulators	Connection between the real and paper economies gives regulators and investors a better view of systemic	Bank of England PRA

[13] Heede, R. (2014). 'Tracing anthropogenic carbon dioxide and methane emissions to fossil fuel and cement producers', 1854–2010, *Climate Change,* 122(1): 229-241.

		risk	
Disclosure monitoring and verification	Financial regulators, civil society	Transparency and verification of companies' disclosure	TCFD
Policy and corporate engagement	Investors, civil society	Engagement on policy design and corporate strategy	Coal Plant Tracker; Green Belt and Road Initiative (BRI) Data and Analysis Platform

Asset Owners

Asset owners include pension funds, insurers, banks, sovereign wealth funds, foundations and endowments, and high net worth individuals. Asset owners may delegate part or all of the management of their assets to asset managers. The benefits of asset-level data for asset owners described here are in addition to the benefits described for asset managers below.

Many asset owners are universal owners. They invest across a broad investable universe to maximise diversification benefits in their portfolios. As such, asset owners may take an interest in asset classes which have externalities affecting other parts of their portfolios. Data concerning the universe of assets (rather than just companies) will help asset owners identify the leading causes of these externalities, and quantify and address them.

Many asset owners have liabilities and liquidity requirements (to pay pensions, insurance claims, operating budgets, account withdrawals, etc). Asset-level information can help asset owners identify whether the assets they hold are adequate and of sufficient health to meet their liability and liquidity requirements. Asset-level data may also help asset owners determine where exposure to environment-related risks might compound on both sides of their balance sheet – for instance if their assets are exposed to environment-related risks which could also result in liquidity needs or the payment of a liability.

Asset owners are beginning to consider the missions of their organisations in allocating assets. Particularly where funds exist for a charitable or social purpose, asset owners may now consider it appropriate to allocate funding in a way which aligns with their mission. The transparency of asset-level data can help asset owners identify investment opportunities which are mission-aligned and those which are not.

Asset owners may also seek to engage with companies directly in order to mitigate risk and seize opportunities, particularly those embedded within environmental, social, and governance issues. Asset-level data reduces information asymmetry between investors and company managers, allowing investors to engage with their companies in ways that are targeted and impactful. Asset-level data would help many groups of asset owners better respond to environment-related risks, and would support the work of groups like Preventable Surprises,[14] the Aiming for A coalition,[15] and the Institutional Investors Group on Climate Change.[16]

[14] See, e.g. Preventable Surprises (2015). "Institutional Investors and Climate-Related Systemic Risk." [http://bit.ly/2arpvsS]
[15] See, e.g. Wildsmith, H. (2012). "Why We're Aiming for A", *Responsible Investor.* [http://bit.ly/29WyK37]
[16] See IIGCC (2016). [http://bit.ly/2atEUsu]

Box 1: Is an asset compatible with a given carbon budget?

The Assets@Risk database has been prepared to enable sophisticated analysis of carbon lock-in. Further, the Assets@Risk database approaches *collective exhaustion* – almost all the global CCCEs for each sector are included in the database. This unlocks a variety of analysis comparing cross-sections of assets directly to company, sectoral, regional, and global carbon budgets. One such analysis is the use of committed emissions merit order curves (CEMOCs) to compare ordered stacks of asset CCCEs directly to gross carbon budgets.

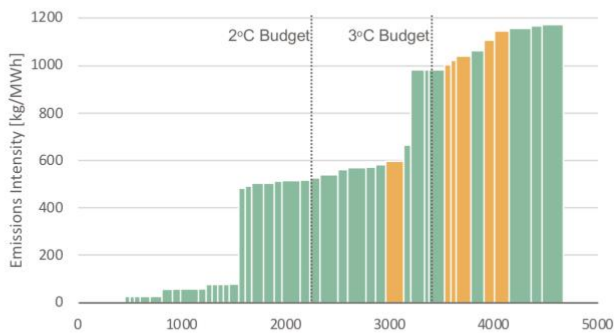
To generate a CEMOC, the collectively exhaustive set of assets corresponding to a given cross-section and associated carbon budget are gathered. Some metric of 'merit' is chosen and the assets are placed in an ordered ranking according to this metric. A metric of merit might be the carbon-normalised economic value of the asset, its efficiency, its carbon-normalised revenue or profit, etc. Thresholds can then be applied to this ordered list of assets corresponding to the carbon budgets for that sector. CEMOCs can also be generated as future projections, using the selection of assets and carbon budget for a projected time in the future. At longer time horizons, their method must be augmented with assumptions about asset replacement (or more complicated techno-economic pathways), as the current pipeline of assets will be inherently near-term.

An example is shown in Figure 4 below for the power sector. A subset of the global carbon budget has been chosen which corresponds to a subset of the global fleet of power stations. All the power stations matching the subset criteria have been selected. The efficiency metric chosen is carbon intensity – in kg/mWh. The power stations have been ordered according to their carbon intensity and stacked with their CCCE. The carbon budget thresholds are shown on the figure. Power stations to the right of each threshold might be considered 'at risk' for that threshold.

The choice of subset, carbon budget threshold, and ordering metric reflects investment beliefs about climate change risk. An investor might expect a policy, for example, to shut down power stations exceeding a certain carbon intensity consistent with a 2°C carbon budget constraint. The CEMOC would allow this investor to test what this carbon intensity might be, and compare it to assets in their own portfolio. The CEMOC is in this way a framework for interrogating the potential impact of the energy transition on individual assets – not a normative tool for prescribing policy (although a policymaker may use it thus).

There are a variety of methods available for generating carbon budgets at various geographic, sectoral, and corporate scales. These are subsets of the global carbon budget which is driven by climate science and is well-documented by the IPCC. Dividing the global carbon budget further inherently involves choices about the allocation mechanism. These choices might be ethical, as in Robiou du Pont, Y. et al,[1] or techno-economic (e.g. capital-efficiency, minimisation of costs or stranded assets, minimisation of damages), as in the modelling of the IEA and many others. Many techno-economic methods for allocating carbon budgets do not explicitly articulate a budget for different geographies and sectors, but the budget allocations they prescribe can be back-calculated from their published emissions pathways. It is beyond the scope of this document to interrogate this subject any further than highlighting these axes of choice an analyst has in choosing carbon budgets.

Figure 4: Power plant 'emissions merit order' example



Asset Managers and Intermediaries

Asset owners may delegate the management of some or all of their assets to asset managers. Asset managers are generally classified as either active or passive, according to whether they track market indices. Investment intermediaries are the consultants and advisers who have specialised knowledge or who may be contracted to provide due diligence on behalf of the asset owner.

Asset-level data has tremendous potential to improve the efficiency of investments managed by asset managers and informed by their intermediaries. The fundamental asset-level data will unlock sophisticated analysis and competition among both passive and active managers. Passive asset managers may incorporate the data into their asset allocation models. For active managers, there is an opportunity to use the asset-level data to deliver superior risk-adjusted returns. The high-resolution asset-level data will allow better comparisons of company, sector, and geography-related risk, improving investment efficiency and more accurately pricing company debt and equity.

With asset-level data, asset managers may adjust their investment strategies to be more forward looking. Rather than projecting historic performance of companies, asset managers will be able to project the future performance of assets. Asset managers will be better able to anticipate how companies are positioned relative to larger technological and economic trends, and what these trends mean for the health of the assets and the company.

There is a growing array of environmental and ESG metrics which will benefit substantially from asset-level data. ET Risk consortium member 2DII leads the SEI Metrics research consortium (CDP is a member), which develops 'science-based' metrics for financial portfolios using asset-level data.[17]

Policymakers

The universal capture of asset-level data has substantial use in policymaking: for conducting top-down tracking of progress on policy implementation, for targeting policy imperatives for risk mitigation, and for understanding the full political-economic impacts (e.g. on displaced or redundant workers, economic growth, marginalised populations) of a developed policy by examining the bottom-up impacts of policy implementation.

For example, in the definition of EU countries' Transitional National Plans, it is common practice for energy and power-related emissions – typically the most significant component of national inventories – to be based on the full characterisation of the asset base for the country. In this case the economics, security of supply, and environmental aspects are all taken into consideration, requiring the listing of production capacities; retirement age; abatement costs; amortisation; diversity of supply; reliability of supply, etc.

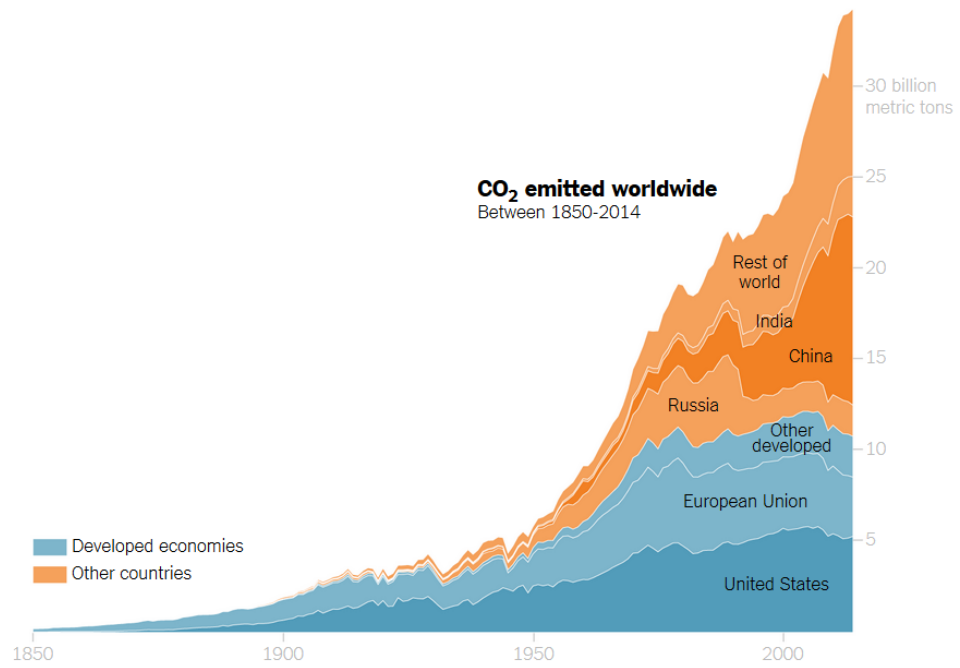
All of these factors are considered in planning the retirement of high-carbon capacity and the bringing on-line of alternative, low-carbon capacity. For example, in Portugal energy and climate planning during the early 2000s was based on detailed consideration of the plants which would be retired and when the new renewable capacity would be brought online (wind power, hydro). This strategy has brought the percentage of renewable electricity within the system to an average (annually) > 50% of final electricity consumption, with increasing network service levels. Likewise, based on the analysis of the country's assets, there is awareness that in order to meet its 2030 targets, the coal power stations of Sines and Pego will have to close between 2020 (Sines) and 2030 (Pego). Such measures involving specific assets have been the subject of detailed scenarios advanced in the National Plan for Climate Change 2020/2030.

[17] 2dII (2015). "Developing Sustainable Energy Investment (SEI) Metrics, Benchmarks, and Assessment Tools for the Financial Sector." [http://bit.ly/2aardcq]

Box 2: Historical responsibility

Aggregating asset-level emissions up to the national level enables comparisons of national committed cumulative carbon emissions. The relevance of historical responsibility for carbon emissions is noted in the UNFCCC and generally acknowledged to be an important factor in shaping policy response strategies that are widely acceptable. This concept has also become noteworthy since, in the run-up to the 1997 Kyoto Protocol negotiations, the Brazilian government advanced a specific proposal that would have apportioned GHG emissions targets according to each country's historical responsibility for the global temperature rise.[1,1] Although this proposal was not adopted, the topic has continued to be debated in the context of the UNFCCC process.[1] Following this reasoning, policymakers have argued that current Chinese emissions targets should take account of the fact that to date China has only been responsible for a sixth of cumulative carbon emissions, while the US – historically the world's largest carbon emitter – is responsible for almost a third.[1] However, our analyses in Table 14 show that for five major carbon emitting industries, China currently has infrastructure either existing or in the pipeline to release nearly five times as much carbon as the US, and India nearly twice as much. Taking account of the committed carbon emissions embedded within national infrastructure allows for a holistic assessment of emissions equity and appropriate international policy measures.

Figure 5: Annual global carbon emissions, 1850-2014



Source: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory[1]

Of the 197 parties to the UNFCCC, only 50 or so regularly make an inventory or update their mitigation actions and policies. National asset-level data, together with financial and energy policies, could illuminate serious concerns associated with the achievement of climate targets.

Financial Regulators

Financial regulators are empowered to maintain stability and address systemic risk in financial markets. By connecting company ownership to real economy assets, asset-level data links the real and the financial economies. Asset-level data will help to assess potential price shocks in these 'physical' and 'paper' (derivatives) markets. A shock may have an impact on the whole system and it is essential to measure its amplitude and to understand its potential transmission to other markets.

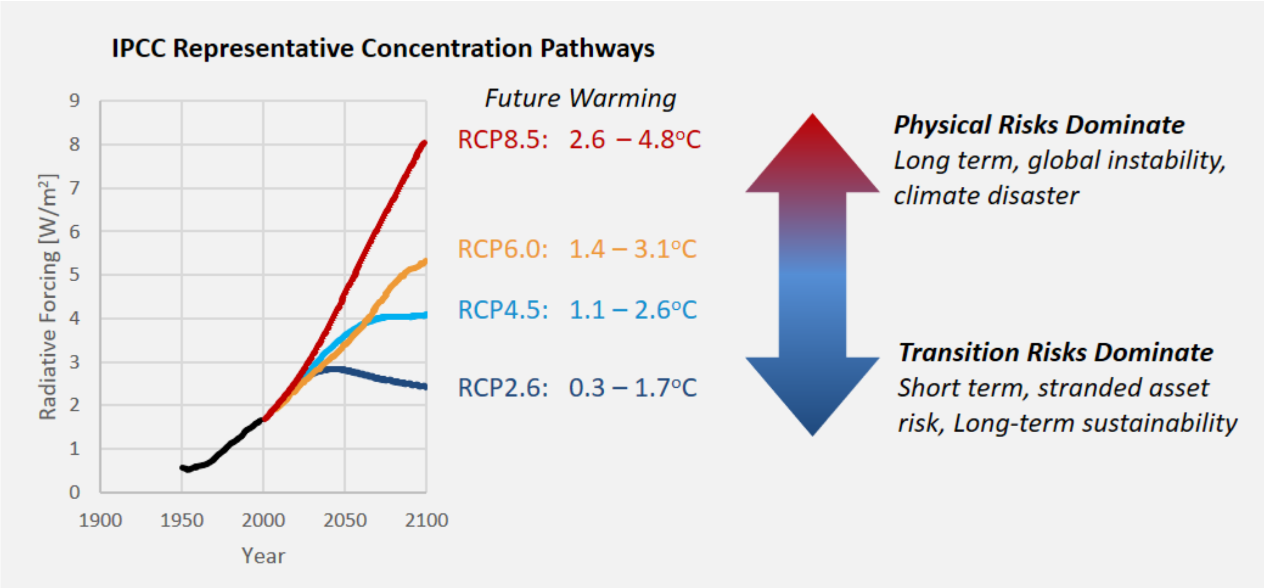
The establishment of the FSB Task Force on Climate-related Financial Disclosures (TCFD) has helped to place climate-related risks (physical, transitional, and legal) on the agenda of financial regulators around the world. Financial regulators concerned with both systemic risk as well as the efficient functioning of capital

Box 3: Tracking emissions goals

Aggregating asset-level emissions up to the global level allows for bottom-up objective assessments of the feasibility and practicality of global emissions goals. For instance, it is estimated that in order for the climate to have an equal chance of warming less than 2°C, the CO_2 budget for power as of mid-2016 (commensurate with our data) is approximately 300 GtCO2.[1] However, in Table 6 we show that the power industry alone is slated to register nearly double the required CCCEs to achieve this level of warming (566 GtCO2). Combining committed emissions from Steel, Automobiles, Aviation, and Shipping for existing and pipeline assets yields 646 GtCO2 (Table 14). Indeed, this level of emissions alone is commensurate with estimations for temperature rises exceeding 3°C by 2100.[1] It is therefore clear that if the 2°C carbon budget is to be maintained then deep carbon emission cuts will have to be made, either in the form of premature asset retirement or through asset retrofits which reduce carbon emissions.

Asset-level data uniquely has the potential to take this analysis a step farther by determining the micro and macro scale physical, environmental and transition risks attributable to each asset and consequently which companies and locations would be most exposed. From this perspective we can view the emissions reduction question as a trade-off (see Figure 6), on the one hand complying with low emissions targets may allow us to avoid physical risks associated with climate change, but on the other hand this could bring about greater transitional risks (stranded assets, premature decommissioning, reputational and legal risks, etc). Asset-level data allows us to make this trade-off explicit, and to quantify their impacts with respect to multiple scenarios and to any level of aggregation that we wish.

Figure 6: Transition vs Physical Risk Relationship



markets are now increasingly interested in observing climate-related risks. The members of ADI have engaged constructively with the TCFD on the usefulness of asset-level data for tracking capital market function[18] as well as long-term physical risks, and Task Force members have grown increasingly interested due to the inherent advantages of asset-level data.

Civil Society and NGOs

Civil society has long been interested in tracking the 'brown' business activities conducted by companies in the real economy (e.g. fossil fuel companies, utilities, etc.) as well as by financial institutions that fund such activities. Civil society organisations track these activities in order to engage with companies and policymakers on solutions to environmental challenges, leveraging pressure from the public when necessary.

Physical asset-level data is already collected and/or used by some NGOs, though such data is tracked at great effort, making it difficult to keep data up to date and simultaneously use it in engagement with companies and financial institutions. Broadly available data on both 'brown' and 'green' investments could greatly help such NGO campaigns to redirect current efforts at data gathering toward further analysis and engagement activities.

Examples of such work include Coalswarm/Sierra Club/Greenpeace Coal Plant Tracker;[19] Rainforest Action Network, Sierra Club, and Banktrack's work on tracking coal financing;[20] the work of Carbon Tracker Initiative;[21] the global divestment movement,[22] and many others. Some analyses have begun also to incorporate tracking of green investment, notably BankTrack's recent *Undermining Our Future* report,[23] which compared funding by large banks for 'brown' activities and 'green' activities.

Companies

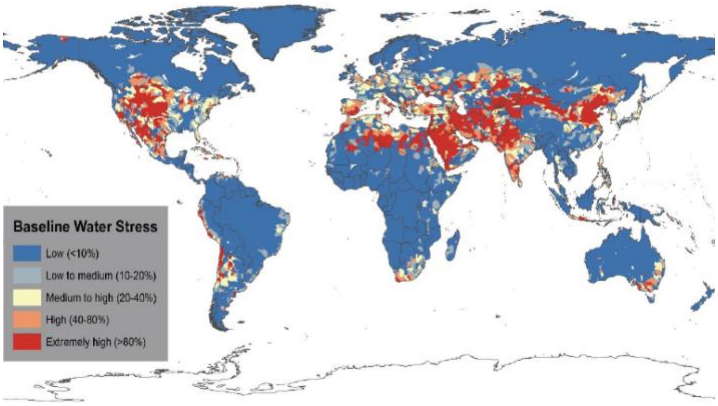
Asset-level data can give a company the information it needs to assess its exposure to environment-related risk and its risk management performance relative to other companies. Without such data, to develop an opinion on water risk exposure, for example, would mean evaluating its exposure to water stress due to drought, increased risk of flooding, reputational and regulatory risk exposure. But interpreting the materiality of these individual results may be problematic for a single company. However, when it can benchmark these risks against a basket of comparable companies and competitors, it can assess its relative performance and make informed strategic decisions.

[18] See Thomä, J., Dupré, S., Weber, C. (2016). "Reviewing the Evidence: 10 questions for the FSB Climate Disclosure Task Force." [http://bit.ly/1QtzHck]
And Dupré, S., Thomä, J., Weber, C., & Caldecott, B. (2016). *Climate Disclosure: How to make it fly*. [http://bit.ly/1ThAn6R]
[19] Endcoal.org (2016). Global Coal Plant Tracker. [http://bit.ly/1G1FqRI]
[20] Banktrack.org (2015). "The End of Coal? Coal Finance Report Card 2015." [http://bit.ly/2adoIXM]
[21] See, e.g. CTI (2013). "Unburnable Carbon 2013: Wasted Capital and Stranded Assets." [http://bit.ly/2ahqSck]
[22] 350.org (2016). "Fossil Free: Divest from fossil fuels." [http://bit.ly/1IDZHPF]
[23] Warmerdam, W., Christopoulo, A., Herder, A. et. al. (2015). "Undermining our Future," Banktrack.org. [http://bit.ly/2aHcEyK]

Box 4: Measuring and tracking risk in companies

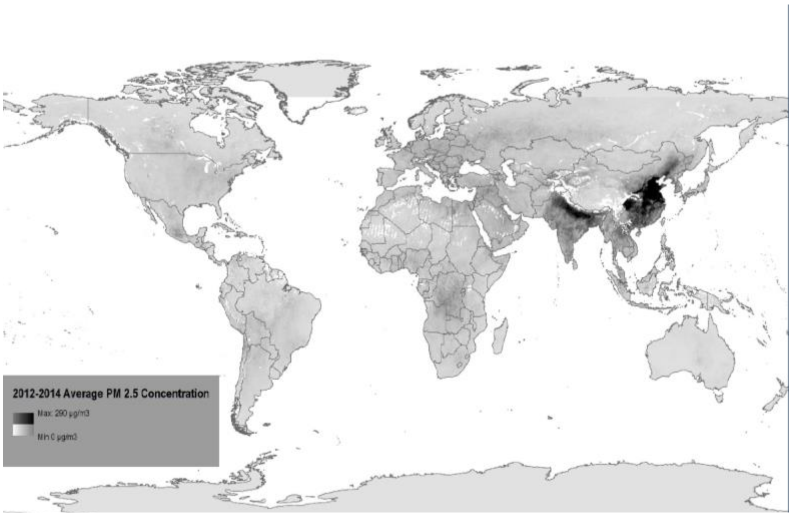
Recognising that many companies do not yet undertake a comprehensive water risk assessment despite the ever-growing threats, investors may wish to perform their own risk assessment for those companies. The characteristics of the assets together with geolocation information can be overlain on a water risk map, for instance, in order to have a preliminary view of a corporate's assets at water risk. Even if an asset is not highly water intensive, its mere presence at a high-risk water basin (all companies require some water) may pose a substantial investment risk due to collapse of the basin or high tariffs or rationing of water usage in the area. An example of such an overlay is presented in Figure 7 below. Such water stress data can be combined with specific asset characteristics which affect water intensity – such as cooling methods in the case of power plants or kiln processes for cement works – to enable a granular and holistic assessment of water-scarcity risk.

Figure 7: Baseline water stress, Data from WRI Aqueduct, 2015



Air pollution is another topical environmental risk in which asset-level data would permit detailed analyses. Industries which produce significant air pollution such as coal-fired power generation and basic oxygen furnace steel-making are more at risk of being regulated and required to either install emissions abatement technologies (e.g. flue gas desulphurisation units and electrostatic precipitators) or to cease operation. Thus, owners of assets in areas of high local pollution will have a greater risk of bearing the financial impacts of these measures, as are owners of power stations which lack these anti-pollution measures.

Figure 8: Global average PM2.5 Concentration, 2012-2014[1]



As a final example, the retrofit of assets with Carbon Capture and Storage (CCS) technology has been frequently touted as broad-base potential solution to containing carbon emissions.[1] However, a significant and under-investigated obstacle to widespread adoption of CCS is the absence of suitable local geology. Overlaying asset-level data against existing maps of CCS geologic suitability (see Figure 9) allows for both an assessment of the potential for CCS to reduce emissions at a global level and appraisal of the geologic and economic feasibility of installing CCS on individual assets, and thereby neutralising potential regulatory, legal, and reputational risks associated with that asset.

Figure 10: CCS Geological Suitability[1]

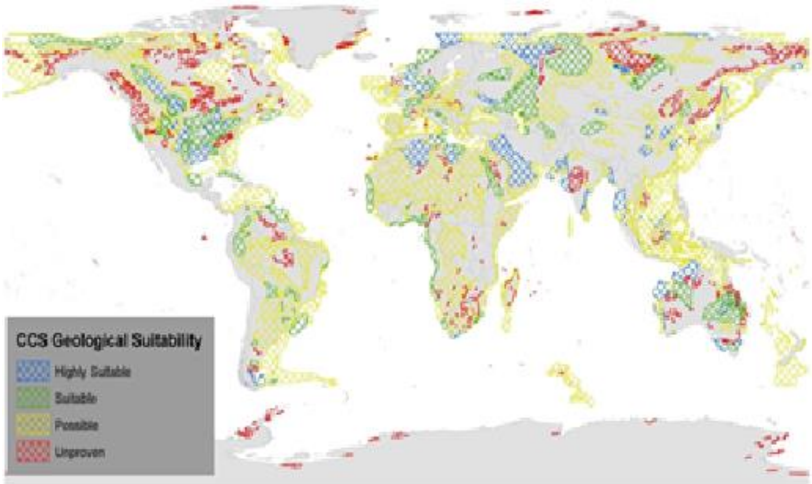


Table 2 below summarises how the different users may employ asset-level data.

Table 2: Summary of users and general cases

User	Use of Asset-Level Data
Asset Managers and Intermediaries	• Optimise portfolio risk and return and increase investment efficiency • Better discovery of costs of debt and equity • Seek competitive advantages through improved analysis and asset allocation • Better projections of future company performance
Asset Owners	As with asset managers *plus* • Develop robust perspective on global risk exposure and systemic risk • Increased transparency aligns investment with investor mission • Assess changing liability exposure and liquidity risks • Empower active ownership and stewardship
Financial Regulators	• Assess global exposure to downside environment-related risk • Provide accountability and verifiability to company disclosures (e.g. disclosed risk exposure)
Policymakers	• Assess the future impact of environment-related risk on real assets at high resolution

	• Bottom-up assessment of the future impact of policy designed to mitigate environment-related risk on, for example, companies and the people they employ • Develop clarity of the relationship between the real and financial economies
Civil Society and NGOs	• Provide accountability and verifiability to company disclosures (e.g. sustainability reporting) • Develop and publish policy opinions
Companies	• Compare performance with peer companies • Demonstrate investment value proposition • Access lower cost of debt

Asset-level data has the potential to revolutionise the understanding and management of environment-related risks across private and public sectors. In response to the widespread potential of this data, we have developed a demonstrator database (Assets@Risk) comprised of six major carbon-emitting industries (Power, Cement, Steel and Iron, Automobiles, Airlines, Shipping), and the RCCCE_Options database, which details the specific carbon-reducing retrofit technologies which can be applied to these assets as well as their effectiveness and costs.

Assets@Risk database search and description

The Assets@Risk database was established as a demonstrator of what is possible using asset-level data. The database has applications across the investment chain and beyond, including asset managers, asset owners, financial regulators, policymakers, civil society, NGOs, and companies. It enables these actors to: identify the leading causes of externalities for various assets, and to quantify and address them; identify whether these assets are adequate and of sufficient health to meet liability and liquidity needs; determine where environment-related risks might materialise; better position assets relative to larger technological and economic trends; conduct top-down tracking of progress on policy implementation; and benchmark performance against these criteria, among others.

The database was constructed through a rigorous examination of the available global data in each of the sectors in scope, and methodical consultation of the emissions literature. First, the available public and proprietary databases for six industries were investigated through consultation with industry experts and internet research. Over 40 databases were identified and each systematically assessed in terms of their comprehensiveness of global asset coverage, availability of emissions-relevant data, accuracy, timeliness, ability and usefulness to be combined with other databases, and cost. From these assessments individual databases were chosen to be incorporated into Assets@Risk. Multiple databases were used for a single industry as required to improve industry coverage, timeliness, and comprehensiveness; duplicate assets within them were manually matched to avoid double counting. In this exercise it became apparent that in order to obtain the required data we primarily had to use proprietary datasets. The drawback of this approach however is the reduced ability to share data among consortium members and externally. For proprietary datasets, our requirements were discussed with the data providers, and prices were negotiated. This process yielded the current Assets@Risk database as summarised in Table 3 below.

Table 3: *Assets@Risk database datasets and estimated coverage*

Sector	*Database(s)*	*Estimated Global Asset Coverage*
Power	*WEPP, CoalSwarm, Greenpeace, Kikonet, Sekitan*	*~95%+*

Automotive	*WardsAuto, EEA, EPA*	*~100%*
Aviation	*FlightGlobal, ICAO*	*~90%+*
Shipping	*SeaWeb, RightShip*	*~100%*
Steel and Iron	*VDEH PlantFacts*	*~90%+ worldwide ex China (~50%)*
Cement	*Global Cement Directory*	*~90%+ worldwide ex China (~50%)*

The Assets@Risk database comprises the data enumerated below. The power dataset comprises the global population of operating and planned carbon emitting utility assets, and is particularly timely and comprehensive with regard to coal, the most carbon-intensive fuel used for power generation at scale. The automotive dataset comprises 100% of light duty vehicles produced globally 2002-16 and projections from 2017-23. The aviation dataset comprises existing global passenger and cargo aircraft. The shipping dataset comprises roughly 100% of the global existing, on order, and planned fleet of container, bulker, and tanker cargo ships. The Steel and Iron dataset comprises global steel and iron plants. Unfortunately, while China has roughly half of global capacity our dataset only comprises around half of existing steel plants in China. This is a systemic problem with all available steel and iron datasets, as many Chinese plants are young and reliable data on them is difficult to acquire. The case of cement is similar, where global data on plants also has excellent coverage with the exception of China. For these reasons the Steel and Iron and Cement databases are the least comprehensive, but still should exceed the required two-thirds of global emissions in these industries.

Following protocols developed in academic and industrial literature, expected CCCEs were estimated across each asset in the target industries according to their remaining lifetime, the fuels and technologies employed, and other characteristics particular to each industry. This exercise required the integration of numerous studies and reports in order to present the most accurate picture possible for each asset class. Asset-specific characteristics available in the data were further used to calculate the potential to reduce CCCE and the fixed and variable costs required for these reductions. Where average retrofit costs and emissions reductions for a particular technology were not available from the literature, if it was possible to identify specific instances where assets had been retrofitted, the details of these instances were used to extrapolate emissions reduction and cost values for our datasets.

For stationary assets the calculation of CCS feasibility also required the integration of asset-level geolocation calculations and digital maps of global CCS-suitable geology. These various emissions reductions and costs were then homogenised across all assets for direct comparability. The specific methodologies employed for these calculations were developed through a survey of the literature and consultations with leading academics in the field of committed emissions. In instances where an emissions reductions technology is theoretically possible for some assets, but the required data to ascertain whether it is feasible to retrofit the specific asset is not available, this emissions reduction is omitted. Similarly, if specific emissions reductions or costs could not be identified for a given CCCE reduction technology or where the technology is unproven, this technology is not incorporated into the data. Therefore, the dataset only contains emissions reductions that are known to be feasible for each specific asset, and for which all required data for the calculation of emissions reductions and their costs is available.

The rest of this report is intended to accompany the Assets@Risk and RCCCE_Options databases and provides a justification for our analytical approach, as well as methodological details on how the Assets@Risk database was assembled. It also provides high-level quantitative results of our CCCE and RCCCE analyses at the industry level aggregated for relevant geographies. Further, while the project partners aim to make the RCCCE_Options database publicly available, licensing restrictions mean that the

Assets@Risk database of individual assets is not. These demonstrator databases and the accompanying CCCE and RCCCE analyses could help financial institutions manage risks and opportunities arising from the transition to global environmental sustainability. The databases also have significant potential applications for policymakers, regulators, companies, civil society, and NGOs.

Definitions of 'Cumulative Committed Carbon Emissions' (CCCE) and 'Reductions in CCCE' (RCCCE)

Cumulative committed carbon emissions and their Reduction options

Cumulative Committed Carbon Emissions (CCCE) are the carbon emissions an asset is expected to emit over the remaining lifetime of its use under a business-as-usual scenario, and without substituting inputs, upgrading assets (existing assets made more efficient), retrofitting assets (existing assets augmented with additional assets), replacing assets (old assets replaced by new assets), or refurbishment (lifespan increase).[24,25] CCCEs can relate to both direct and indirect emissions,[26,27] and be considered both in terms of existing assets or the 'asset pipeline' related to long-term production processes (e.g. the likely future emissions of aircraft based on the order book of a manufacturer, its production capacity, and R&D pipeline).[28,29] However, in our case, as we are examining multiple industries simultaneously, we focus solely on direct emissions in order to avoid double counting. CCCEs are a function of the lifetime of the asset,[30] their activity factor/utilisation rate, and their carbon intensity.[31] CCCEs can be reduced (in terms of not materialising) through early retirement, energy efficiency retrofit, switch to renewable fuels, or Carbon Capture and Storage.

We term the reduction of CCCEs within this paper Reducing Cumulative Committed Carbon Emissions (RCCCEs). Following Brown, Gambhir, Florin, and Fennel (2012),[32] the RCCCEs we identified consist of (1) substituting fuels or inputs used in the production process with more carbon-efficient alternatives, (2) upgrading assets (making existing assets made more efficient), and (3) carbon capture and storage technologies (CCS). In calculating these RCCCE abatement potentials we focused on proven technologies that can be deployed at a commercial scale in the immediate future. Although there may be dozens of potential RCCCEs for any given asset type, we focused on RCCCEs which, given the asset characteristics available from our chosen data, we are confident could be applied to specific assets (as opposed to a certain proportion of all assets). By necessity, we also limited our scope of RCCCEs to those whose attributable carbon emissions reductions and costs were identifiable in the literature. As improvements to the

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[24] Davis, S. J. and Socolow, R. H. (2014) "Commitment accounting of CO_2 emissions", *Environmental Research Letters*, 9(8), p. 84018. doi: 10.1088/1748-9326/9/8/084018.
[25] Davis, S. J., Caldeira, K. and Matthews, H. D. (2010) "Future CO_2 emissions and climate change from existing energy infrastructure", *Science*, 329(5997), pp. 1330–33. doi: 10.1126/science.1188566.
[26] The GHG Protocol distinguishes scope 1 (direct emissions of a power plan), scope 2 (electricity consumption related to a production process), and scope 3 (all other indirect emissions, related to product in use for instance).
[27] Carlson, K. M., Curran, L. M., Ratnasari, D., Pittman, A. M., Soares- Filho, B. S., Asner, G. P., Trigg, S. N., Gaveau, D. a., Lawrence, D. and Rodrigues, H. O. (2012) "Committed carbon emissions, deforestation, and community land conversion from oil palm plantation expansion in West Kalimantan, Indonesia.", *Proceedings of the National Academy of Sciences of the United States of America*. doi: 10.1073/pnas.1200452109.
[28] Pfeiffer, Alexander, Cameron Hepburn, Adrien Vogt-Schilb, and Ben Caldecott. 2017. "Committed emissions from existing and planned power plants and consequent levels of asset stranding required to meet global warming goals", Working Paper. Oxford, UK.
[29] Pfeiffer, Alexander, Adrien Vogt-Schilb, Daniel J. Tulloch, and Cameron Hepburn. 2017. "Dead on Arrival? Implicit Stranded Assets in Leading IPCC Scenarios." Working Paper. Oxford, UK.
[30] Lifetime of the asset is defined as the average timeframe over which operating the asset is expected to be profitable, and is taken from historical analysis of asset operating lifetimes until voluntary closure.
[31] Pfeiffer, A., Millar, R., Hepburn, C. and Beinhocker, E. (2016) "The 2- degree Celsius capital stock for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy", *Applied Energy*, 179, pp. 1395–1408. doi: 10.1016/j.apenergy.2016.02.093.
[32] Grantham Institute (2012). "Reducing CO_2 emissions from heavy industry: a review of technologies and consideration for policy makers." Grantham Institute for Climate Change, Briefing paper No 7.

Assets@Risk database allow for additional individual asset characteristics to be identified and additional literature on abatement magnitudes and costs becomes available, the scope of RCCCE covered in the Assets@Risk database will increase. In addition, care was taken to ensure that RCCCE costs reflect retrofitting the assets as opposed to new builds.

Note that for all RCCCE cost calculations the discount rate is assumed to be zero. Cost analyses of long-lived capital stock, which is characteristic of much carbon-emitting infrastructure, are highly sensitive to the discount rate employed. Due to the contentious nature of discount rate choice for such assets,[33] and the secularly low and even negative discount rates currently employed by many central banks, it was decided to use a discount rate of zero. The summated costs accruing throughout the life of an RCCCE retrofit using a zero discount rate can be thought of as an upper bound of such costs. Therefore, if investments meet profitability thresholds in spite of this discount rate, then they can be considered profitable in all discount rate scenarios. However, the use of a zero discount rate also means that there is a slight bias favouring RCCCEs whose main expenditures are closer in time as opposed to those whose main expenditures are further away.

Distinction between technically and economically feasible emissions reductions

The distinction between technical and economic feasibility in reducing emissions is an important one. For almost all of the sectors analysed in this report, while it is often technically feasible to reduce carbon emissions to near zero through the simultaneous adoption of multiple RCCCEs options, the cost of doing so would generally be prohibitive. In deciding between abatement options given finite resources, it is important to distinguish between the most and least cost-effective means for achieving specific levels of emissions reductions. The determination of least-cost RCCCE bundles for a given level of emissions reductions involves solving for the least cost combination of non-mutually exclusive RCCCE options which achieve the desired level of emissions reduction. In the RCCCE analyses that follow, we provide emissions abatement potentials and costs for the technical maximum emissions abatement feasible within each of the three RCCCE classes listed in Section 1.2.1, and global maximum feasible emissions abatement potentials and their costs from combining these three emissions abatement classes.

Utilising the Assets@Risk database as a demonstration, we have completed an analysis of the CCCEs associated with each asset identified and classified in Assets@Risk. We have also created a new database of all the technical options available to reduce CCCEs within Assets@Risk. This database is called the RCCCEs Options Database ('RCCCE_Options').

[33] For an overview of this debate see; Lind, R. C. (Ed.) (1982). *Discounting for time and risks in energy policy*. Washington, DC: Resources for the Future; Portney, P. R., & Weyant, J. P. (Eds.) (1999). *Discounting and intergenerational equity*. Washington, DC: Resources for the Future; and Stern, N. H. (2007). *The Economics of Climate Change: The Stern review*. Cambridge: Cambridge University Press.

Database descriptions, methodologies, and results

Power

Description of data

Data sources

The Power database comprises a number of data sources to provide a comprehensive analysis of carbon-based fuel-powered utilities. Operational, under construction, and planned power plant capacities were determined by manually merging all coal power plants from the most recent versions of CoalSwarm (Feb 2017c), Platts World Electric Power Plants Database (WEPP) (Q4 2016), Greenpeace's planned China coal plant database (August 2016), Sekitan's Japan coal-fired power plant database (Q1 2016), and Kiko Network's Japan coal-fired power plant database (Q1 2016). This merger was done through manually confirming unique power plant; names, locations, current status, year of start, and capacity; and was supplemented with internet research as required. The most recent data is used where matched plants have conflicting fields (for example, different operating statuses).

CoalSwarm has data on all coal-fired power plants existing and planned, and WEPP has global coverage of all power plants regardless of fuel source but excluding micro-generators. WEPP is updated quarterly (we currently use data from the Q4 2016 release). The merger between these datasets has produced a database that effectively defines the locations of all the world's power plants, their ownership, age, fuel type, and capacity. It is particularly current and comprehensive for coal-fired power stations.

- **Core Data**: Combined database unit-level fields include:
    - Unit Name
    - Plant Name
    - Country
    - City
    - Parent Owner/Operating Company
    - Fuel
    - Fuel Sub-type
    - MW Capacity
    - Boiler Efficiency

Key assumptions and calculation steps

- The power database is comprised of several databases from different sources to provide a comprehensive analysis of currently operating, retired, and planned fossil fuel powered electricity generators around the world. To avoid double-counting jointly-owned capacity, we proportionately separate capacity among joint-owners.
- Generation capacities were determined by manually merging all power plants from the most recent versions of the following databases:
    - CoalSwarm (Feb 2017)
    - Platt's UDI World Electric Power Plants (WEPP) database[34] (Q4 2016)
    - Greenpeace's database of planned coal generators in China (August 2016)
    - Sekitan's Japan coal-fired power plant database (Q1 2016)
    - Kiko Network's Japan coal-fired power plant database (Q1 2016)

[34] WEPP has global coverage of all power plants regardless of fuel source but excluding micro-generators and is updated quarterly.

- Known gaps are in micro-generation and for generators in China (for WEPP); however, CoalSwarm and Greenpeace combined have good China coverage
- Three different additional sources of data have been used for the calculation of committed CO_2 emissions:
    - Current and historic heat rates from the US Energy Information Agency (EIA) and the US Environmental Protection Agency (EPA)
    - Emission factors for individual fuels from the EIA and the UK Department for Environment, Food, and Rural Affairs (Defra)

CCCE and RCCCE estimation methodology

Sources of CO_2 emissions

Carbon emissions in the power sector arise from the burning of carbon-based fuel. The most common carbon-based fuels used in power generation are coal, oil, and gas. Carbon efficiencies can vary considerably according to specific technologies and fuels. This is especially the case for coal, where power is typically generated between 800-1,200kg CO_2/MWh. Gas generation shows less variability, typically around 400kg CO_2/MWh, and oil carbon intensity is usually between the two, but can have even higher CO_2 intensities than coal in the case of small inefficient plants. Biofuels though also carbon-based are given emission factors of zero in this analysis in accordance with the rules under the EU ETS.[35] Although our databases variously contain power plants covering 50 separate fuel types, we have aggregated related fuels into 13 separate categories, see Table 4 below. These 13 categories comprise four categories of carbon-emitting fuels: coal, oil, gas, and waste, for which we separately estimate carbon emission intensities at the asset level.

Committed emissions

In the Power sector, the Cumulative Committed Carbon Emissions (CCCE) for each power station is calculated from the following equation:

$$CCCE_i = MW\ capacity_i \times heat\ rate_i \times fuel\ emission\ factor_f \times utilisation\ rate_f \times remaining\ lifespan_i$$

For asset i and fuel type f.

- **Emission factor/heat rate**: (ton CO_2/MWh)
    - The EIA provides data on current and historic heat rates for different generators, turbine types, and fuels (historic data on technology level goes back to 2001 and aggregated data for all fossil fuels back to 1949 [36,37])
    - Datasets obtained from the EIA contain emission factors for different fuels, i.e. the amount of CO_2 in relationship to the energy content of coal, lignite, oil, etc.[38]
    - For oil, gas, and biomass generators the decisive factor for the heat rates is, in addition to fuel, the turbine type
    - For coal the approach is more granular and considers, in addition to the turbine type, the capacity, fuel type (lignite, bituminous, sub-bituminous, etc.), and steam type (critical, sub-critical, super-critical, etc.)

[35] European Commission (2012). "Commission Regulation (EU) No 601/2012 on the Monitoring and Reporting of Greenhouse Gas Emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council."
[36] EIA (2016). "Average tested heat rates by prime mover and energy source, 2007-2015." http://www.eia.gov/electricity/annual/html/epa_08_02.html
[37] EIA (July 2017). "Total Energy", Monthly Energy Review. http://www.eia.gov/totalenergy/data/monthly/index.php#appendices
[38] EIA (Feb 2016). "Environment, Carbon Dioxide Emissions Coefficients. » http://www.eia.gov/environment/emissions/co2_vol_mass.cfm

- For all generators year-specific heat rates are matched based on the on-line year of the generator to adjust for advances in heat rates over time[39]

Table 4: Fuel Classification

ET Risk classification	Original classification
COAL	Coal
COAL	Coal seam gas
COAL	Syngas from coke
COAL	Coke oven gas
COAL	Coke
COAL	Coal water mixture
COAL	Corex process off-gas
OIL	Oil
OIL	Kerosene
OIL	Jet fuel
OIL	Naptha
OIL	Orimulsion
OIL	Bitumen
OIL	Tar sands
OIL	Shale oil
OIL	Gasified crude oil or refinery bottoms or bitumen
GAS	Gas
GAS	LNG
GAS	Dimethylether
GAS	Flare gas
GAS	Wellhead gas
GAS	Liquified petroleum gas
GAS	Mine gas
GAS	Refinery off-gas
GAS	Top gas
GAS	Volatile organic compounds
WASTE	Refuse
WASTE	Refuse gas
WASTE	Paper mill waste or sludges
WASTE	Waste paper and/or waste plastic
WASTE	Hazardous waste
WASTE	Tires
WASTE	Industrial waste
WASTE	Medical waste
WASTE	Landfill gas
WASTE	Waste gas
WASTE	Wastewater sludge
WASTE HEAT	Waste heat
SUN	Sun
WATER	Water
WIND	Wind

[39] Note that regional differences in power plant heat rates will therefore be captured at the asset level in the differing use of fuel types, turbine and steam efficiencies, and plant age.

GEOTHERMAL	Geothermal
URANIUM	Uranium
BIOMASS	Biomass
BIOMASS	Manure
BIOMASS	Peat
BIOMASS	Wood
BIOMASS	Lignin
BIOMASS	Bagasse
BIO-OIL	Ethanol
BIO-OIL	Pulping liquor
BIO-OIL	Bio-derived liquid fuels such as palm oil or vegetable oils, biodiesel, bio-oil or other bio-liquids
BIO-GAS	Digester gas
BIO-GAS	Biogas
BIO-GAS	Hydrogen (H2)
BIO-GAS	Helium
BIO-GAS	Woodgas
BIO-GAS	Methanol
UNKNOWN	Unknown

- **Utilisation rate**:
  - Global technology specific load factors (utilisation rates) for power generators from the IEA's World Energy Outlooks (WEO) 2005-15

- **Lifetime Factor**: Individual plant lifetimes are estimated by applying random numbers from a Poisson distribution with the expected lifetime of that generator as mean, where expected lifetime is derived from the age at retirement of retired plants in our database (the randomisation accounts for the fact that generators are rarely retired exactly after their expected lifetime)

- Annual max. emissions of a given generator are then calculated incorporating information about its max. capacity (MW).

- Missing information about online years and expected lifetimes of generators in the database are estimated by using available information from similar clusters within the database, namely same; fuel, generator, capacity category, and year online.

RCCCE technologies and their costs

RCCCE Methodology

In the literature carbon emissions reductions used in association with the Power sector are defined in terms of percentage reduction of total emissions. The equation used to define the lifetime RCCCE for asset i and reduction technology e applied to that asset is:

$$RCCCE_{ie} = CCCE_i \times percentage\ reduction_e$$

RCCCE Costs Methodology

In the Power sector literature, emissions reduction costs consist of either variable costs, fixed costs, or both. The formula utilised to calculate this present value is:

$$RCCCE\ costs_{ie} = (fixed\ cost_e \times MW\ capacity_i) + \sum_{t=1}^{T} \frac{variable\ cost_e \times annual\ MWh_i}{(1+r)^t}$$

where;

fixed cost$_e$ = the fixed cost of applying technology *e* per MW of annual capacity
annual MWh$_i$ = estimated annual MWh output of the power plant
r = Discount rate
t = Lifetime factor

Efficiency/Upgrades/Retrofits

The efficiency by which a power plant converts heat energy into electricity varies considerably according to the technology employed. By utilising boilers which operate at higher pressures and temperatures greater efficiency can be achieved, but this comes at a cost. While most coal plants (especially those in developing countries) employ the least efficient subcritical technologies, more efficient supercritical, ultra supercritical, and advanced ultra supercritical technologies are also now available. As the WEPP and CoalSwarm databases contain certain data on the boiler technology employed by coal plants, we use this information to ascertain which assets could be converted from subcritical to supercritical efficiencies. Asset-level data on other efficiency enhancing technologies such as pulverising coal fuel and fluid-bed combustion were unavailable.

Fuel Switching

Of the fossil fuels, coal has the highest carbon emissions intensity. [40] By comparison the emissions factor of natural gas is just over half that of coal.[41] Although no hypothetical or actual retrofits' costs of converting power plants from coal to gas fuel were identified, we were able to find estimates of the costs of converting existing coal plants to burn biomass and gas plants to burn biogas. An important caveat to this exercise is that we do not account for the fact that it may not be technically feasible to convert biofuels at a global scale or even if it is costs may increase substantially.

Geologic CCS

Geologic Carbon Capture and Storage (CCS) has the potential for substantial carbon emissions reductions in power: 90+% with fossil fuels and even negative emissions when combined with biofuels. For power plants we investigate the potential for post-combustion geologic CCS. The geologic focus was chosen because the chemical sequestration of CO_2 streams is generally reserved for cases where this stream is of greater purity than in fuel combustion. While we do estimate costs of geologic CCS storage, it should be noted that there has been wide variability reported in the costs of retrofitting different power plants, sometimes by as much as 100%.[42]

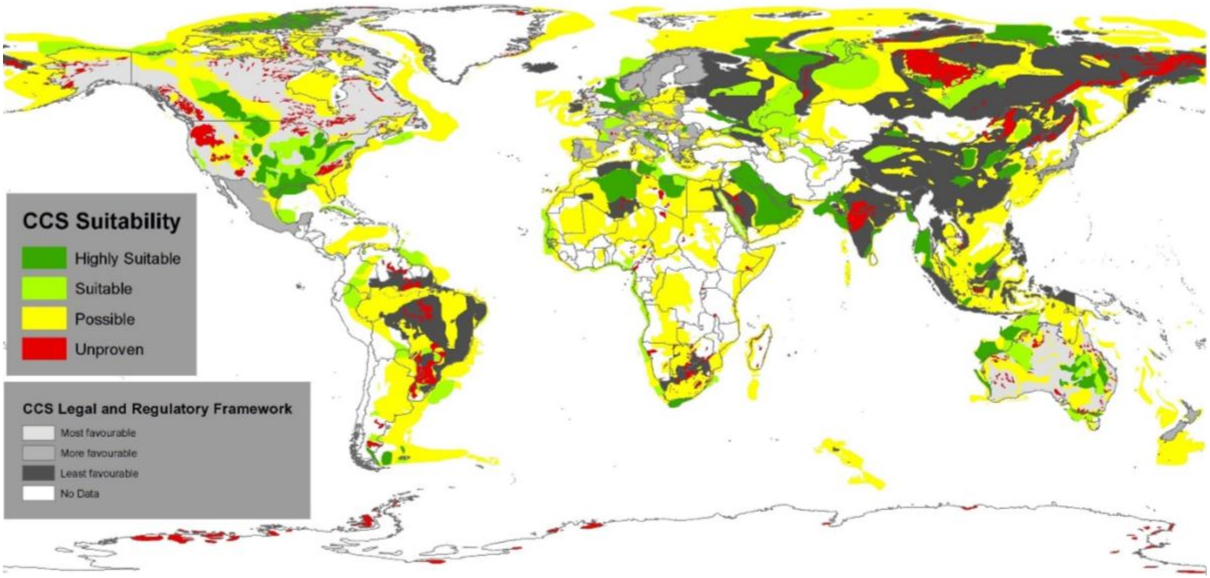
Geologic CCS Retrofitability Methodology

The following approach is taken to identify which coal-fired power generation units may be suitable for geologic CCS retrofits. Power stations with generators larger than 100MW, that are less than 20 years old, and emit <1000g CO_2/KWh are deemed technically suitable for CCS retrofit. This framework follows a recent IEA report on the technical feasibility of retrofitting global coal plants to CCS.[43] These coal plants are then mapped against the Global CCS Suitability geospatial dataset, and it is then ascertained whether these

[40] Grantham Institute (2012). "Reducing CO_2 emissions from heavy industry: a review of technologies and consideration for policy makers." Grantham Institute for Climate Change, Briefing paper No 7.
[41] Ibid.
[42] Dillon, D., J. Wheeldon, R. Chu, G. Choi and C. Loy (2013). "A Summary of EPRI's Engineering and Economic Studies of Post Combustion Capture Retrofit Applied at Various North American Host Sites", *Energy Procedia*, Vol. 37, Elsevier, Amsterdam, pp. 2349-2358.
[43] IEA (2012) CCS Retrofit: Analysis of the Globally Installed Coal-Fired Power Plant Fleet.

power stations are within 40km of areas highly suitable for CCS. If they are, we characterise them as also geographically suitable for CCS retrofit. Power stations that are both technically and geographically suitable for CCS retrofit are deemed to be 'CCS Retrofitable'. Figure 11 shows global CCS Geographic Suitability and national CCS Legal Support.

Figure 11: CCS Geological Suitability and CCS Legal Support[44]



[44] Reproduced with permission of IEA GHG and Geogreen

CCCE by major country

Figure 12: Power CCCEs by Generation-Fuel and Major Country (t CO2)

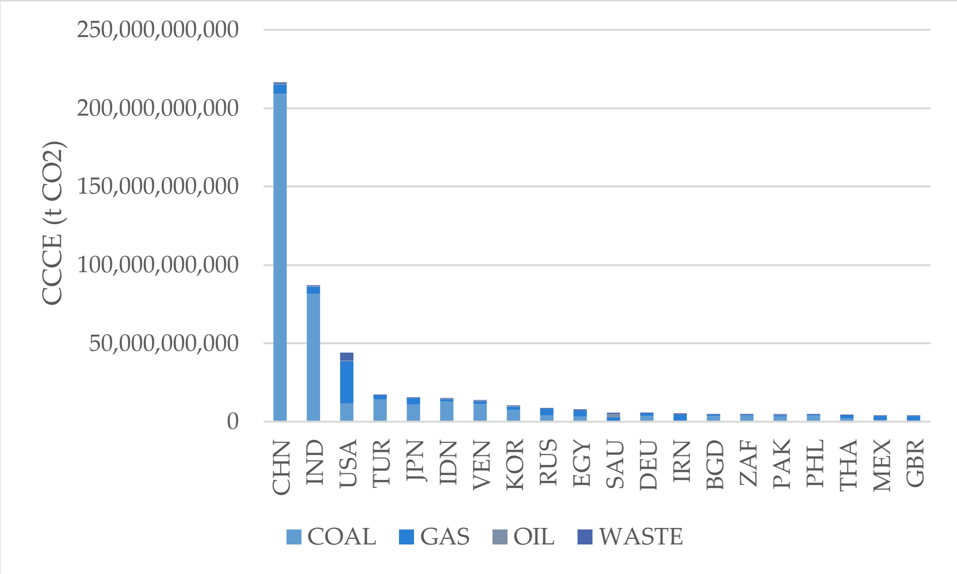


Table 5: Power CCCEs by Generation-Fuel and Major Country (t CO2)

	COAL	GAS	OIL	WASTE	Grand Total
CHN	209,167,160,300	6,193,462,886	176,152,780	847,146,961	216,746,163,247
IND	81,746,243,196	4,591,528,096	252,172,416	558,069,608	87,538,868,177
USA	11,575,148,487	27,032,526,473	343,456,840	5,017,605,586	44,492,761,558
TUR	14,241,784,027	2,441,506,808	68,943,333	307,807,997	17,078,378,671
JPN	10,720,193,978	4,262,014,910	296,817,564	280,665,883	15,655,012,017
IDN	13,203,075,237	1,253,304,219	177,613,625	143,602,164	14,937,707,552
VEN	11,481,494,981	1,450,541,626	289,395,418	240,520,994	13,483,775,318
KOR	7,358,143,795	2,399,800,312	63,422,979	517,602,404	10,349,007,267
RUS	4,151,591,616	4,281,089,318	39,042,223	417,497,838	8,904,838,312
EGY	3,237,244,612	3,746,622,446	106,490,934	853,890,695	7,944,933,059
SAU	0	2,762,411,936	2,332,425,438	771,093,924	5,866,001,097
DEU	3,616,690,387	1,542,425,378	29,329,655	216,296,784	5,519,630,164
IRN	478,122,199	4,009,133,366	146,931,275	620,303,985	5,255,499,531
BGD	3,420,090,120	963,083,363	195,190,007	165,487,666	4,746,803,712
ZAF	4,208,956,422	211,377,930	156,263,180	57,103,273	4,656,567,292
PAK	3,239,505,926	935,675,928	234,977,440	197,905,510	4,654,306,713
PHL	4,015,896,474	417,179,960	84,550,499	47,164,321	4,651,462,069
THA	1,917,944,544	2,141,347,012	5,186,052	387,140,293	4,566,765,783
MEX	917,826,929	2,619,206,107	161,146,431	520,842,273	4,306,520,972
GBR	655,476,973	2,805,619,880	65,544,483	290,713,874	4,163,153,462

Figure 13: Power CCCEs by Operational Status (t CO2)

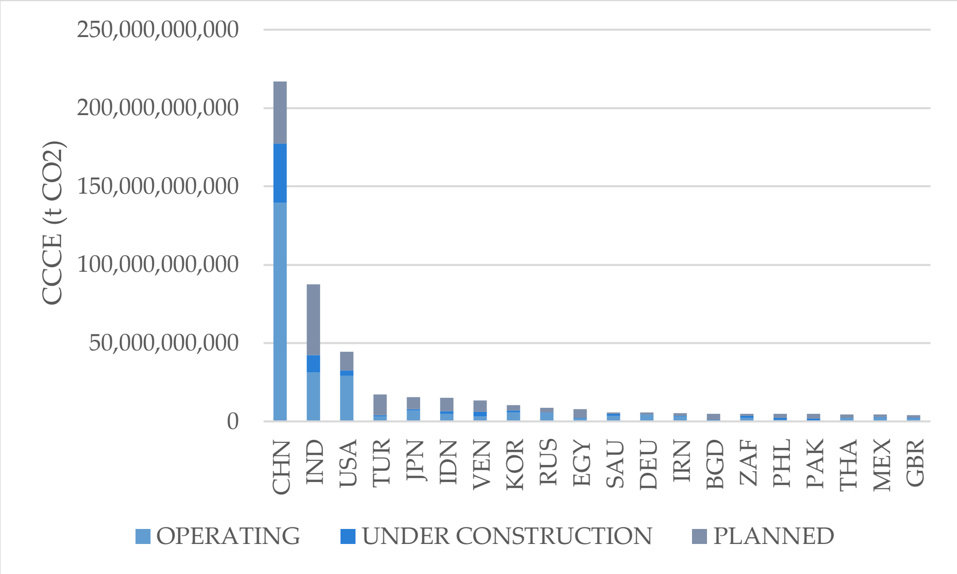


Table 6: Power CCCEs by Operational Status (t CO2)

	OPERATING	UNDER CONSTRUCTION	PLANNED	Grand Total
CHN	139,496,443,937	37,867,986,890	39,381,732,421	216,746,163,247
IND	31,091,555,785	11,211,420,753	45,235,891,640	87,538,868,177
USA	29,317,118,427	3,149,111,463	12,026,531,667	44,492,761,558
TUR	3,043,694,018	858,338,972	13,176,345,681	17,078,378,671
JPN	6,859,785,296	1,169,364,364	7,625,862,357	15,655,012,017
IDN	4,848,269,985	1,635,403,138	8,454,034,428	14,937,707,552
VEN	3,254,925,523	2,755,939,420	7,472,910,375	13,483,775,318
KOR	5,737,069,802	1,448,313,357	3,163,624,108	10,349,007,267
RUS	5,112,700,804	738,260,185	3,053,877,323	8,904,838,312
EGY	1,759,054,319	636,652,972	5,549,225,768	7,944,933,059
SAU	3,773,209,331	1,268,976,788	823,814,979	5,866,001,097
DEU	4,372,725,571	228,981,376	917,923,217	5,519,630,164
IRN	2,978,299,975	686,879,265	1,590,320,291	5,255,499,531
BGD	627,480,586	286,534,942	3,832,788,183	4,746,803,712
ZAF	2,184,246,696	1,280,244,374	1,192,076,222	4,656,567,292
PHL	1,148,659,659	951,559,337	2,554,087,717	4,654,306,713
PAK	634,153,220	1,101,859,621	2,915,449,228	4,651,462,069
THA	2,213,226,683	295,187,750	2,058,351,350	4,566,765,783
MEX	2,283,013,809	534,615,098	1,488,892,065	4,306,520,972
GBR	2,075,134,662	53,105,337	2,034,913,463	4,163,153,462
World	**293,947,143,177**	**77,718,650,539**	**194,819,382,440**	**566,485,176,157**

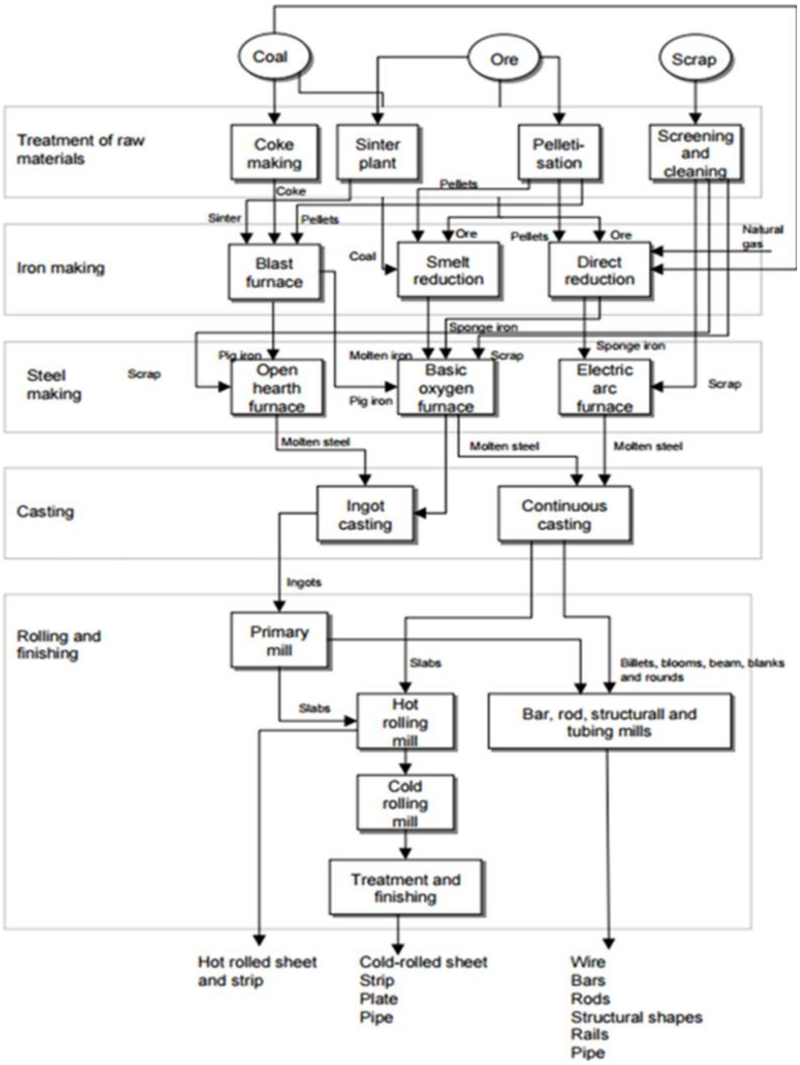
Steel and Iron

Description of data

Data Sources

Steel and Iron data was taken exclusively from the VDeH's PlantFacts database, which has the most comprehensive data on the steel industry available. Comparing estimated production to country totals from WorldSteel suggests the main gap is China, where only roughly 50% of production is captured (https://www.worldsteel.org/en/dam/jcr:37ad1117-fefc-4df3-b84f-6295478ae460/Steel+Statistical+Yearbook+2016.pdf). However, Chinese plants comprise roughly half of global steel and iron production. Data from other countries is close to complete suggesting ~75% global coverage. We do not consider emissions related to the treatment of raw materials or post-production casting, rolling and finishing: see Table 7 below. However, we do cover steel and iron-making: the main sources of carbon emissions in the steel and iron industry. We therefore expect that this database comprises slightly under three-quarters of global steel and iron making emissions.

Table 7: Steel and Iron Production Tree



Available data from VDeH PlantFacts is as follows;

- **Core Data**: Fields are richly detailed in terms of technical specifications for different types of relevant 'plants' (plants are defined in this database as individual process types which may be co-located at the same integrated works location. For example, an integrated works location can contain coking plants, sintering plants, blast furnaces, and (BOF) plants. Common variables across all plant types include:
    - Works name and ID
    - Plant name and ID
    - Operating company
    - Country and city/town
    - Nominal production capacity (in varying units: tons coke/yr, tons steel/yr, etc.)
    - Year of start-up
    - Year of modernising.
    - In addition, relevant technical details for different plant types are kept to inform on potential GHG reduction options, including:
        - Fuel type (BOF/EAF)
        - Charge type (Blast furnace, DRI plant)
        - Continuous and/or ingot casting method

1.4.1.1 Key assumptions and calculation steps

- The analysis sought to cover the most energy intensive processes of iron and steel-making but does not cover all emissions at iron and steel facilities due to auxiliary combustion units or post-steelmaking processes (rolling, casting, etc.)
- Plant capacity information was available for only ~85% of plants. For the remaining 15% of plants capacity was estimated using the average size of plants in the same country and of the same technology (e.g. AC EAF/Austria).
- Where fuel type is unavailable/unknown, the predominant fuel mix for the relevant country/technology are taken from IEA (2015).
- Operating companies are matched to listed company tickers and global ultimate owners using web search and fuzzy matching of company names to listed universe compiled in SEI Metrics project.
- If a plant has been modernised, its year of initial operation is set to the year of modernising, representing the start of a new useful lifetime.
- Plant geolocations were not available from base data and were estimated using the R package GGMAP's geocode() function using a combination of (plant name, country). Geocoding was readily available from the Data Science Toolkit for 97% of plants.
- Estimates were validated using US EPA facility level CO_2 emissions data and were generally within 15-20% of reported values though usually underestimated, likely due to the inclusion of only primary iron and steelmaking processes (https://ghgdata.epa.gov/ghgp/main.do).

CCCE and RCCCE estimation methodology

Sources of CO2 emissions

The greenhouse gas emissions from steel production arise from three sources: (1) the combustion of fossil fuels, (2) the use of electrical energy, and (3) the use of coal and lime as feedstock.[45] Iron and Steelmaking produce about 27% of global industrial CO_2 emissions, and about 10% of the global total.[46] The main production processes are Basic Oxygen Furnace steelmaking (BOF) and Electric Arc Furnace steelmaking (EAF).[47] BOF accounts for roughly 72% of world steel production, EAF 20%, and the inefficient Open Hearth Furnace method which accounts for the remainder is being gradually phased out.[48] BOF and OHF steelmaking is used to produce steel derived from ore, whereas in EAF steelmaking the primary input is used steel scrap. The average emissions intensity of BOF is 2.8 tons of CO_2 per ton of steel, whereas EAF is more than four times less CO_2 intensive than BOF at 0.6 tons.[49] Although EAF is more energy and carbon efficient than BOF steelmaking, EAF is limited by the availability of scrap.

Committed emissions

In the Steel and Iron sector CCCE is calculated from the following equation:

$$CCCE_i = emissions\ factor_i \times activity\ factor_i \times lifetime\ factor_i$$

where;
emissions factor = CO_2/ton steel|iron
activity factor = ton steel|iron /year
lifetime factor = 25 years

For asset *i*.

[45] Worrell, E. et al. (2009). "Industrial Energy Efficiency and Climate Change Mitigation." Berkeley National Laboratory.
[46] IEA (2008a). "CO_2 Capture and Storage: A Key Carbon Abatement Option."
[47] Columbia Climate Center (2010) "Mitigating Iron and Steel Emissions." Global Network for Climate Solutions.
[48] Watson, C. et al. (2003). "Can Transnational Sectorial Agreements Help Reduce Greenhouse Gas Emissions?" Organization for Economic Cooperation and Development. Paris: OECD.
[49] Watson, C. et al. (2003). "Can Transnational Sectorial Agreements Help Reduce Greenhouse Gas Emissions?" Organization for Economic Cooperation and Development. Paris: OECD.

Steel and Iron Emissions factors, Activity factors, and Lifetime factors used to calculate committed emissions were derived from the following sources:

- **Emission Factor**: Emissions factors by process type are taken from a combination of:
  - IEA Tracking Clean Energy Progress 2015 (energy and electricity intensities by process)
  - IPCC 2007 GHG Methodologies – average CO_2 emissions factors by fuel
  - IEA CO_2 emissions from Fossil Fuels (CO_2 factors for electricity by country)
  - US EPA Technical Support Document for GHG Reporting (https://www.epa.gov/sites/production/files/2015-02/documents/tsd_iron_and_steel_epa_9-8-08.pdf); process-related CO_2 emissions from reduction.
  - Emissions factors included :
    - Blast furnace energy use (ton CO_2/ton hot metal)
    - BOF reduction (ton CO_2/ton steel)
    - EAF reduction (ton CO_2/ton steel)
    - EAF (AC and DC) electricity use (MWh/ton steel)
    - Coking plant (ton CO_2/ton steel)
    - Sintering plant (ton CO_2/ton steel)
    - Direct Reduction of Iron (DRI) process energy use (ton CO_2/ton hot metal)
    - DRI reduction (ton CO_2/ton hot metal)

- **Activity Factor**: (utilisation rate ; range 52-74%) taken from WorldSteel estimates by region (https://www.worldsteel.org/media-centre/press-releases/2016/May-2016-crude-steel-production.html).

- **Lifetime Factor**: (yr) Expert interviews from previous EY work suggest a lifetime of 25 years is relevant for most types of iron and steelmaking equipment.

RCCCE technologies and their costs

There are four primary ways that CO_2 emissions can be reduced in the iron and steel industry.[50] The most effective method is through switching to more efficient production processes. In particular, OHF to BOF (although favourable economics is already driving this transition), and BOF to EAF (though this conversion is limited by the availability of scrap steel). The second method entails the increased recovery of gases and heat integration from furnaces. Third, the utilisation of efficient methods for finishing the final crude steel product. And fourth, the adoption of CCS technology.

RCCCE Methodology

In the literature carbon emissions reductions associated with the Steel and Iron sector are defined in terms of either: (1) a percentage reduction of total emissions, or (2) in terms of a quantity of CO_2 for a given quantity of output. In the first case the equation used to define the lifetime RCCCE for an asset i and reduction technology e applied to that asset is;

$$RCCCE_{ie} = CCCE_i \times percentage\ reduction_e \quad (1)$$

In the latter case the equation applied is:

$$RCCCE_{ie} = annual\ ouput_i \times emissions\ reduction\ factor_e \times T \quad (2)$$

[50] Grantham Institute (2012). "Reducing CO_2 emissions from heavy industry: a review of technologies and consideration for policy makers". Grantham Institute for Climate Change, Briefing paper No 7.

where;

annual output = the annual capacity of the asset in tons of output multiplied by its *activity factor*
emissions reduction factor = the reduction in the quantity of CO_2 emitted for each ton of output
T = Lifetime Factor

Notice that the only practical difference between equations (1) and (2) is that equation (1) requires the estimation of asset level CCCEs, and therefore an estimate of the emissions intensity of the asset itself. As we estimate CCCEs for all assets regardless, whether authors define emissions reductions in terms of a percentage or emissions reduction factor does not constrain our ability to calculate RCCCEs.

RCCCE Costs Methodology

In the Steel and Iron literature, emissions reduction costs consist of either variable costs, fixed costs, or both. The formula utilised to calculate this present value is;

$$RCCCE\ costs_{ie} = (fixed\ cost_e \times annual\ capacity_i) + \sum_{t=1}^{T} \frac{variable\ cost_e \times annual\ capacity_i}{(1+r)^t}$$

where;

fixed cost$_e$ = the fixed cost of applying technology *e* per ton of annual capacity
annual capacity$_i$ = tons per year of output which can be produced
r = Discount rate
t = Lifetime Factor

Note that for RCCCE cost calculations the discount rate was assumed to be zero.

Efficiency/Upgrades/Retrofits

In the iron and steel sector the potential for significant decreases in CO_2 emissions in the production process is limited by the fact that a significant proportion of CO_2 emissions arise from a chemical reaction due to the reduction of iron ore. Therefore, absent the development of breakthrough technologies, the potential for efficiency upgrades to reduce CO_2 emissions will be incremental rather than saltatory.[51] Nevertheless, the biggest potential for emissions reductions lies in converting from OHF and BOF to EAF production processes. While OHF plants can switch to a BOF process, the availability of scrap poses a natural limit to conversion to an EAF process.[52]

Fuel Switching

We cannot examine the possibility of switching steel plants which use coal to natural gas, as this fuel data was not available from our dataset.

CCS

CCS is the only steel technology with the possibility of achieving large reductions in CO_2 emissions. Unlike Power, the high purity of effluent CO_2 streams makes it economically feasible to utilise chemical CCS technologies in addition to geologic CCS.

CCCE by major country

Figure 14: Steel CCCEs by Status and Major Country (t CO2)

[51] European Commission (2013). "Energy efficiency and CO_2 reduction in the iron and steel industry."
[52] Boston Consulting Group (2013). "Steel's contribution to a low-carbon Europe 2050."

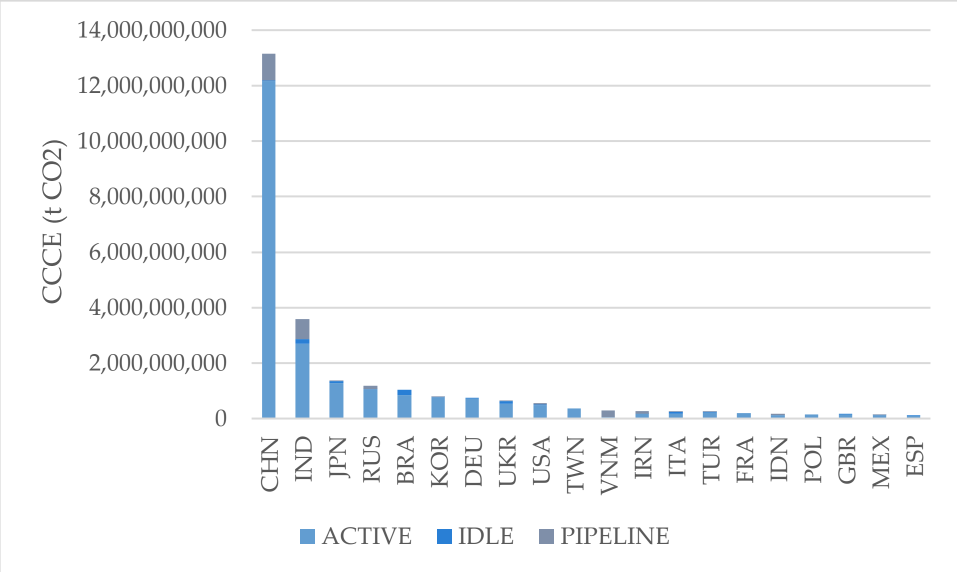


Table 8: Steel CCCEs by Status and Major Country (t CO2)

	ACTIVE	**IDLE**	**PIPELINE**	**Grand Total**
CHN	12,162,845,863	34,354,948	957,558,420	13,154,759,231
IND	2,693,101,483	181,907,550	715,693,864	3,590,702,897
JPN	1,272,813,450	68,975,026	2,887,650	1,344,676,127
RUS	1,058,745,479	5,308,051	109,348,462	1,173,401,992
BRA	838,636,506	189,894,655	0	1,028,531,161
KOR	775,129,473	4,438,224	1,522,920	781,090,617
DEU	723,960,205	7,722,250	0	731,682,455
UKR	542,431,067	90,209,421	12,593,850	645,234,338
USA	494,275,495	23,399,223	33,111,364	550,786,082
TWN	367,760,839	0	0	367,760,839
VNM	49,332,816	0	241,939,929	291,272,745
IRN	181,371,118	816,936	89,535,866	271,723,920
ITA	161,161,858	82,307,094	7,636,230	251,105,182
TUR	228,281,095	20,333,807	359,352	248,974,254
FRA	202,797,739	0	0	202,797,739
IDN	127,644,272	0	43,626,867	171,271,138
POL	153,784,607	0	0	153,784,607
GBR	136,089,198	14,887,857	0	150,977,055
MEX	116,566,879	53,903	5,390,280	122,011,062
ESP	98,361,971	9,141,573	0	107,503,543
World	**23,781,779,731**	**859,101,584**	**2,361,634,920**	**27,002,516,235**

Cement

Description of data

Data Sources

Cement data was taken exclusively from the Global Cement Directory 2016, whose core database has the most comprehensive data available. This database has close to complete coverage of all non-Chinese plants, which comprise roughly half of global cement production. Estimated global production for active plants is largely within 20% of reference values from USGS (https://minerals.usgs.gov/minerals/pubs/commodity/cement/mcs-2017-cemen.pdf) with the exception of China, where coverage is poor (28%) due to a highly dispersed industry. We therefore expect that this database consists of slightly under three-quarters of global cement emissions. Available data from the Global Cement Directory is as follows:

- **Core Data**: Global Cement Directory. Fields include:
  - Plant Name
  - Country
  - City (partial)
  - Operating Company
  - Company Group affiliation (partial)
  - Total cement capacity by technology (dry vs. wet, partial)

Key assumptions and calculations

- Plant ownership is assumed to be the same as the listed plant operator when given no further information. For plants where a group ownership is given (e.g. 35% LafargeHolcim), the portion indicated is allocated to the global parent while the remaining is allocated to the local company.
- Plant status is assumed to be operational where no further information is given. Sometimes plant status is provided alongside the plant listing (e.g. 'Due in 2018') and in these cases, status is manually coded to match other databases (e.g. Active, Pipeline, Decommissioned).
- The Global Cement Directory has two types of plants: grinding only and integrated mills. Integrated mills are assumed to have the full production chain (milling, clinker production, grinding), whereas grinding mills are assumed to only have the grinding process.
- Kiln type (dry/wet) is given in approximately 72% of plants. Where kiln type is not available it is assumed, using WBCSD GNR data for the most used production process in the region.
- Calcination factors (kg CO_2/ton clinker), Energy intensities (MJ/t clinker) and carbon intensities of regional fuel mixes (kg CO_2/MJ) are taken from WBCSD GNR and matched to the region the plant is located in.
- For grinding and cement plant power consumption, country emissions factors are taken from IEA CO_2 Emissions from Fuel Combustion Database (2013 values).
- Estimates are validated using US EPA facility level CO_2 emissions data and are generally within 15-20% of reported values (https://ghgdata.epa.gov/ghgp/main.do).
- Plant geolocations are not available from base data and are estimated using the R package GGMAP's geocode() function using a combination of (plant name, country). Geocoding was readily available from the Data Science Toolkit for 97% of plants.

CCCE and RCCCE estimation methodology

Sources of CO_2 emissions

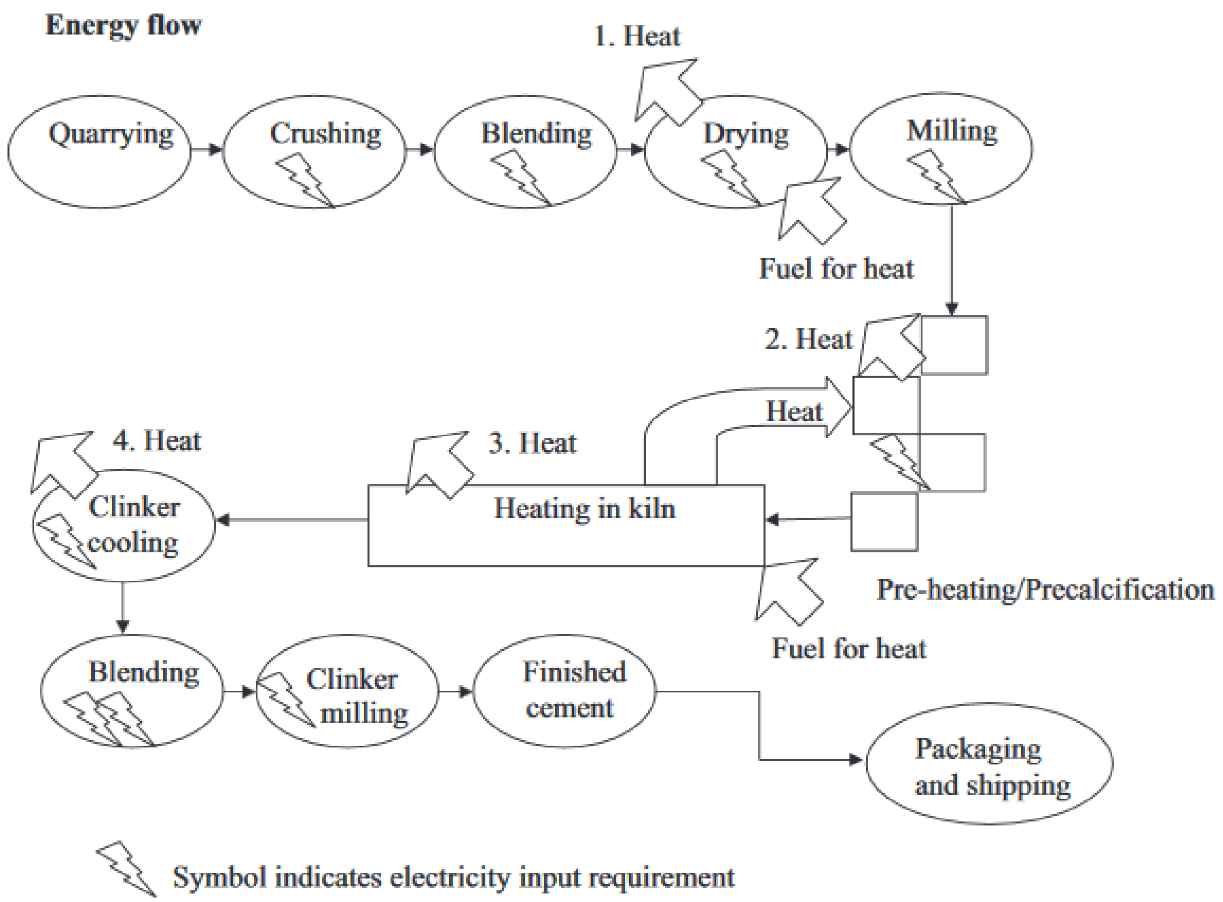
Approximately 5% of global CO_2 emissions arise from cement production.[53] Carbon emissions in the cement industry arises from fuel combustion (33-40% of the total), and the release of CO_2 arising from the decomposition of limestone into CO_2 and clinker (50-66% of the total).[54] The reported emissions intensity of cement production varies in the literature from 650-730kg CO_2 per ton of cement in Western Europe, Brazil,

[53] IPCC. (2007). "Climate Change 2007: Mitigation." Contribution of Working Group III to the Fourth Assessment Report. Intergovernmental Panel on Climate Change. Section 7.4.5.1: Minerals – Cement.

[54] IEA (2008b). "CO_2 Capture in the Cement Industry." Technical Study, Report Number: 2008/3; WRI. (2005). Navigating the Numbers: Greenhouse Gas Data and International Climate Policy. World Resources Institute. p. 74.

and Japan; to 900-935kg CO_2 per ton in China and India; and 900-990 kg CO_2 per ton in the US.[55] The variation in carbon intensity is due to the fuel used to heat the clinker (most commonly coal and coke), whether the kiln used to mix the raw materials is wet (inefficient) or dry (efficient), and the ratio of clinker to cement (higher ratios mean higher carbon intensities).[56]

Figure 15: Cement Production Tree



Committed emissions

In the cement sector CCCE is calculated from the following equation:

$$CCCE_i = emissions\ factor_i \times activity\ factor_i \times lifetime\ factor_i$$

where:
emissions factor = CO_2/ton cement
activity factor = tons of cement/year
lifetime factor = 25 years

For asset *i*

[55] Summary of; Hendriks et al. (2008). Emissions Reduction of Greenhouse Gases from the Cement Industry, presented at the 4th International Conference on Greenhouse Gas Control Technologies, 30 August-2 September, 1998, Interlaken, Switzerland; Mahasenan et al. (2005). "The Role of Carbon Dioxide Capture and Storage in reducing Emissions from Cement Plants in North America." In *Greenhouse Gas Control Technologies*, Volume I, (Eds.) E.S. Rubin, D.W. Keith, and C.F. Gilboy. Elsevier Science, 2005; IEA Greenhouse Gas R&D Programme (2007). CO_2 Capture Ready Plants. Report 4, May 2007.
[56] Columbia Climate Center (2010). "Mitigating Emissions from Cement."

Cement Emissions factors, Activity factors, and Lifetime factors used to calculate committed emissions were derived from the following sources;

- **Emission factor**: (CO_2/ton cement; kWh/ton clinker; kWh/t Cement; clinker to cement ratio)
  - All region-specific values taken from WBCSD Getting the Numbers Right (GNR), for 2014 (http://www.wbcsdcement.org/GNR-2014/index.html)

- **Activity Factor**: (utilisation rate; range 49-86%) Derived using total capacity by country and production in tonnes based on WBCSD GNR data for 2014 and checked with industry and country data sources including:
  - Global Cement Directory country chapters
  - http://www.cement.org/concrete-basics/manufacturing/cement-industry-overview
  - http://www.globalcement.com/magazine/articles/951-the-cement-industry-of-china-a-new-normal
  - http://articles.economictimes.indiatimes.com/2014-11-03/news/55720212_1_cement-demand-cement-companies-cement-production

- **Lifetime Factor**: (yr) It is not possible to derive this factor for cement data, as age of plant is not available in underlying data. Expert interviews from previous EY work suggest a lifetime of 25 years is reasonable but with no information on age of plants lifetime factor is not useful.

We do not calculate total CCCE or remaining CCCE for cement assets because the data provided lacked a start of operations date, making it impossible to utilise our lifetime factor to estimate CCCEs at the asset level.

RCCCE technologies

RCCCE Methodology

In the literature carbon emissions reductions associated with the cement sector are defined in terms percentage reduction of total emissions. The equation used to define the lifetime RCCCE for asset i and reduction technology e applied to that asset is:

$$RCCCE_{ie} = CCCE_i \times percentage\ reduction_e$$

RCCCE Costs Methodology

RCCCE costs for cement could not be incorporated into the analyses because, as we lack start dates of operations for our assets, the expected remaining timeframe of operations is unknown.

Efficiency/Upgrades/Retrofits

The main ways carbon reductions can be achieved are through increasing the energy efficiency of the kiln used to convert limestone and gypsum into cement. The primary methods to accomplish this are switching to dry-kiln technology, fuel switching from coal to natural gas or biomass, increasing the ratio of clinker substitutes in order to decrease process emissions arising from calcination, and introducing efficient milling and grinding equipment.[57] Economics is already driving the conversion of wet to dry kiln manufacturing as the dry process consumes 13% less electrical energy and 28% less fuel than a wet process.[58]

[57] Grantham Institute (2012). "Reducing CO_2 emissions from heavy industry: a review of technologies and consideration for policy makers." Grantham Institute for Climate Change, Briefing paper No 7.
[58] Madlool, N., Saidur, R., Rahim, N., Kamalisarvestani, M. (2013). "An overview of energy savings measures for cement industries." *Renew. Sustain. Energy Rev.* 19, 18e29.

Fuel Switching

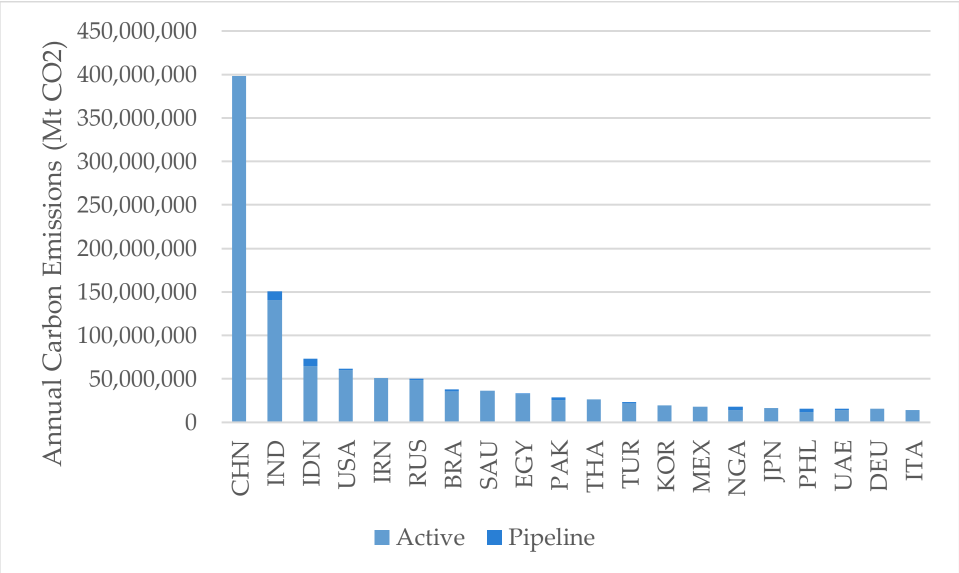
The most common sources of fuel in the cement industry are: coal, fuel oil, petroleum coke, natural gas, and diesel.[59] Unlike steel, in cement the fuel is not utilised chemically in the production process but only as a source of heat necessary for cement formation. Therefore, it is possible to replace high carbon intensity fuels such as coal with lower carbon fuels such as natural gas or theoretically even 100% biomass.[60] Unfortunately, our data does not include information on the fuel type utilised so this emissions-reducing option could not be incorporated into our analyses.

CCS

Like steel and iron, carbon emissions from cement primarily arise from a chemical reaction taking place in the production process. Therefore, absent a technological breakthrough, CCS is the only existing technology with the possibility of achieving large reductions in CO_2 emissions. Similarly to steel and iron, the relatively high purity of effluent CO_2 streams also makes it economically feasible to utilise chemical or geologic CCS technologies. The three main CO_2 capture technologies are: (1) post-combustion capture, (2) oxy-combustion in which fuel is burnt in oxygen instead of air resulting in a flue gas consisting mainly of CO_2, and (3) chemical adsorption.[61]

CCCE by major country

Figure 16: Cement Annual Carbon Emissions by Status and Major Country (Mt CO2)



[59] Madlool, N., Saidur, R., Rahim, N., Kamalisarvestani, M. (2013). "An overview of energy savings measures for cement industries." *Renew. Sustain. Energy Rev.* 19, 18e29.
[60] EPA (2010). "Available and emerging technologies for reducing greenhouse gas emissions from the Portland cement industry."
[61] IEA (2008a). "CO_2 Capture and Storage: A Key Carbon Abatement Option."; IEA (2008b). "CO_2 Capture in the Cement Industry." Technical Study, Report Number: 2008/3.

Table 9: Cement Annual Carbon Emissions by Status and Major Country (Mt CO2)

	Active	**Pipeline**	**Grand Total**
CHN	398,320,629		**398,320,629**
IND	140,801,239	9,607,883	**150,409,122**
IDN	64,878,576	8,226,605	**73,105,181**
USA	60,558,071	919,435	**61,477,506**
IRN	50,758,839		**50,758,839**
RUS	48,673,916	1,446,463	**50,120,378**
BRA	35,369,098	2,273,155	**37,642,254**
SAU	36,353,177		**36,353,177**
EGY	32,892,823	374,050	**33,266,873**
PAK	25,763,695	2,777,440	**28,541,135**
THA	26,316,038		**26,316,038**
TUR	21,768,806	1,446,846	**23,215,653**
KOR	19,757,003		**19,757,003**
MEX	18,195,259		**18,195,259**
NGA	14,183,208	3,702,477	**17,885,685**
JPN	16,412,455		**16,412,455**
PHL	12,176,515	3,646,852	**15,823,367**
UAE	14,060,819	1,605,561	**15,666,379**
DEU	15,503,695		**15,503,695**
ITA	14,512,038		**14,512,038**
Total	**1,067,255,899**	**36,026,767**	**1,103,282,666**

Automobiles

Description of data

Data sources

Automobile data consists of ~100% of light duty vehicles sold/produced globally from 2002-16 and projections from 2017-23 and was sourced from WardsAuto and WardsAutoForecastSolutions. Available data from these sources is as follows:

- **Core Data**: (Sales) Fields include:
  - Make
  - Model
  - Year of production
  - Country of production
  - Vehicle class (e.g. subcompact, light SUV, etc.)
  - Powertrain type (fully electric, HEV, ICE only)
  - Fuel type (e.g. gasoline/diesel)

Key assumptions and calculation steps

- US EPA data is preferred over EEA data for historical accuracy and is used where available.
- Drive cycles are corrected to EPA using values from ICCT: http://www.theicct.org/sites/default/files/publications/ICCT_LDV-test-cycle-conversion-factors_sept2014.pdf
- Unique make/model are matched manually to US EPA and EEA data by model name (and year in the case of EPA data). Where models are sold under different names in different countries they were corrected where possible to the US or EU model name. This resulted in ~70% of global sales in 2016 being matched to make/model level emissions factor data
- Models without make/model level emissions factor data were gap filled using median values taken in order of priority:
  - Segment/region/powertrain package (hybrid/ICE/EV)
  - Segment/ powertrain package (hybrid/ICE/EV)
  - Segment only
- To avoid double counting of emissions in other sectors (focus on Scope 1 CO_2), emissions from fully electric vehicles were set to zero. Plug-in hybrid vehicles use standard emissions factors.
- Past models' emissions factors where historical fuel economy data are not available are adjusted for average fuel economy increases by country as tracked by GFEI: https://www.globalfueleconomy.org/media/203446/gfei-state-of-the-world-report-2016.pdf
- Future models' emissions factors are set to the most recent model's fuel economy with no further extrapolation.

CCCE and RCCCE estimation methodology

Sources of CO_2 emissions

Carbon emissions from automobiles come from the combustion of non-biomass derived carbon-based fuels. Typically, liquid gasoline and diesel fuels are used for this purpose, and more rarely pressurised natural gas can be used. However, after the recent 'Dieselgate' scandal, concern has been raised that official test-derived fuel efficiency figures may considerably under-report emissions. For instance, it has been shown that cars sold in the EU in 2015 on average consumed 42 per cent more fuel in real world conditions that in official laboratory tests.[62] Electric vehicles and biomass have zero direct emissions related to their use. But in order

[62] Financial Times (21 December, 2016). "Car fuel efficiency figures fail real-world test." https://www.ft.com/content/62d2c466-c6cd-11e6-9043-7e34c07b46ef

to truly have no emissions, electric vehicles' charges must be obtained from non-fossil fuel related sources (eg renewable energy) and biomass must be produced and transported without carbon emissions.

Committed emissions

In the automobile sector CCCE for each sold automobile is calculated from the following equation:

$$CCCE_i = emissions\ factor_i \times activity\ factor_i \times lifetime\ factor_i$$

where:
emissions factor = CO_2/km
activity factor = km/year
lifetime factor = years

For asset *i*.

The Automobile Emissions factors, Activity factors, and Lifetime factors used to calculate committed emissions were derived from the following sources:

- **Emission Factor**: CO_2/km)
  - EU EEA database: http://www.eea.europa.eu/data-and-maps/data/co2-cars-emission-10/monitoring-of-co2-emissions-from-1/co2_passenger_cars_v11_csv.zip/at_download/file
  - US EPA historical fuel economy database: (CO_2/mi) https://www.fueleconomy.gov/feg/download.shtml

- **Activity Factor**: (km/yr) Taken from previous work by EY based on expert interviews, region and vehicle class-specific estimates, ranging from 12,700km/yr to 18,260km/yr

- **Lifetime Factor**: (yr) Taken from previous work by EY based on literature and expert interviews, region and vehicle class-specific estimates, ranging from six to 24 years

Emissions reduction technologies and their costs

RCCCE Methodology

In the literature the carbon emissions reductions associated with the automobile sector that we identified were defined in terms of percentage reduction of total emissions. The equation used to define the lifetime RCCCE for asset *i* and reduction technology *e* applied to that asset is:

$$RCCCE_{ie} = CCCE_i \times percentage\ reduction_e$$

1.4.1.1.1 RCCCE Costs Methodology

In the automobile literature, emissions reduction costs consist of either variable costs, fixed costs, or both. The formula utilised to calculate this present value is:

$$RCCCE\ costs_{ie} = (fixed\ cost_e) + \sum_{t=1}^{T} \frac{variable\ cost_e \times activity\ factor_i}{(1+r)^t}$$

where:

fixed cost$_e$ = the fixed cost of applying technology *e* to a vehicle
variable cost$_e$ = the cost of applying technology *e* per km
r = *Discount rate*

t = Lifetime Factor

Note that for RCCCE cost calculations the discount rate was assumed to be zero.

Efficiency/Upgrades/Retrofits

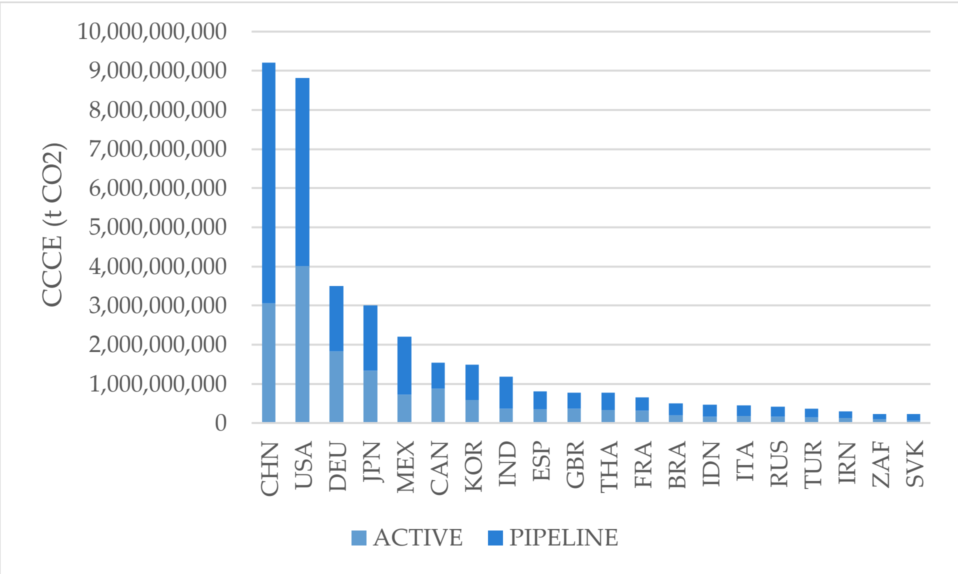
Although 21 specific RCCCE efficiency upgrades for automobiles were identified in the literature, these could not be used because given our data it could not be ascertained to which assets these could be applied.[63] However future work could break down model characteristics to a sufficient degree to be able to apply these potential RCCCEs to emissions and cost calculations.

Fuel Switching

Given our data, fuel switching was the only feasible RCCCE for study. We have examined costs for petrol and diesel conversion to biofuels, petrol conversion to LPG, conversion to hybrid engines, conversion to plug-in hybrid-electric (PHEV), and full electric vehicle conversion.

CCCE by major country

Figure 17: Automobile CCCEs by Status and Major Country (t CO2)



[63] For example: regenerative braking, low rolling-resistance tyres, dual-clutches, engine downsizing with turbocharging, continuously variable transmission, electrically assisted steering, and optimised gearbox ratios among many others.

Table 10: Automobile CCCEs by Status and Major Country (t CO2)

	ACTIVE	PIPELINE	Grand Total
CHN	3,066,223,134	6,141,146,462	9,207,369,596
USA	4,019,824,189	4,803,944,285	8,823,768,475
DEU	1,828,353,232	1,668,484,769	3,496,838,001
JPN	1,337,867,959	1,677,362,168	3,015,230,127
MEX	728,704,359	1,484,464,439	2,213,168,798
CAN	885,622,189	659,427,908	1,545,050,097
KOR	595,856,875	898,310,955	1,494,167,831
IND	371,003,603	811,403,574	1,182,407,177
ESP	346,045,357	464,712,650	810,758,007
GBR	365,972,861	408,795,764	774,768,625
THA	325,935,920	442,645,195	768,581,115
FRA	322,390,970	341,069,785	663,460,755
BRA	195,521,743	307,783,259	503,305,002
IDN	160,642,869	304,728,645	465,371,514
ITA	187,299,880	257,593,557	444,893,437
RUS	158,274,162	264,679,322	422,953,483
TUR	137,059,736	229,236,428	366,296,163
IRN	123,216,205	170,439,294	293,655,499
ZAF	93,147,119	144,828,819	237,975,938
SVK	66,190,476	166,702,532	232,893,008
World	**16,136,771,256**	**22,792,399,153**	**38,929,170,409**

Airlines

Description of data

Data for the airline industry comes from FlightGlobal and ICAO. The core database from FlightGlobal represents 90% or more of the global airline industry.

The original datasets are provided by Flightglobal and the International Civil Aviation Organization (ICAO). Flightglobal provides the characteristics, ownership information, and status for aircraft, while ICAO data provides fuel consumption (kg) per flight distance (nm)[64] for 312 distinctive aircraft types, covering 75% of global flight operations. This table is available from the following link:

https://www.icao.int/environmental-protection/CarbonOffset/Documents/Methodology_ICAO_Carbon_Calculator_v9_2016.pdf

Our study is conducted for all the assets provided by Flightglobal and being in service only. We observe an overlap of 74% of aircraft type codes between both sources, constituting the basis for the subsequent calculations. The specific data available from FlightGlobal and ICAO is presented below.

- **Core Data**: FlightGlobal and ICAO :
    - Aircraft model
    - Ship name
    - Company operator
    - Company manager
    - Company owner
    - Operator country
    - Engine manufacturer and type
    - EVDI (estimated CO_2 intensity; g CO_2/tkm) and Rightship GHG Rating (peer comparison score)
    - Operational status
    - Usage (passenger, cargo, etc)
    - Build year
    - Maximum take-off weight
    - Number of seats
    - Cumulative hours and cycles
    - Noise category
    - Fuel consumption (kg) per flight distance (nm) for 312 distinct aircraft types

- Following the White Paper issued by Avolon (2015),[65] we consider an average retirement age for commercial jet aircrafts of 25.7 years. Given that 93.28% of our data falls within this category we extend this retirement standard to all aircraft in our database

CCCE and RCCCE estimation methodology

Sources of CO_2 emissions

Direct carbon emissions in aviation arise solely from the burning of carbon-based fuels, primarily jet fuel. However, it is possible to mix kerosene with biofuels.

Committed emissions

Cumulative committed carbon emissions across aircraft was estimated as follows:

[64] *nm* stands for nautical miles.
[65] Forsberg, D. "Aircraft Retirement and Storage Trends: Economic Life Analysis Reprised and Expanded," Avolon, 2015.

1) Let N be the total number of distinct aircraft type codes under study and $N_1 \leq N$ the total number of distinct aircraft type codes under study of category A, i.e., for which we have the average route length flown and that are covered by the ICAO table. For $0 \leq i \leq N_1$, we compute the Annual Average Route Length $AARL_i(nm)$ as:

$$AARL_i = \frac{\sum_{j=1}^{M}(Average\_KMs)_{i,j}}{M} \times Conversion\_Factor ,$$

with $Conversion\_Factor = 0.539957$ the conversion factor between km and nm, M the number of repetitions of the aircraft type code i within the data provided by Flightglobal, and $(Average\_KMs)_{i,j}(km)$ the average distance corresponding to the aircraft type code i, j^{th} repetition.

The $AARL_i(nm)$ constitutes the basis to determine the exact annual fuel consumption expressed in (kg) and committed emissions.

2) For each aircraft type code under study of category A, $0 \leq i \leq N_1$, we report, from the ICAO table, the fuel consumption expressed in (kg) corresponding to the $AARL_i(nm)$ computed in the previous step. If the fuel consumption is not specifically stated for the computed $AARL_i$, we use a linear interpolation.

3) Let $N_0 = N - N_1$[66] be the total number of distinct aircraft type codes under study of category B, i.e., which do not belong to category A. For each aircraft type code under study of category B, $0 \leq i \leq N_0$, we infer the fuel consumption using a linear regression. We therefore proceed as follows:

   a) We perform the following regression to test the significance and effect of the explanatory variables (i.e. maximum take-off weight and age, provided by Flightglobal,) on the dependent variable (i.e. fuel consumption), using the characteristics of the aircraft under study of category A (see step 2):

$$\begin{pmatrix} FC_1 \\ \vdots \\ FC_{N_1} \end{pmatrix} = \begin{pmatrix} 1 & Weight_1 & Age_1 \\ \vdots & \vdots & \vdots \\ 1 & Weight_{N_1} & Age_{N_1} \end{pmatrix} \begin{pmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \end{pmatrix} + \begin{pmatrix} \varepsilon_1 \\ \vdots \\ \varepsilon_{N_1} \end{pmatrix},$$

   with N_1 (defined in step 1), and where for $0 \leq i \leq N_1$, ε_i is the error term, $FC_i(kg)$, $Weight_i$ (lb), and Age_i (yr) are respectively the fuel consumption from step 2, the maximum take-off weight, and the age for the aircraft type code i, and where β_i, $0 \leq i \leq 2$ is the regression coefficient. The choice of these explanatory variables can be justified by the fact that the fuel consumption data comes from ICAO whose methodology accounts for weights and age. We do not consider the number of seats as we assume that they are already included in the weight variable.

   The results from the regression are provided in Appendix 1.1**Error! Reference source not found.** (see Table A1). The size of the coefficients varies. The regression does reveal that the maximum take-off weight is the most influential factor with a positive coefficient around 1.355. The model has an R Square over 0.97 and relatively small standard errors. The Significance F as well as P-values assess the soundness of the regression, and the explanatory power of the regression precludes further refinement. We will therefore appeal to those explanatory variables and estimated coefficients to impute the fuel consumption in b) below.

   b) For each aircraft type code under study of category B, $0 \leq i \leq N_0$, we use the following equation to infer the fuel consumption $FC_i(kg)$, i.e:

[66] with N_1 defined in step 1)

$$FC_i = \beta_0 + \beta_1 Weight_i + \beta_2 Age_i \,,$$

where β_0, β_1, and β_2 are estimates from the regression.

Additional information:

- *For some aircraft, the weights are missing (37 entries are missing including the weights appearing with a zero). We have completed the data for the entries corresponding to aircraft that are in service. We have therefore completed the data for 20 entries. For each entry we have used the average of the available weights of assets with identical flight type codes.*

- *In both regressions, we have taken the natural logarithm of the maximum take-off weight and fuel consumption. The purpose of this transformation is that we believe the relationship between fuel consumption and maximum take-off weight is based on a percent/ratio, rather than unit scale.*

4) We then calculate for each aircraft type code, $0 \leq i \leq N$[67], the committed lifetime emissions, the $CCCE_i\ (t)$, using the following equation:

$$CCCE_i = \frac{FC\_i}{1{,}000} \times Emission\_Factor\_Conventional\_Fuel \ \times Remaining\_Lifetime_i \,,$$

with $FC_i(kg)$ the fuel consumption for the aircraft type code i (remind step 2) and 3)) and where from Section 1.2 in the Appendix we have:

$$Emission\_Factor\_Conventional\_Fuel\ (t\ CO_2/t\ fuel) = \ 3.15 \,,$$

$$Remaining\_Lifetime_i\ (year) = 25.7 - Age_i \,,$$

with Age_i the age of the aircraft with type code i. We remind that if $Age_i \geq 25.7$ we disregard the asset as we consider it as retired.

RCCCE technologies and their costs

RCCCE Methodology

Following section 1.3 in the Appendix, we appeal to the use of biojet fuels to reduce CCCE. More precisely, we assume the use of HEFA/F-T fuel with a blend of 50% in fuel and therefore a reduction of 50% in the CCCE (see Section 1.2). Therefore, for each aircraft type code, $0 \leq i \leq N$[68], the $RCCCE_i\ (t)$ is computed as:

$$RCCCE_i = 50\% \times CCCE_i \,,$$

with the $CCCE_i\ (t)$ computed as above.

1.4.1.1.2 RCCCE Costs Methodology

Following section 2.2.2.2 above, we compute for each aircraft type code, $0 \leq i \leq N$[69], the following annual variables:

$$Costs_i^{FT}(€) = 50\% \times \frac{FC_i}{1{,}000} \times \frac{Cost\_FT}{(1+\rho)\text{^}3},$$
$$Costs_i^{HEFA}(€) = 50\% \times \frac{FC_i}{1{,}000} \times \frac{Cost\_HEFA}{(1+\rho)\text{^}3},$$

[67] with N defined in step 1)
[68] with N defined in step 1)
[69] with N defined in step 1)

$$Extra\_Costs_i^{FT}(€) = Costs_i^{FT} - 50\% \frac{FC_i}{1{,}000} \times \frac{Cost\_Conventional\_Fuel}{(1+\rho)\hat{}3},$$
$$Extra\_Costs_i^{HEFA}(€) = Costs_i^{HEFA} - 50\% \frac{FC_i}{1{,}000} \times \frac{Cost\_Conventional\_Fuel}{(1+\rho)\hat{}3},$$
$$Costs_i^{HEFA}(\$/\text{t}\, reduced\ CO_2) = \frac{1}{(1+\rho)\hat{}3}\left[\frac{Cost\_HEFA}{Emission\_Factor\_Conventional\_Fuel} \times FX\_Rate\right],$$
$$Costs_i^{FT}(\$/\text{t}\, reduced\ CO_2) = \frac{1}{(1+\rho)\hat{}3}\left[\frac{Cost\_FT}{Emission\_Factor\_Conventional\_Fuel} \times FX\_Rate\right],$$

where we remind that $FC_i(kg)$ is the fuel consumption as computed above. For the aircraft type code i, and where from Appendix Section 1.2 and Appendix Section 1.4 we have:

$$Cost\_FT\ (€/\text{t}) = 1{,}800\,,$$
$$Cost\_(€/\text{t})HEFA\ = 1{,}300\,,$$
$$Cost\_Conventional\_Fuel\ (€/\text{t}) = 739.2\,,$$
$$\rho\ (\%) = 2\,,$$
$$Emission\_Factor\_Conventional\_Fuel\ (t\ CO_2/t\ fuel) = 3.15\,,$$
$$FX\_Rate\ (EUR/USD) = 1.165$$[70].

Efficiency/Upgrades/Retrofits

Although potential RCCCE efficiency upgrades for aircraft were identified in the literature, these could not be used because, given our data, it could not be ascertained to which assets these could be applied. However, future work could attribute relevant individual characteristics to each specific aircraft model in order to apply these potential RCCCEs to emissions and cost calculations.

Fuel Switching

Fuel switching to various proportions of biofuel was the only method of emissions reductions that was feasible to analyse given data and resource limitations since this could be applied to every aircraft regardless of specific characteristics. We examine renewable jet fuel processes that are currently certified for use in commercial aviation such as the Hydroprocessed Esters and Fatty Acids (HEFA) process (also known as Hydrotreated Renewable Jet fuel) and biomass-to-liquid (BTL) via a Fischer-Tropsch (F-T) process.[71] HEFA production is currently the leading process for producing renewable jet fuel,[72] and can be blended with conventional jet fuel up to a ratio of 50%.[73] However, HEFA production processes using plant oils such as palm oil have received a lot of criticism as being unsustainable,[74] whereas the F-T pathway benefits from greater flexibility and a wide availability of feedstocks.[75]

[70] Bloomberg, "Bloomberg Markets," 2017, https://www.bloomberg.com/quote/EURUSD:CUR. (As of 2:49 PM EDT 7/25/2017)
[71] Winchester et al., "Economic and Emissions Impacts of Renewable Fuel Goals for Aviation in the US."
[72] Kousoulidou and Lonza, "Biofuels in Aviation : Fuel Demand and CO_2 Emissions Evolution in Europe toward 2030."
[73] Kousoulidou and Lonza, "Biofuels in Aviation : Fuel Demand and CO_2 Emissions Evolution in Europe toward 2030."
[74] Rob Bailis et al., "Supply and Sustainability of Carbon Offsets and Alternative Fuels for International Aviation," 2016.
[75] Bailis et al., "Supply and Sustainability of Carbon Offsets and Alternative Fuels for International Aviation."

CCCE by major country

Figure 18: Airlines CCCEs by Country (Mt CO2)

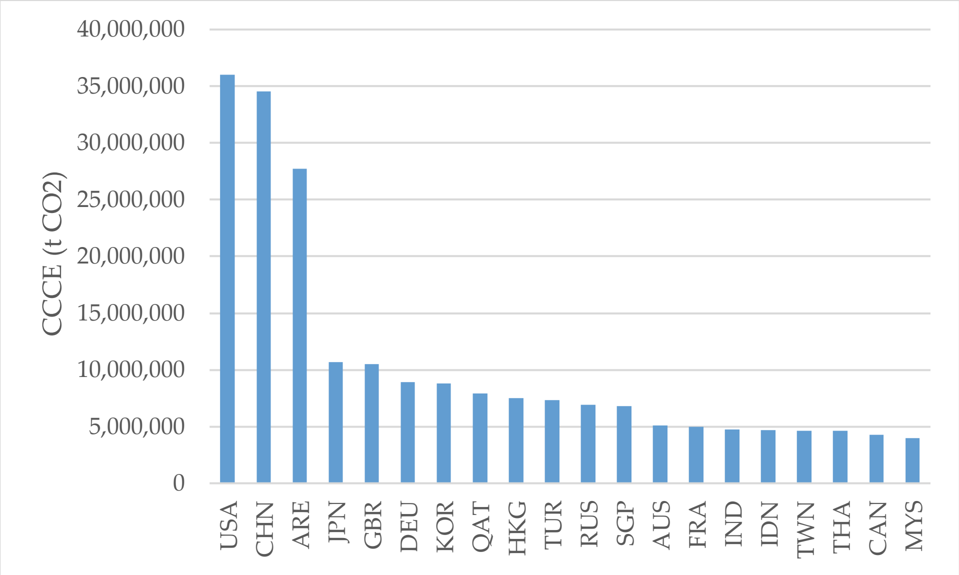


Table 11: Airlines CCCEs by Country (Mt CO2)

	In Service
USA	35,988,443
CHN	34,574,428
ARE	27,718,060
JPN	10,660,825
GBR	10,490,845
DEU	8,937,459
KOR	8,785,130
QAT	7,911,459
HKG	7,501,081
TUR	7,351,348
RUS	6,929,212
SGP	6,801,820
AUS	5,094,809
FRA	4,992,401
IND	4,757,462
IDN	4,688,524
TWN	4,631,139
THA	4,617,916
CAN	4,252,655
MYS	3,961,951

World	**261,122,669**

Shipping

Description of data

Data sources

Data for the shipping industry comes from SeaWeb and RightShip. The core database from Rightship represents 75% of global shipping industry (by number of ships) in each ship class (containers, bulkers, tankers, etc.), and the RightShip data is used to estimate carbon emissions. The data available from SeaWeb and RightShip is presented below.

- **Core Data**: Rightship Existing Vessel Design Index (EVDI) data. Fields include:
  - IMO ship number
  - Ship name
  - Company owner
  - EVDI (estimated CO_2 intensity; g CO_2/tkm) and Rightship GHG Rating (peer comparison score)
  - Year of build
  - Ship deadweight and TEU (for container ships)
  - Ship status

Key assumptions and calculation steps

- Annual emissions are estimated as the product of estimated activity (ton-km/yr) by design efficiency (EVDI; g CO2/tkm)
- Given that ships are mobile, geographical indicators are only tracked by ship flag. More detailed geolocation data is available for some ships from AIS data but this is outside the scope of this work.
- Ships with an estimated year of retirement (year of build + 25) before 2017 that remain operational are assigned a retirement year of 2018

CCCE and RCCCE estimation methodology

Sources of CO_2 emissions

Direct carbon emissions in shipping arise solely from the burning of carbon-based fuels. Maritime fuels are heavier, thicker and produce more carbon emissions than comparable oil distillate-based fuels in other mass transportation sectors such as automobile-based ground transportation or civil aviation.[76,77] The main fuel type denominations in the maritime transportation sector are Heavy Fuel Oil (HFO), Marine Diesel Oil (MDO), and Marine Gas Oil (MGO), with the former occupying the largest share by a significant margin (ca. 90% of the total maritime fuel consumption).[78] HFO is also known as Residual Oil (RO) or Nr.6 fuel with the most dominant type being Intermediate Fuel Oil 380 (IFO380).[79]

Committed emissions

In the Shipping sector CCCE for each sold automobile is calculated from the following equation;

$$CCCE_i = emissions\ factor_i \times activity\ factor_i \times lifetime\ factor_i$$

[76] Chevron, "Everything You Need to Know About Marine Fuels."
[77] "Heavy Fuel Oil (HFO) | Glossary | Marquard & Bahls."
[78] "The End of the Era of Heavy Fuel Oil in Maritime Shipping." International Council on Clean Transportation.
[79] Winebrake and Corbett, "Emissions Tradeoffs among Alternative Marine Fuels: Total Fuel Cycle Analysis of Residual Oil, Marine Gas Oil, and Marine Diesel Oil."

where:
emissions factor = CO2/ton-km
activity factor = ton-km/year
lifetime factor = years

For asset *i.*

Shipping Emissions factors, Activity factors, and Lifetime factors used to calculate committed emissions were derived from the following sources:

- **Emission Factor**: Taken directly from Rightship EVDI estimates. It should be noted that operational GHG emissions can vary from design intensities but here are taken to be representative of actual operational emissions.

- **Activity Factor**: average ton-nm moved per year by ship class and size class is taken from ADEME GHG factors http://www.developpement-durable.gouv.fr/IMG/pdf/Information_CO2_ENG_Web-2.pdf
And validated with the IMO 3rd GHG Study (2014)
http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Third%20Greenhouse%20Gas%20Study/GHG3%20Executive%20Summary%20and%20Report.pdf

- **Lifetime Factor**: (yr) Based on expert interviews performed by EY in work for the SEI Metrics project, technical and economic ship life is ~25 years.

RCCCE technologies and their costs

Efficiency/Upgrades/Retrofits

Although numerous potential RCCCE efficiency upgrades for shipping were identified in the literature, these could not be used because, given our data, it could not be ascertained to which assets these could be applied. However, future work could attribute relevant individual characteristics to each specific ship and engine types in order to apply these potential RCCCEs to emissions and cost calculations. The most efficient operational carbon emissions reduction measures encompass speed reductions, defined as 'slow steaming' in the maritime sector, and fuel switching to either liquefied natural gas (LNG), as a cleaner fossil option than regular oil-based maritime fuels, or alternative fuels obtained from biomass.[80] These have been identified as obtaining the most substantial reduction technologies requiring either little or no technical modification, thus limiting complicated and costly retrofit requirements.[81]

Although slow steaming leads to a higher degree of fuel efficiency, it comes at the expense of longer transportation times.[82] Slow steaming is a proven economically feasible and easily implementable method to reduce GHG emissions.[83,84,85] One of the drawbacks of slow steaming is that to be applied in periods of strong demand, the lower transportation capacities of a slow steaming fleet would have to be offset by additional vessels, ship and engine modifications, higher inventory costs, monitoring costs, and additional administrative costs related to the adjustment of logistical chains to compensate for the longer travel times between ports.[86] In our slow steaming analyses we do not attempt to account for the additional costs and emissions necessitated by such a larger fleet. Notwithstanding these limitations, it is accepted that the overall emissions would still be lower with a slow steaming fleet given the exponential relationship between

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80 Bouman, E., Lindstad, E., Rialland, A., and Stromman, A. (2017) "State-of-the-Art Technologies, Measures, and Potential for Reducing GHG Emissions from Shipping? A Review." Transportation Research Part D*: Transport and Environment*, 52(A): 408-421.
81 Eide, Chryssakis, and Endresen, "CO_2 Abatement Potential towards 2050 for Shipping, Including Alternative Fuels."
82 Faber et al., "Regulated Slow Steaming in Maritime Transport: An Assessment of Options, Costs and Benefits Report."
83 Ibid.
84 Faber et al., "Regulated Slow Steaming in Maritime Transport: An Assessment of Options, Costs and Benefits Report."
85 Dinwoodie, "Moments, Motivation, Slow Steaming and Shipping's Carbon Emissions."
86 Ibid.

fuel consumption and elevated operational speeds.[87]

Fuel Switching

Natural gas fuel used in the form of LNG has seen an increase in consideration in recent years, accompanying the drop of world gas prices caused in large part by the rise of shale gas developments in the United States.[88] Despite these developments, LNG as a maritime fuel remains very marginal, mostly due to the low volume/energy ratio, thus necessitating lager fuel tanks to service the same routes.[89] This constitutes the main limitation to the expansion of LNG, given that many fleet operators prioritise cargo capacities over fuel cost.[90] Biofuels offer the advantage of having similar properties in terms of energy content and volume, thus eliminating the need for extensive retrofit investments, while at the same time offering higher GHG emissions reduction potential than LNG.[91] LNG is therefore considered as being the least favourable option in terms of retrofits, given the high associated upgrade costs and the wide availability of low-sulphur fuel options, originally one of the main drivers justifying the fuel switch.[92] Henceforth LNG-retrofits were not considered as a practicable solution.[93]

Biodiesel is considered the biofuel most suited to replace regular maritime fuels as it can be used in existing motor technologies without any or with very few modifications.[94] The most relevant biodiesel type is Fatty Acid Methyl Esters (FAME), usually produced from varieties of vegetable oils (e.g. soy, rapeseed, sunflower or palm).[95] Biodiesel production is increasing at high rates and is becoming widely available, despite the criticism that this growth, stemming from monoculture-based agricultural practices or deforestation, occurs at the expense of the biodiversity.[96] Since regular, untreated biodiesel still contains organic matter and water at higher levels than regular oil-based fuels, technical problems, such as instability of on-board stored fuel, corrosion, and bio-fouling, might lead to more rapid depreciation of ship engines and increased maintenance needs.[97] Nonetheless, previous test runs indicated that even pure biodiesel (B100) could act as a substitute to IFO380 without any or with minor technical adaptations to ship engines.

However, empirical data and overall experiences with biodiesel-heavy blend ratios are scarce and the effects of higher blend ratios have not been researched enough to guarantee a safe use in non-adapted engines. As a result, the International Standard Organisation (ISO) only allows a maximum B7 blend ratio in their latest iteration of the ISO8217 standard for maritime fuels (ISO8217-2017).[98] Notwithstanding their still limited application in the maritime sector, the B5 (predominant blend ratio in the US) and B7 (predominant blend ratio in the EU) have reached high market penetration rates.[99,100,101,102] In this study B7 was used in favour of B5 in terms of calculation due to the availability of specific EU literature with regards to this maritime fuel sector.[103] Furthermore, in assuming blend ratios of B5 as well as B100, the spectrum for both operational compatibility and maximum emissions reduction is covered.[104,105] Due to the lower energy content of

[87] Ibid.
[88] IMO, "Studies on the Feasibility and Use of LNG as a Fuel for Shipping."
[89] Ibid.
[90] Ibid.
[91] Sames, Clausen, and Andersen, "Costs and Benefits of LNG as Ship Fuel for Container Vessels."
[92] "Cost and Benefits for Ship Owners , WPCI."
[93] DNV-GL, "LNG as Ship Fuel - The Future - Today."
[94] IRENA. (2015). "Renewable Energy Options for Shipping".
[95] EcoFys (2012) "Potential of Biofuels for Shipping,"
[96] Ibid.
[97] IRENA. (2015). "Renewable Energy Options for Shipping".
[98] "ISO 8217:2017(en), Petroleum Products — Fuels (Class F) — Specifications of Marine Fuels."
[99] Department of Energy (US), "Alternative Fuels Data Center: Biodiesel Blends."
[100] European Environment Agency, "EU Fuel Quality Monitoring — 2015."
[101] Department of Energy (US), "Alternative Fuels Data Center: Biodiesel Blends."
[102] European Commission, "Report from the Commission to the European Parliament and the Council in Accordance with Article 9 of Directive 98/70/EC Relating to the Quality of Petrol and Diesel Fuels."
[103] Ibid.
[104] Department of Energy (US), "Alternative Fuels Data Center: Biodiesel Blends."
[105] EcoFys (2012) "Potential of Biofuels for Shipping."

biodiesel, slightly more fuel will be required to cover the same distance. More precisely, the equivalent mass needed to achieve a similar energy output compared with regular oil amounts to 116%.[106]

CCCE by major country

Figure 19: Shipping CCCEs by Status and Major Country (t CO2)

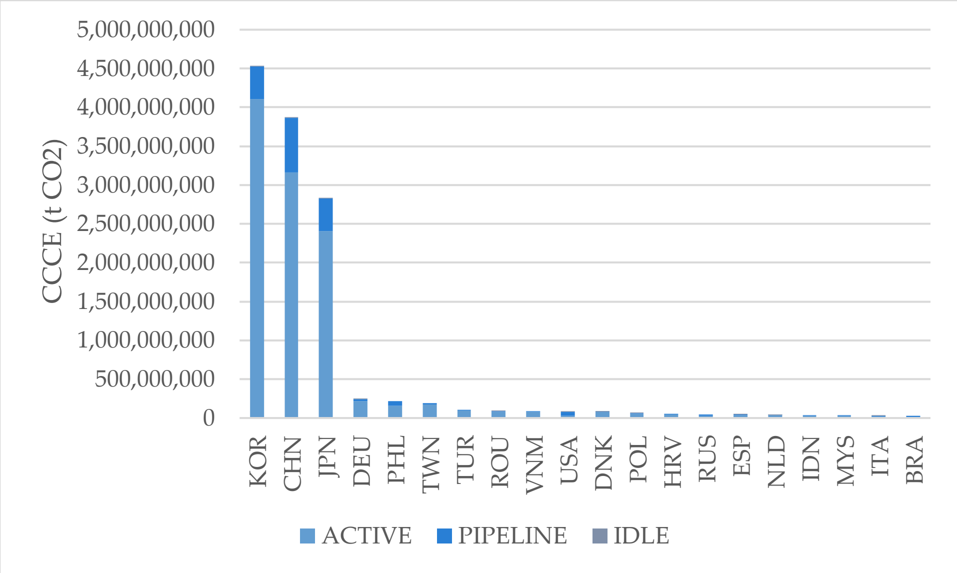

Table 12: Shipping CCCEs by Status and Major Country (t CO2)

	ACTIVE	PIPELINE	IDLE	Grand Total
KOR	4,108,085,117	418,356,561	2,910,300	4,529,351,978
CHN	3,163,117,576	704,952,304	1,014,130	3,869,084,010
JPN	2,409,520,947	421,041,702	1,340,727	2,831,903,377
DEU	220,551,130	20,977,187	557,248	242,085,566
PHL	159,164,915	60,451,110	0	219,616,026
TWN	178,471,453	15,787,140	0	194,258,593
TUR	95,882,812	7,529,561	0	103,412,373
ROU	83,832,273	8,801,420	239,256	92,872,949
VNM	76,542,838	12,096,427	0	88,639,265
USA	32,049,707	48,127,644	1,202,445	81,379,796
DNK	76,803,413	1,201,326	2,920	78,007,660
POL	58,334,975	3,791,407	410,862	62,537,244
HRV	44,679,285	5,537,467	0	50,216,752
RUS	32,332,300	11,652,076	0	43,984,377
ESP	39,280,929	3,760,370	356,970	43,398,269
NLD	36,576,729	4,233,136	10,162	40,820,027
IDN	28,987,761	7,352,640	0	36,340,401
MYS	33,186,749	1,434,813	0	34,621,562

[106] EcoFys (2012) "Potential of Biofuels for Shipping."

ITA	21,828,338	3,538,202	28,927	25,395,467
BRA	13,232,969	11,679,213	0	24,912,181
World	**11,033,792,022**	**1,817,153,572**	**8,598,679**	**12,859,544,272**

Database summary of the six industries

Figures 19 and 20 and Tables 13 and 14 below aggregate the above CCCE results across the six industries (ex cement) by status and national location.

CCCE by major country

Figure 20: All Industry (ex cement) CCCEs by Status (t CO2)

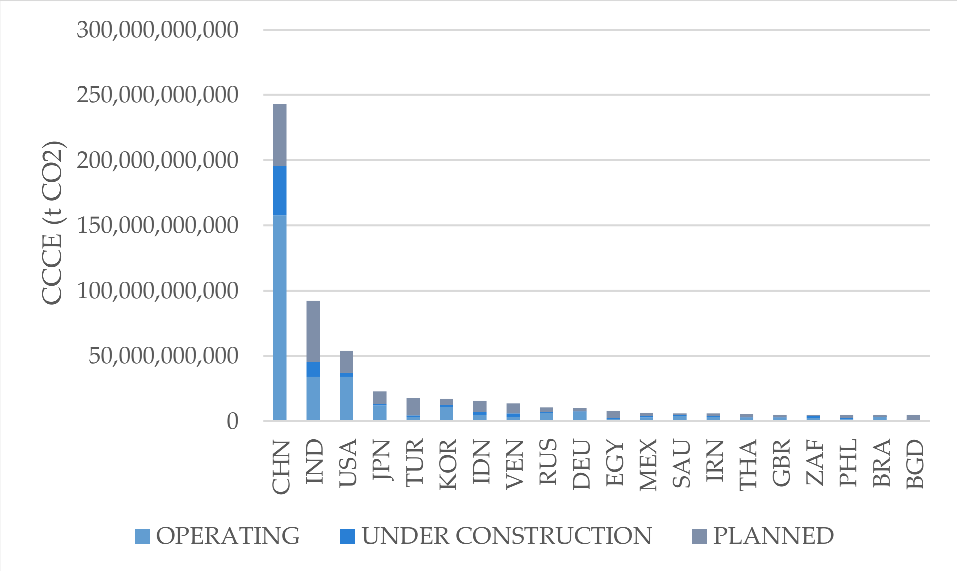

Table 13: All Industry (ex cement) CCCEs by Status (t CO2)

	OPERATING	UNDER CONSTRUCTION	PLANNED	Grand Total
CHN	157,923,204,939	37,867,986,890	47,185,389,607	242,976,581,435
IND	34,177,949,950	11,211,420,753	46,767,057,881	92,156,428,584
USA	33,899,256,262	3,149,111,463	16,911,714,960	53,960,082,685
JPN	11,890,648,477	1,169,364,364	9,727,153,877	22,787,166,718
TUR	3,512,269,008	858,338,972	13,413,471,022	17,784,079,002
KOR	11,224,926,398	1,448,313,357	4,481,814,544	17,155,054,299
IDN	5,170,233,411	1,635,403,138	8,809,742,580	15,615,379,129
VEN	3,306,101,907	2,755,939,420	7,498,747,774	13,560,789,101
RUS	6,368,981,957	738,260,185	3,439,557,183	10,546,799,325
DEU	7,154,527,597	228,981,376	2,607,385,173	9,990,894,147
EGY	1,835,982,857	636,652,972	5,553,721,535	8,026,357,365
MEX	3,130,559,046	534,615,098	2,978,746,784	6,643,920,928
SAU	3,809,293,291	1,268,976,788	825,783,309	5,904,053,387
IRN	3,291,985,934	686,879,265	1,854,429,559	5,833,294,759

THA	2,565,385,168	295,187,750	2,500,996,545	5,361,569,463
GBR	2,590,757,343	53,105,337	2,445,842,749	5,089,705,429
ZAF	2,379,971,290	1,280,244,374	1,336,905,041	4,997,120,705
PHL	1,332,500,740	951,559,337	2,640,334,429	4,924,394,506
BRA	3,259,079,979	279,449,957	1,345,821,805	4,884,351,741
BGD	640,776,756	286,534,942	3,835,273,608	4,762,585,306
World	**345,160,608,855**	**77,718650,539**	**221,790,570,084**	**645,537,529,742**

Figure 21: CCCEs by Major Country and Industry (t CO2)

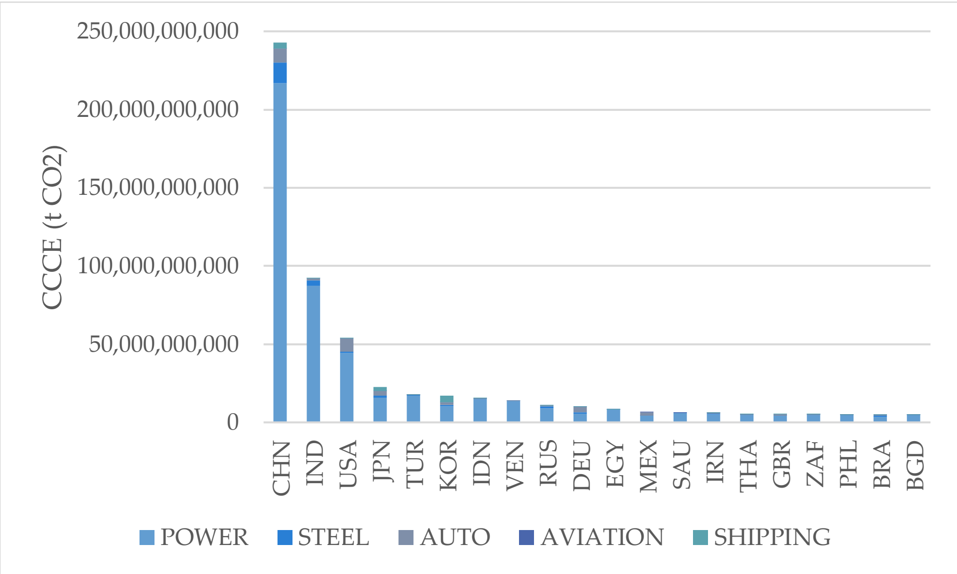

Table 14: All Industry (ex cement) Operating, Under Construction, and Planned Assets' CCCEs by Major Country (t CO2)

	POWER	STEEL	AUTO	AVIATION	SHIPPING	Grand Total
CHN	216,746,163,247	13,120,404,283	9,207,369,596	34,574,428	3,869,084,010	242,976,581,435
IND	87,538,868,177	3,408,795,347	1,182,407,177	4,757,462	21,600,421	92,156,428,584
USA	44,492,761,558	527,386,859	8,823,768,475	35,988,443	80,177,351	53,960,082,685
JPN	15,655,012,017	1,275,701,100	3,015,230,127	10,660,825	2,830,562,650	22,787,166,718
TUR	17,078,378,671	228,640,447	366,296,163	7,351,348	103,412,373	17,784,079,002
KOR	10,349,007,267	776,652,393	1,494,167,831	8,785,130	4,526,441,678	17,155,054,299
IDN	14,937,707,552	171,271,138	465,371,514	4,688,524	36,340,401	15,615,379,129
VEN	13,483,775,318	56,133,737	20,809,417	70,628	0	13,560,789,101
RUS	8,904,838,312	1,168,093,941	422,953,483	6,929,212	43,984,377	10,546,799,325
DEU	5,519,630,164	723,960,205	3,496,838,001	8,937,459	241,528,317	9,990,894,147
EGY	7,944,933,059	77,412,264	0	912,492	3,099,550	8,026,357,365
MEX	4,306,520,972	121,957,159	2,213,168,798	2,241,625	32,375	6,643,920,928
SAU	5,866,001,097	34,460,124	0	3,592,166	0	5,904,053,387
IRN	5,255,499,531	270,906,984	293,655,499	157,737	13,075,008	5,833,294,759
THA	4,566,765,783	20,694,651	768,581,115	4,617,916	909,998	5,361,569,463
GBR	4,163,153,462	136,089,198	774,768,625	10,490,845	5,203,299	5,089,705,429
ZAF	4,656,567,292	101,527,552	237,975,938	885,363	164,561	4,997,120,705
PHL	4,654,306,713	8,126,239	40,080,489	2,265,039	219,616,026	4,924,394,506
BRA	3,513,608,123	838,636,506	503,305,002	3,889,928	24,912,181	4,884,351,741
BGD	4,746,803,712	2,902,250	0	333,693	12,545,651	4,762,585,306
World	**566,485,176,156**	**27,002,516,235**	**38,929,170,409**	**261,122,669**	**12,859,544,273**	**645,537,529,742**

In terms of national geographies, Table 13 above shows that China, India, and the US combined account for over 60% of the 646 GtCO2 expected to be emitted from existing and pipelined assets. Table 15 below depicts the sum of the worldwide CCCE estimates for each of the industries studied (ex cement). This exercise shows that the power industry dominates committed emissions: it is responsible for almost 90% of the 646 billion tons of committed CO_2 emissions attributable to the five industries. The proportion of emissions attributable to the power industry is also expected to increase as 85% (293.9bt/345.2bt) of the CCCEs of active assets arise from power, compared to 90% (272.5bt/299.5bt) of pipelined CCCEs. In addition, it is shown that there is close to an equal split between the committed emissions attributable to currently active assets (53%) and those in the planning pipeline (47%).

Table 15: World All Industry (ex cement) CCCEs by Status (t CO_2CO2)

	ACTIVE	**PIPELINE**	**IDLE**	**Grand Total**	*Proportion*
Power	293,947,143,177	272,538,032,979		**566,485,176,156**	*87.75%*
Steel & Iron	23,781,779,731	2,361,634,920	859,101,584	**27,002,516,235**	*4.18%*
Automobiles	16,136,771,256	22,792,399,153		**38,929,170,409**	*6.03%*
Airlines	261,122,669			**261,122,669**	*0.04%*
Shipping	11,033,792,022	1,817,153,572	8,598,679	**12,859,544,273**	*1.99%*
Total	**345,160,608,855**	**299,509,220,624**	**867,700,263**	**645,537,529,742**	*100.00%*
Proportion	*53.47%*	*46.40%*	*0.13%*	*100.00%*	

The total CCCEs expected to be emitted from both existing and pipelined assets compare unfavourably with common emissions targets. For instance, in order for the climate to have an equal chance of warming less than 2°C, the CO_2 budget for power as of mid-2016 (commensurate with our data) is approximately 300 GtCO2.[107] However, in Table 6 we show that the power industry alone is slated to register nearly double the required CCCEs to achieve this level of warming (566 GtCO2). Combining committed emissions from Steel, Automobiles, Aviation, and Shipping for existing and pipelined assets yields 646 GtCO2 (Table 13). Indeed, this level of emissions is commensurate with estimations for temperature rises exceeding 3°C.[108] It is therefore clear that if the 2°C carbon budget is to be maintained then deep carbon emission cuts will have to be made, either in the form of premature asset retirement or through asset retrofits which reduce carbon emissions.

[107] The calculation is derived from 1,100 GtCO2 total CO_2 budget and 15% as share attributable to power taken from; Pfeiffer, A., Millar, R., Hepburn, C., Beinhocker, E. (2016). "The '2°C capital stock' for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy." *Applied Energy*, 179: 1395-1408.
[108] Ibid.

RCCCE by major country

The specific RCCCE technologies applied to each industry and the research source of each are listed below in Table 16 and divided into their three representative categories: Substituting Inputs, Efficiency Upgrade, and CCS Retrofit.

Table 16: RCCCE Technology Matrix and Sources by Industry and Category

	Substituting Inputs	**Efficiency Upgrade**	**CCS Retrofit**
Power	-Coal to Biomass (Direct/Parallel Co-firing)[109] -Lignite to Coal[110] -Gas to Biogas[111]	-Subcritical to Advanced Supercritical[112]	-Geologic CCS[113,114]
Steel & Iron	-Injection of Coal to Natural Gas[115]	-Blast Furnace to Electric Arc Furnace[116,117] -Top Gas Expansion Turbine[118] -Converter Gas Recovery[119] -Electric Arc Furnace Bottom Stirring[120] -Oxy-fuel Burners/Lancing[121] -Post-combustion Shaft Furnace[122] -Eccentric Bottom Tapping (ECB)[123] -Electric Arc Furnace Raw Material Preheating Device[124] -Convert Electric Arc Furnace from AC to DC[125] -Continuous Charging and Scrap Preheating[126]	-Geologic CCS[133] -Oxyfueling and Chemical Sequestration[134] -CCS with DRI[135]

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[126] Ibid.

		-Thin Slab Casting[127] -Dry-Quenching[128] -Coke Stabilisation Quenching[129] -Biochar as Reducing Agent[130] -Grate-kiln Pelletising Production[131] -Non-Recovery Coke Ovens[132]	
Cement	-Blended Cements[136]	-Wet to Dry Process Kiln Retrofit[137]	-Geologic CCS[138] -Oxy-combustion CCS[139] -Post-combustion CCS[140]
Automotive	-10% |25% Petrol/Diesel to Ethanol[141] -Petrol to LPG[142] -Diesel to Biodiesel[143] -Petrol/Diesel to Hybrid-Electric[144] -Petrol/Diesel to Plug-in Hybrid-Electric (PHEV)[145] -Petrol/Diesel to Electric Vehicle Conversion[146]		
Aviation	-Jet Fuel to Biofuels (HEFA,FT)[147]		
Shipping	-Heavy Fuel Oil to Biofuels (B5,B100)[148,149] -10% Service Speed Reduction[150]		

133 IEA (2008) CO_2 Capture and Storage: A key carbon abatement option
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Table 17 below shows the CCCEs for all industries by major country after technically maximum RCCCEs are applied as well as their costs. As many of these carbon-reducing technologies are mutually exclusive, we cannot apply all applicable technologies to each asset, but instead must choose feasible combinations. For demonstration purposes, we calculate the combination of CCCEs and costs which would result if the maximum technically feasible extent of RCCCE technologies were applied to each asset, and aggregate these within major emitting nations. We see from Table 17 that by applying technically maximum feasible RCCCEs to our databases we would reduce global CCCEs across the six industries from 646 GtCO2 (Table 13) to 504 GtCO2 (Table 17): a reduction of 22%, which would cost $84 trillion.

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Table 17: All Industry CCCEs after Technically Maximum RCCCEs are applied and RCCCE Costs by Major Country (tCO2)

	Power†	Steel & Iron‡	Cement	Auto†	Airlines	Shipping	Total tCO2	Cost (2016 US$)
CHN	158,566,107,664	8,788,029,228	N/A	0	17,287,214	0	**167,371,424,106**	**21,807,538,517,172**
IND	70,120,768,128	2,929,851,769	N/A	0	2,378,731	0	**73,052,998,628**	**3,782,570,947,098**
USA	41,902,048,950	73,705,111	N/A	0	17,994,222	0	**41,993,748,283**	**10,773,416,058,198**
JPN	13,126,918,248	1,205,207,723	N/A	0	5,330,413	0	**14,337,456,384**	**8,645,181,320,441**
TUR	14,772,642,922	205,643,022	N/A	0	3,675,674	0	**14,981,961,618**	**1,059,446,867,881**
KOR	9,161,878,142	735,966,198	N/A	0	4,392,565	0	**9,902,236,905**	**4,910,431,196,520**
IDN	12,354,795,054	142,598,470	N/A	0	2,344,262	0	**12,499,737,786**	**1,063,260,708,417**
VEN	11,606,807,110	50,689,534	N/A	0	35,314	0	**11,657,531,958**	**76,407,824,395**
RUS	8,222,442,634	1,110,480,545	N/A	0	3,464,606	0	**9,336,387,785**	**1,310,702,672,783**
DEU	4,837,234,486	292,787,056	N/A	0	4,468,730	0	**5,134,490,272**	**5,667,226,624,119**
EGY	7,447,705,032	70,452,135	N/A	0	456,246	0	**7,518,613,413**	**8,408,779,437**
MEX	4,147,342,776	105,923,852	N/A	0	1,120,813	0	**4,254,387,441**	**2,956,475,799,499**
SAU	5,866,001,097	5,834,817	N/A	0	1,796,083	0	**5,873,631,997**	**5,132,418,789**
IRN	5,175,372,451	222,790,009	N/A	0	78,869	0	**5,398,241,329**	**1,145,718,838,655**
THA	4,260,375,399	15,482,912	N/A	0	2,308,958	0	**4,278,167,269**	**1,680,485,560,731**
GBR	4,065,372,105	72,600,246	N/A	0	5,245,423	0	**4,143,217,774**	**1,582,368,689,031**
ZAF	3,385,776,691	96,056,714	N/A	0	442,682	0	**3,482,276,087**	**570,622,518,028**
PHL	4,008,410,674	6,669,591	N/A	0	1,132,520	0	**4,016,212,785**	**149,427,168,373**
BRA	3,321,245,332	781,832,137	N/A	0	1,944,964	0	**4,105,022,433**	**2,104,619,432,524**
BGD	2,924,472,563	139,614	N/A	0	6,272,826	0	**2,930,885,003**	**100,802,264,720**
World GtCO2	**483,729,152,411**	**20,158,135,990**	**N/A**	**0**	**134,561,334**	**0**	**504,021,849,735**	**N/A**
World Cost	**3,393,522,232,298**	**670,136,966,315**	**N/A**	**76,398,190,924,967**	**121,912,568,924**	**3,385,918,006,885**	**N/A**	**83,969,680,699,389**

† Excludes biomass use, as this solution is trivial and impractical at scale for Power and Auto
‡ Excludes Blast Furnace to Electric Arc Furnace (EAF) conversion as EAF is practically limited by the availability of recycled steel

Table 18 below presents each of the RCCCEs, their total CO_2 reductions, and total costs; arranged in ascending order with respect to the abatement cost (2016 US$/tCO2). We see that the first RCCCE (Injection of Coal to Natural Gas) actually represents a cost saving and therefore displays a negative value. All other identified RCCCEs abatement costs are positive and vary from $6 to $46,737tCO2.

Table 18: RCCCE Abatement Cost Curve Data

Sector	Technology	Code	Total RCCCE reduction (tCO2)	Total cost (2016 US$)	Abatement cost (2016 US$/tCO2)
STEEL	Injection of Coal to Natural Gas	steel_4	644,842,046	-29,513,461,875	-46
STEEL	EAF Bottom Stirring	steel_15	132,787,983	781,028,163	6
STEEL	Post-Combustion Shaft Furnace	steel_17	451,666,867	3,665,389,478	8
STEEL	Convert EAF from Alternating Current (AC) to Direct Current (DC)	steel_20	607,030,780	5,084,340,199	8
STEEL	Oxy-Fuel Burners/Lancing	steel_16	265,575,966	2,932,311,583	11
POWER	Lignite to Coal	power_7	4,790,230,557	53,002,325,818	11
POWER	Subcritical to Advanced Supercritical	power_6	62,629,340,977	703,645,270,598	11
STEEL	Continuous Charging and Scrap Pre-Heating	steel_6	417,333,661	6,493,253,748	16
SHIPPING	HFO to Biodiesel B100	shipping_2	213,304,378,897	3,922,161,003,039	18
STEEL	Blast Furnace (BOF) to Electric Arc Furnace	steel_5			20

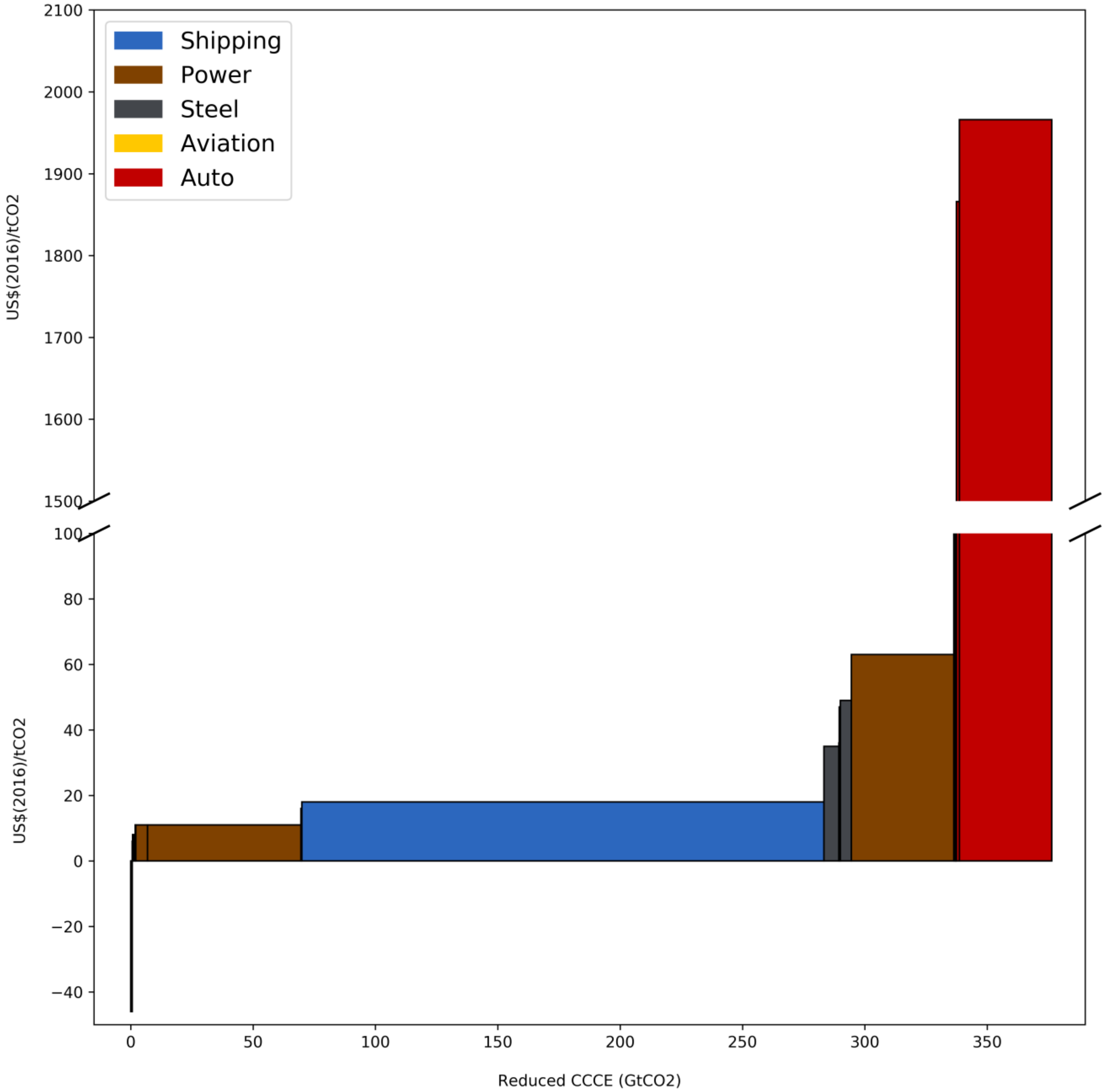
	(EAF)		16,077,950,217	321,347,347,765	
CEMENT	Oxy-Combustion	cement_1	274,514,168	5,811,883,201	21
POWER	Gas to Biogas	power_9	80,141,245,142	2,113,523,322,902	26
STEEL	Geologic CCS	steel_2	6,100,542,737	211,877,064,612	35
STEEL	Electric Furnace Raw Material Pre-Heating Device	steel_19	187,800,147	6,732,003,809	36
POWER	Coal to Biomass	power_10	391,433,381,108	15,368,164,789,115	39
POWER	Lignite to Biomass	power_8	30,415,078,354	1,287,866,146,049	42
STEEL	Grate-Kiln Pelletising Production	steel_11	429,014,446	20,283,495,120	47
STEEL	Biochar as Reducing Agent	steel_10	4,486,879,084	222,013,809,446	49
CEMENT	Chemical Adsorption	cement_3	363,939,238	20,138,383,299	55
CEMENT	Geologic CCS	cement_2	386,815,419	23,174,884,264	60
POWER	Geologic CCS	power_1	41,878,517,889	2,636,874,635,882	63
POWER	Coal IGCC Selexol	power_3	191,239,414	12,189,497,175	64
POWER	Coal Steam Cycle CA Oxyfueling	power_2	202,488,792	12,920,711,409	64

AUTO	Diesel to 10% Ethanol	auto_7	3,772,144,868	255,385,521,738	68
POWER	Gas CC Oxyfueling	power_5	5,141,459,862	352,846,072,253	69
CEMENT	Blended Cements	cement_4	388,216,819	27,596,107,028	71
POWER	Gas CC CA	power_4	4,600,253,561	335,777,701,491	73
AUTO	Petrol to 10% Ethanol	auto_1	120,596,128	9,137,331,934	76
STEEL	Converter Gas Recovery	steel_14	510,859,227	51,344,011,973	101
POWER	Coal to 20% Biomass (parallel co-firing via separate boiler used for biomass and steam generation)	power_12	78,286,676,222	9,443,159,598,449	121
STEEL	CCS with DRI	steel_3	624,267,978	75,375,924,019	121
AUTO	Diesel to 25% Ethanol	auto_8	9,430,362,169	1,231,641,609,542	131
AUTO	Petrol to 25% Ethanol	auto_2	301,490,321	40,842,834,529	135
AUTO	Diesel to Biodiesel	auto_9	37,721,448,676	7,661,565,652,154	203
STEEL	Eccentric Bottom Tapping (ECB)	steel_18	94,848,559	23,373,394,970	246
SHIPPING	HFO to Biodiesel B5	shipping_1	10,955,251,664	3,385,918,006,885	309
STEEL	Thin Slab Casting	steel_7			327

			274,871,125	89,772,295,920	
POWER	Coal to 5% Biomass (direct co-firing using a single boiler with either common or separate burners)	power_11	19,571,669,055	8,332,221,125,199	426
STEEL	Dry-Quenching	steel_8	95,130,776	55,298,029,169	581
AUTO	Petrol to Hybrid-Electric Conversion	auto_4	361,788,385	249,996,482,002	691
AUTO	Petrol to LPG	auto_3	132,655,741	94,631,764,640	713
AUTO	Diesel to Hybrid-Electric Conversion	auto_10	11,316,434,603	8,238,691,398,550	728
AVIATION	50% of HEFA fuel and 50% of Conventional Oil	aviation_1	134,561,334	121,912,568,924	906
AUTO	Petrol to Plug-in Hybrid-Electric (PHEV) Conversion	auto_5	874,321,930	1,007,860,817,190	1,153
AUTO	Diesel to Plug-in Hybrid-Electric (PHEV) Conversion	auto_11	27,348,050,290	33,214,284,373,255	1,215
AVIATION	50% of FT fuel and 50% of Conventional Oil	aviation_2	134,561,334	169,278,158,617	1,258
AUTO	Petrol to Electric Vehicle Conversion	auto_6	1,205,961,283	2,249,968,338,016	1,866
AUTO	Diesel to Electric Vehicle Conversion	auto_12	37,721,448,676	74,148,222,586,951	1,966
STEEL	Coke Stabilisation Quenching (CSQ)	steel_9	34,593	1,616,765,797	46,737

Figure 22 below graphically displays the RCCCE cost data above in a Marginal Abatement Cost Curve, from lowest to highest cost. This cost curve allows us to identify the most economically efficient carbon technologies. This figure shows that the primary sources of emissions reductions from this exercise are from the RCCCEs; Power_6 (Subcritical to Advanced Supercritical), Shipping_2 (HFO to Biodiesel B100), Power_1 (Geologic CCS), and Auto_12 (Diesel Electric Vehicle Conversion).

Figure 22: RCCCE Marginal Abatement Cost Curve (2016 US$/tCO2)



Conclusion

This paper outlines the potential benefits and users of asset-level data and details the construction of a demonstrator asset-level database: the Assets@Risk database. This database aggregates asset-level data across the globe for the major carbon emitting industries: Power, Steel & Iron, Cement, Automobile, Airlines, and Shipping industries, and applies robust peer-reviewed methodologies for the construction of Cumulative Committed Carbon Emissions (CCCEs) and technologies for Reducing Cumulative Committed Carbon Emissions (RCCCEs) to each individual asset. Furthermore, each industry database comprises sufficient assets to account for at least two-thirds of total global emissions within its industry. This combined database uniquely allows for the granular estimation of global climate related risks and the potential for their mitigation.

As a preliminary demonstration of the capabilities of this database, we report the Cumulative Committed Carbon Emissions (CCCEs) for each asset, and aggregate these across major emitting nations and asset status. According to the results presented in Table 14, the power industry dominates committed emissions, accounting for 88% of the 646 billion tons of committed CO_2 emissions attributable to the five industries. The Steel & Iron and Automobile industries comprise another 10% of emissions covered, and Airlines and Shipping have minor contributions.[151] The proportion of emissions attributable to the power industry is also expected to increase as 85% (293.9bt/345.2bt) of the CCCEs of active assets arise from power, compared to 90% (272.5bt/299.5bt) of pipelined CCCEs. Furthermore, across the five industries it is shown that there is roughly an equal split between the committed emissions attributable to currently active assets (53%) and those in the planning pipeline (47%). In terms of national geographies, Table 13 shows that China, India, and the US combined account for over 60% of the 646 GtCO2 expected to be emitted from existing and pipelined assets.

The total CCCEs expected to be emitted from both existing and pipelined assets compare unfavourably with common emissions targets. For instance, in order for the climate to have an equal chance of warming less than 2°C, the CO_2 budget for power as of mid-2016 (commensurate with our data) is approximately 300 GtCO2.[152] However, in Table 6 we show that the power industry alone is slated to register nearly double the required CCCEs to achieve this level of warming (566 GtCO2). Combining committed emissions from Steel, Automobiles, Aviation, and Shipping for existing and pipelined assets yields 646 GtCO2 (Table 13). Indeed, this level of emissions is commensurate with estimations for temperature rises exceeding 3°C.[153] It is therefore clear that if the 2°C carbon budget is to be maintained then deep carbon emission cuts will have to be made, either in the form of premature asset retirement or through asset retrofits which reduce carbon emissions.

In order to investigate the viability of retrofitting assets in order to reduce carbon emissions, this report also compiles carbon reducing technologies (RCCCEs) from the existing climate-related literature and applies these to individual assets across the six industries according to applicable asset-specific characteristics. As many of these carbon-reducing technologies are mutually exclusive, we cannot apply all applicable technologies to each asset, but instead must choose feasible combinations. For demonstration purposes, we calculate the combination of CCCEs and costs which would result if the maximum technically feasible extent of RCCCE technologies were applied to each asset, and aggregate these within major emitting nations. We see from Table 17 that by applying technically maximum feasible RCCCEs to our databases we would reduce global CCCEs across the six industries from 646 GtCO2 (Table 13) to 504 GtCO2 (Table 17): a reduction of 22%, which would cost $84 trillion. This amounts to 107% of current global GDP ($78.28 trillion[154]). However, 91% of this cost arises from converting

[151] Cement is thought to generate about 5% of global emissions[151], due to data limitations we were not able to estimate its CCCEs or RCCCEs.
[152] The calculation is derived from 1,100 GtCO2 total CO2 budget and 15% as share attributable to power taken from; Pfeiffer, A., Millar, R., Hepburn, C., Beinhocker, E. (2016). "The '2°C capital stock' for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy." *Applied Energy*, 179: 1395-1408.
[153] Ibid.
[154] CIA. (2014). *World Factbook*.

fuel-burning automobiles to fully electric drive-trains and would reduce emissions by only 39 GtCO2. By contrast, power and shipping RCCCE costs both account for just 4% ($3.39 trillion) of the total, but their technically feasible RCCCEs would lower emissions by 82 and 13 GtCO2, respectively.

This wide variation in costs is depicted in the RCCCE Marginal Abatement Cost curve in Figure 22, comprising only the combination of technically maximum RCCCEs. This figure shows that the primary sources of emissions reductions from this exercise are from the RCCCEs: Power_6 (Subcritical to Advanced Supercritical), Shipping_2 (HFO to Biodiesel B100), Power_1 (Geologic CCS), and Auto_12 (Diesel Electric Vehicle Conversion). It should be borne in mind that these estimations do not necessarily represent the actual extent and costs of feasible carbon emissions reducing technologies, rather they express only the emissions reduction potential which, given our data on individual asset characteristics, we are certain can be applied to each individual asset in our database. Therefore, the technically maximum RCCCEs we report represent a *minimum* level of possible carbon reductions. Although we do not analyse either CCCEs and RCCCEs at the company level, our data allows for this future extension.

Physical environmental change and societal responses to environmental change, particularly climate change and the transition to a net zero emissions economic system, create diverse and significant risks for the global economic system. A key barrier to responding to these challenges is the lack of asset-level data, which prevents market actors from appropriately understanding environmental risks, returns, and potential impacts. In response, we have developed the Assets at Risk Database (Assets@Risk), which synthesises asset-level data globally across six major carbon-emitting industries (Power, Cement, Steel and Iron, Automobiles, Airlines, Shipping). This paper has demonstrated only a fraction of the potential capabilities of asset-level data, but it is hoped that a case has been made for the potential of asset-level data to meet now deferred emissions goals and more effectively respond to economic and climate uncertainty.

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Appendix

1.1 Airlines CCCE Estimation Regression Output

Table A1: Airlines CCCE Estimation Regression Output

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.9885459
R Square	0.977223
Adjusted R	0.977221
Standard E	0.1788773
Observatic	22692

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regressior	2	31147.50871	15573.75	486723.8	0
Residual	22689	725.9823442	0.031997		
Total	22691	31873.49105			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-7.497491	0.017642001	-424.98	0	-7.532070437	-7.462911375	-7.532070437	-7.462911375
ln(MTOW)	1.3556304	0.001420417	954.3891	0	1.352846262	1.358414491	1.352846262	1.358414491
Age	0.0036786	0.000129124	28.48874	2E-175	0.003425478	0.003931661	0.003425478	0.003931661

1.2 Emission Factor & Aircraft Retirement

We consider that conventional Jet A-1 has an emission factor of 3.15 $t\ CO_2/t\ fuel$.[155] Moreover, we associate an emission factor of 0 for biojet fuel as under the EU ETS.[156] For sake of transparency and tractability, we do not integrate the aircraft efficiency and maintenance, distance travelled, load carried (passengers and cargo), weather conditions, nor the altitude at which non-carbon dioxide (CO_2) is released[157,158]

Following the White Paper issued by Avolon (2015),[159] we consider an average retirement age for commercial jet aircrafts of 25.7 years. Given that 93.28% of our data falls within this category we extend this retirement standard to all aircrafts in our database, for sake of simplicity.

[155] Dutch Emissions Authority and UK Environment Agency, "Guidance for the Aviation Industry Monitoring and Reporting Annual Emissions and Tonne Km Data for EU Emissions Trading," 2009.
[156] Rosillo-calle, Teelucksingh, and Seiffert, "The Potential and Role of Biofuels in Commercial Air Transport - Biojetfuel."
[157] Non-carbon dioxide (CO_2) gases (e.g., water vapour and nitrogen oxides (NOx)) emitted at high altitude amplify global warming, but with an uncertain impact relative to the CO_2 emissions alone.
[158] IATA, "IATA Carbon Offset Program Frequently Asked Questions," 2015.
[159] Forsberg, D. (2015). "Aircraft Retirement and Storage Trends Economic Life Analysis Reprised and Expanded." *Avolon*.

1.3 Certification and Approved Blend Ratios

As intimated in the previous section, ASTM approved HEFA fuel under the alternative fuel specification D7566 'Standard Specification for Aviation Turbine Fuel Containing Synthesised Hydrocarbons'. [160] Under this specification, HEFA fuel can be blended with conventional jet fuel, up to a ratio of 50%.[161] HEFA is the dominant biofuel production process and a number of airlines (e.g. Aeroméxico, Air China, Air France, Finnair, Iberia, KLM, Lufthansa, and United) have already used HEFA fuel on commercial passenger flights with a blend of up to 50%.[162] Similarly, F–T fuel was certified by the ASTM D7566 standard in September 2009 for a 50% blend with Jet-A1 fuel.[163,164,165] This limit ensures the presence of 'aromatics' in the fuel which are critical for the 'integrity' of engine seals but which are missing in biofuels.[166] O.R. Tambo International Airport in Johannesburg is currently using a 50% blend of F–T synthetic fuel with conventional fuels in commercial aviation.[167]

1.4 Costs

The analysis of costs for biofuel is challenging as alternative jet fuels are produced in small amounts due to a low level of demand. Such amounts of production are justified by the high cost of production, knowing that 30% of the total airline operating cost come from fuel.[168] The cost of producing biofuel is much higher than the cost of producing fossil-derived jet fuel. The HEFA pathway, which is the only mature process, heavily depends on significant feedstock costs. For example, future soybean oil prices are forecast to range between $1.07 and $0.66 above the price of jet fuel.[169,170] Using oilseed crops grown in 'rotation with other crops on land that would otherwise be left fallow' may be a way to reduce the costs.[171,172] On the other hand, the F-T pathway suffers from small commercial volumes of biojet from biomass because of several challenges (e.g., syngas clean up, catalyst contamination, and economies of scale).[173]

For the purpose of this study we rely on the projections from IEA Bioenergy (2012)[174] for the year 2020 and use the following costs: 1,800 $€/t$ for F-T jet fuel based on forest wood, 1,300 $€/t$ for HEFA jet fuel based on palm

[160] Winchester, N., McConnachie, D., Wollersehim, C., and Waitz, I. (2013). "Economic and Emissions Impacts of Renewable Fuel Goals for Aviation in the US." *Transportation Research Part A: Policy and Practice*, 58: 116-128.
[161] Kousoulidou, M., and Lonza, L. (2016). "Biofuels in Aviation: Fuel Demand and CO_2 Emissions Evolution in Europe toward 2030." *Transportation Research Part D: Transport and Environment,* 58: 116-128.
[162] IATA (2012). "Annual Review 2012".
[163] Winchester, N., McConnachie, D., Wollersehim, C., and Waitz, I. (2013). "Economic and Emissions Impacts of Renewable Fuel Goals for Aviation in the US." *Transportation Research Part A: Policy and Practice*, 58: 116-128.
[164] Kousoulidou, M., and Lonza, L. (2016). "Biofuels in Aviation: Fuel Demand and CO_2 Emissions Evolution in Europe toward 2030." *Transportation Research Part D: Transport and Environment,* 58: 116-128.
[165] ASTM International (2016). "Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons." West Conshohocken, PA, ASTM D7566-16b.
[166] Corporan, E., et al. (2011). "Chemical, Thermal Stability, Seal Swell, and Emissions Studies of Alternative Jet Fuels," *Energ. Fuels*, no. 22: 955–66.
[167] Winchester, N., McConnachie, D., Wollersehim, C., and Waitz, I. (2013). "Economic and Emissions Impacts of Renewable Fuel Goals for Aviation in the US." *Transportation Research Part A: Policy and Practice*, 58: 116-128.
[168] IRENA (2017). "Biofuels for Aviation."
[169] EIA and US Department of Energy (2012). "Annual Energy Outlook 2012 with Projections to 2035."
[170] USDA and Interagency Agricultural Projections Committee, (2015). "USDA Agricultural Projections to 2021.".
[171] Shonnard, D., Williams, L., and Kalnes, T. (2010). "Camelina-Derived Jet Fuel and Diesel: Sustainable Advanced Biofuels," *Environmental Progress & Sustainable Energy* 29, no. 3: 382–92, doi:10.1002/ep.10461.
[172] Federal Register (2013). "Regulation of Fuels and Fuel Additives: Identification of Additional Qualifying Renewable Fuel Pathways Under the Renewable Fuel Standard Program."
[173] IRENA (2017). "Biofuels for Aviation."
[174] Rosillo-calle, Teelucksingh, and Seiffert, "The Potential and Role of Biofuels in Commercial Air Transport - Biojetfuel."

oil, and 739.2 €/t for conventional jet fuel. We also use an inflation rate of 2% as projected by the ECB over the medium term.[175]

[175] European Central Bank (2017). “Monetary Policy."

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