IRENA
International Renewable Energy Agency

STRANDED ASSETS AND RENEWABLES

How the energy transition affects the value of energy reserves, buildings and capital stock

WORKING PAPER
based on global REmap analysis

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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

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Disclaimer

CONTENTS

FIGURES

TABLES

BOXES

ABBREVIATIONS

°C	degrees Celsius
bln	billion
CCS	carbon capture and storage
CO_2	carbon dioxide
EU	European Union
GBPN	Global Buildings Performance Network
Gt	gigatonnes
GW	gigawatt
IRENA	International Renewable Energy Agency
m^2	square metres
mbd	million barrels per day
n. d.	no date
OECD	Organisation for Economic Co-operation and Development
PAYS	Pay As You Save
REmap	Renewable energy roadmap analysis by IRENA
trln	trillion
UK	United Kingdom
USD	United States Dollar
VaR	value at risk

EXECUTIVE SUMMARY

The objective of this working paper is to examine the potential magnitudes of asset stranding in the power generation, upstream, industry and building sectors (i. e. residential and commercial) in order to realise a decarbonisation of the global energy system in line with the Paris Agreement. Asset stranding results when assets have suffered from unanticipated or premature write-downs, devaluations or conversion to liabilities (Caldecott et al., 2013, p. 7). The idea of stranded assets, created by physical climate change impacts and the transition to a low carbon economy, has risen considerably on the agenda in recent years. The process of asset stranding and its implications are relevant to a wide range of investors, companies, policy makers and regulators.

The stranded asset analysis helps us to understand whether the scale of asset stranding will differ in the event that the policy action to achieve the Paris Agreement is delayed. The analysis contained in this report is part of a broader study, undertaken by the International Renewable Energy Agency (IRENA) and commissioned by the German government, the latter of which holds the 2017 G20 Presidency. Its intention is to inform the G20 Energy and Climate Working Groups (IEA & IRENA, 2017).

This working paper furthers existing analyses of stranded upstream fossil fuel assets and undertakes a new analysis of asset-stranding downstream, specifically in power generation, buildings and industry, three large sectors that are responsible for approximately three-quarters of today's direct global energy-related carbon dioxide (CO_2) emissions. Refined methodologies are applied to estimate the potential magnitudes of asset stranding in these three sectors, as well as the global upstream fossil fuel production sector by 2050. These stem from accelerated renewable energy and energy efficiency deployment when using IRENA's REmap analysis.[1] The REmap programme aims to assess technology options for and scenarios of accelerated renewable energy development in terms of technical and economic potentials through a series of activities, including global, regional and country studies. As of mid-2017 the REmap programme has expanded to 70 countries, accounting for 85% of world energy use.

Based on the REmap 2050 analysis, this working paper examines two cases. The first case relates to accelerated renewables and energy efficiency deployment from today until 2050 which will deliver emissions reductions that have a two-out-of-three chance of maintaining a global temperature change below two degrees Celsius (2°C) above pre-industrial levels (this case is called "REmap"). Under the REmap case, a carbon emission budget of 880 gigatonnes (Gt) CO_2 has been defined for the period 2015–50. This includes fossil fuel and other (e. g. land use, industrial process) emissions. This case assumes action will commence soon through new policy initiatives.

The second case assumes a business-as-usual scenario that continues until 2030 (represented by the Reference Case here). However, after 2030 the deployment of renewables and energy efficiency accelerates to ensure that the global energy system remains within the same emission budget by 2050 ("Delayed Policy Action"). Comparing these two cases provides an understanding of whether or not the scale of asset stranding will differ should policy action to achieve the objectives of the Paris Agreement be delayed.

The impact on stranded assets of Delayed Policy Action

The seriousness of early action is hard to overemphasise. With delayed action, the chance of having stranded assets will increase. The main objective of this paper, therefore, is to estimate the extent to which delayed policy action would impact stranded assets. Although beyond the scope of this paper, if action is delayed, total investment costs will rise and costly negative emission technologies will be required to limit planetary warming.

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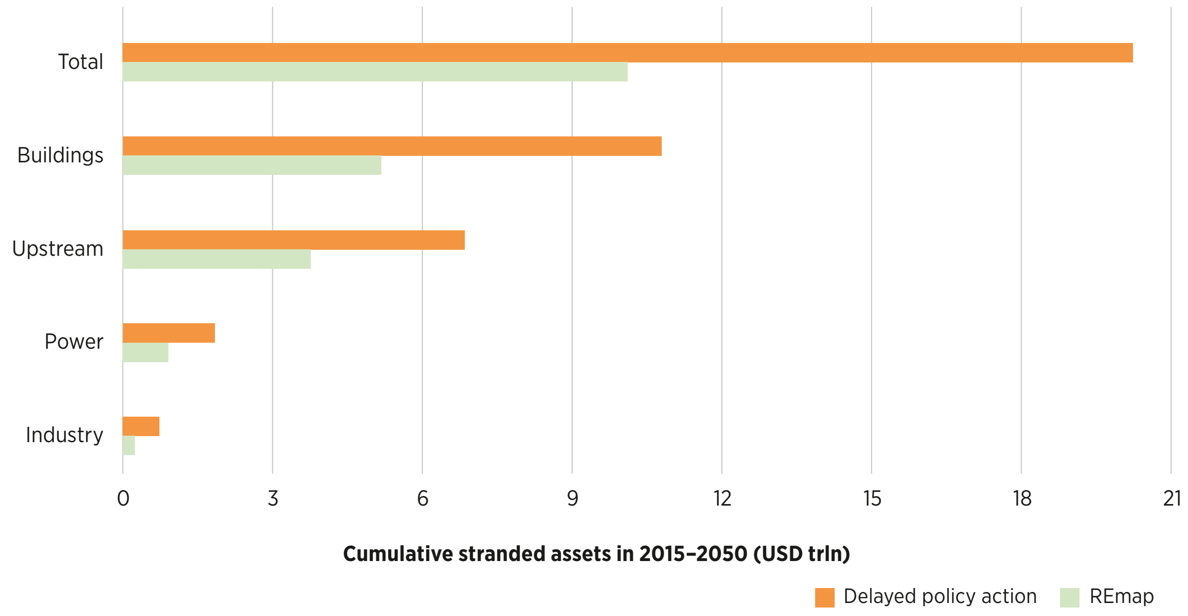
[1] Further details on IRENA's REmap analysis can be found at http://www.irena.org/remap/

Figure 1: Stranded assets by sector with REmap and Delayed Policy Action



Source: IRENA analysis

Delayed Policy Action would result in significant asset stranding in comparison to the REmap case, where accelerated deployment begins now. The total value of stranded assets across upstream energy, power generation, industry and buildings under Delayed Policy Action is found to double to USD 20 trillion (trln), compared to USD 10 trln in the REmap case (Figure 1). To put this into context, USD 20 trln is approximately 4% of global wealth in 2015 (estimated at USD 250 trln, according to Credit Suisse, 2015).

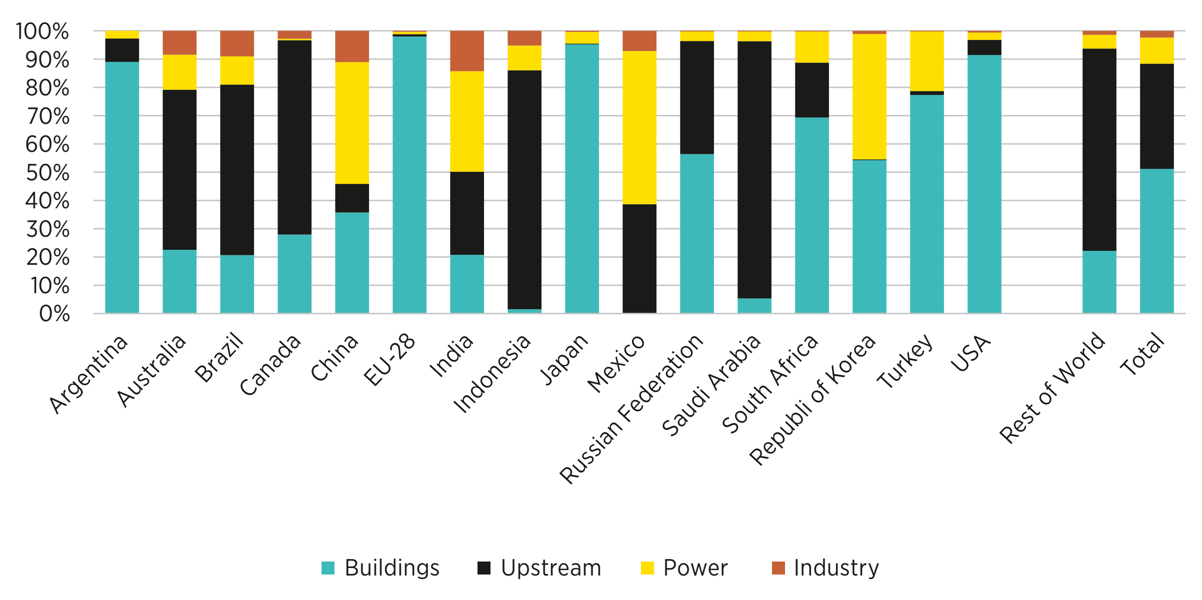
Who will be most affected?

The sector that experiences the largest amount of asset stranding on a global scale is buildings, with approximately USD 10.8 trln stranded under Delayed Policy Action. This is double the amount in the Remap case. The low stock turnover rate of buildings means that stranded assets (i. e. buildings with an inefficient building envelope, equipment, among others) cannot be avoided, even if all new buildings are constructed to the highest of standards in terms of energy efficiency and with integrated renewable energy systems. This is especially true in the United States and Western Europe where the growth in building stock is slow and new buildings account only for a marginal share of the total stock.

Upstream energy is the second largest sector in terms of stranded assets, at approximately USD 7 trln under Delayed Policy Action, USD 3 trln more than in REmap. Large capital expenditures in upstream infrastructure until 2030 under Delayed Policy Action would result in significant stranding in the period after 2030.

The undiscounted value of fossil fuel producer assets is expected to fall to an estimated USD 10.2 trln under REmap and USD 7.1 trln under Delayed Policy Action, with crude oil production decreasing from 100 million barrels a day (mbd) in 2015 to 31 mbd in the REmap case in 2050 and 2 mbd in the Delayed Policy Action case in 2050. The production figure for oil is lower in the Delayed Policy Action case than in the REmap case as there is a need to make up for higher fossil fuel related emissions pre-2030 and emissions will need to decline drastically after that time. The stranded assets would represent 45–85% of the assumed valuation of today's oil upstream producers. This level of oil supply, however, could pose a challenge since the technical substitution solutions are lacking in key oil markets, such as petrochemicals and parts of the transportation sector.

Figure 2: Stranded assets by sector and country with REmap



Source: IRENA analysis

Power generation is the third largest sector in terms of stranded assets, at USD 1.9 trln under Delayed Policy Action, which is twice as much as the REmap amount of USD 0.9 trln. The build-out of coal power plants in the developing world with Delayed Policy Action has a large impact: under business as usual, the coal-fired capacity would be greatly expanded and would need to be stranded after 2030 to meet decarbonisation targets. In comparison, under REmap, an average 40 gigawatts of coal capacity would be stranded each year between 2015 and 2050 worldwide. Average gas capacity that would be stranded between 2015 and 2050 would be approximately 20 gigawatts a year worldwide.

Stranded industrial assets with Delayed Policy Action are estimated at USD 740 billion (bln), three times higher than that estimated under REmap (USD 240 bln). Under REmap, stranded industrial assets between 2015 and 2050 would have a value of USD 7 bln a year on average, an amount that could be compensated through lower energy bills if industry were to achieve a 1.2% a year improvement in energy efficiency.

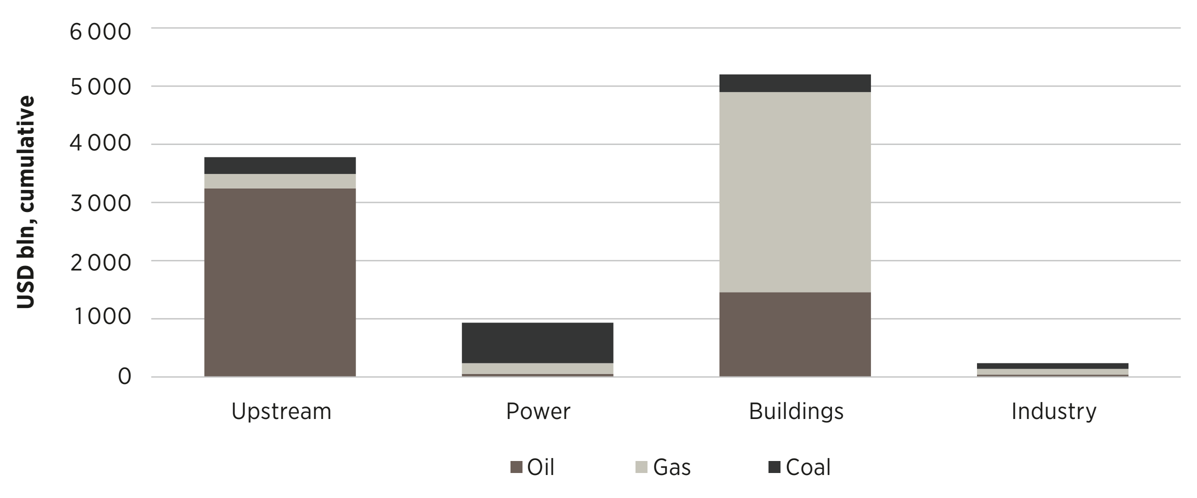
There are very large differences in the total impact and sectoral distributions of anticipated stranded assets across countries and regions (Figure 2). This is true under the Delayed Policy Action and REmap cases, although here the focus is only on the REmap case. In the European Union, Japan and the United States, the value stranded is concentrated in buildings, with more than 95% of total value stranded under REmap being from that sector. This reflects the fact that these are advanced economies with well-developed property markets, extensive mortgage liabilities and high average property values. Buildings are also, on average, older and there are very low levels of building turnover (i. e. new buildings).

In China and India, power generation would have the largest share of total stranded assets at between 25% and 45% of total value. This reflects the large exposure these countries have to coal-fired power plants that are relatively new and not fully depreciated. These power plants would absorb the brunt of efforts to decarbonise the power sector.

Countries such as Brazil and China would experience significant stranding of industrial assets. This would indicate that they have large and inefficient industrial sectors, particularly in heavy industry.

Significant stranding of upstream energy assets would occur in countries that have large oil, gas and coal reserves. Australia, Brazil, Canada, Indonesia, Mexico, the Russian Federation, Saudi Arabia and South Africa would have the largest proportion of stranded upstream assets.

Figure 3: Stranded assets by sector and fuel type with REmap



Source: IRENA analysis

Note: The total value of the bars represents stranded assets in each sector. For each, a breakdown by fuel type is provided. This refers to the total volume of stranded assets related to that fossil fuel capacity installed to produce fuels or generate heat and electricity from those fuels.

The clear majority of stranded oil assets would occur upstream, rather than in power generation, buildings or industry. Oil is primarily used in transport. As ultra-low emissions and electric vehicles reach maturity, projected oil demand will decrease, reducing prices, and thus also lessening the value of oil reserves. Compared to the demand for oil in transport, demand from power generation, heating in buildings, and industry is minor.

Gas assets would be stranded across each of the four sectors, the value of which would be large in buildings. Those assets would be stranded based on the replacement of the gas heating systems that are widely used – particularly in advanced economies in the Northern Hemisphere – with systems powered by electricity based on renewables. Although gas is cleaner than oil and coal, it remains incompatible with the required levels of decarbonisation. As a result, the REmap case shows significant gas stranding upstream and in gas-fired power generation.

Coal assets are also stranded across each of the four sectors, although the sector that would have by far the largest amount is power generation. Coal-fired power generation is a major source of direct CO_2 emissions (approximately 25% of the global total). Stranded coal-fired power assets, however, have only modest value. Since coal plants also comprise high levels of carbon emissions, stranding these assets would be a cost-effective way in which to achieve decarbonisation. Furthermore, it has the potential to contribute to the avoidance of “carbon lock-in”.

What do these findings imply for the various stakeholders?

Developing countries, in particular, are able to prevent the amount of assets that would be stranded by accelerating policy action today. Delaying action and prolonging business as usual will exacerbate efforts of future course corrections, resulting in significantly more asset stranding. Developed countries with low ambition plans for decarbonisation also are affected by this issue and should, therefore, seriously consider increasing their levels of ambition to avoid stranded assets in the future, as well as the ensuing negative economic impacts.

In addition to these macro variances among fossil fuel sectors and countries, different stakeholders also will be affected by stranded assets in diverse and potentially significant ways. The four key groups of stakeholders that will be affected are companies, investors, governments and workers.

Companies

Corporations, whether listed, state-owned or non-listed, already suffer from holding stranded assets in key markets. The challenges that companies face include their often short-term focus and the issue of sunk costs. Endemic short-termism is well documented, particularly among listed companies that report on a quarterly basis. A short-term outlook makes it difficult for companies and their executives to take pre-emptive action to avoid asset stranding (Generation Foundation, 2013).

Moreover, companies may not act promptly in the light of emerging signals about forthcoming stranded assets. There is a well-documented behavioural tendency to continue with activities already invested in, despite the fact that such activities may not be economically rational (Kahneman and Tversky, 1979). In the case of asset stranding, these sunk costs could be a very significant barrier to companies that act in accordance with decarbonisation policies and goals. Companies could be wedded to previous strategies (their sunk costs), particularly when it may be economically irrational to do so. This could exacerbate the stranded assets issue as companies "throw good money after bad" and further delay action due to "loss aversion", despite the illogicality. There is also the potential that companies will actively lobby to reduce the scale and pace of the low carbon transition.

Financial institutions

Potential financial loss from stranded assets may be very significant, particularly in the event of delayed action. Many segments of the investment chain in mature and developing capital markets will be affected in various ways by stranded assets.

Financial institutions, however, share common characteristics that challenge risk accounting, such as stranded assets that are novel, non-linear and medium-to-long term (Kay, 2012; Thomä & Chenet, 2017). These include endemic short-termism, misaligned incentives, and misinterpretations of fiduciary duty (Kay, 2012; Carney, 2015). These issues can make it challenging for many financial institutions to engage with stranded assets and the broader topics that relate to environmental change.

The Bank of England and other central banks have, at the highest levels, demonstrated sustained interest in stranded assets (Bank of England, 2015). This interest has sent a signal to the market, encouraging operations within the financial institutions that were not previously engaged in the issue to become more so.

In addition to these developments, new products are increasingly being launched to address stranded assets. They include indices that are weighted away from the risk of stranded assets (Fossil Free Indexes, n. d.), exchange traded funds that employ such indices (State Street Global Advisors, 2016) and credit ratings that integrate stranded asset risks (Standard & Poor's, 2014; Center for International Environmental Law, 2015).

Government liabilities and reduced tax take

Current or planned investments made directly by government departments or via state-owned banks or investment vehicles could be at risk from stranded assets. Governments could also have indirect exposure to such investments through loan guarantees or other contingent liabilities. Moreover, important tax revenues that depend on the economic activities based on these assets are at stake.

Governments that are highly dependent on revenue from fossil fuels are likely to be the most significantly affected, and delayed action will potentially make the process of adjustment difficult. The ability to borrow from capital markets could be curtailed, with credit rating downgrades occurring as the implication of fiscal impacts becomes clearer. In contrast, timely action to diversify the tax base should reduce the risk of fiscal shocks.

The issue of stranded assets is compelling, not only for existing fossil fuel producers but also for countries that are considering and developing which sectors to promote and develop. The development model led by fossil fuel exports may no longer be viable for such countries.

Workers

Decarbonisation is expected to strand assets in carbon-intensive sectors, and the scale of such asset stranding would be significantly higher were policy action delayed. This issue can potentially destabilise low-carbon transitions and hinder the realisation of Nationally Determined Contributions. The mere threat of stranded assets could cause groups that are potentially affected to slow down or block low-carbon transitions. In particular, the most active of such groups could be those that would lose employment because of asset stranding. National governments and other stakeholders, however, can and should avoid such opposition through good transition planning.

The sectors most likely to generate substantial political economy "frictions" from asset stranding are those that are large employers, especially where such employment is highly concentrated. Upstream fossil fuel production and manufacturing are two sectors that share these characteristics. Stranded building assets are less likely to create labour disputes, although they are more likely to generate concern among property owners.

The reallocation of resources and transition assistance subsidies for those individuals and communities affected by climate change and related policies may facilitate a just transition (Caldecott et al., 2016; Newell and Mulvaney, 2013). These approaches are more likely to be implemented in developed countries, where citizens tend to demand higher relocation costs and where stronger unions call for increased settlements for loss in earnings (Funk, 2014). The provision of adequate support for sectors that are losing out in a low-carbon future and the generation of employment opportunities in low-carbon sectors, particularly in developing countries, are critical to ensuring a just transition.

Are there ways to minimise stranded assets while achieving decarbonisation targets?

To avoid asset stranding caused by devastating physical climate change impacts, polluting assets should be stranded before they emit the emissions that will irreversibly alter the climate. Fortunately, stranding assets to ensure timely decarbonisation can be done with significantly less cost if acted upon sooner rather than later.

There are also significant co-benefits of acting early that are not indicated here, but which are captured in IRENA's global REmap analysis which this working paper is also a part of (IEA and IRENA, 2017). There is the avoided cost of climate damage from warming above two degrees Celsius (2°C), which is estimated at USD 1.5–3.3 trln a year in 2050, according to IRENA's REmap analysis. There are also avoided costs from improved human health as a result of reduced air pollution from road transport and power generation. These avoided costs are estimated at USD 2.3–6.5 trln a year in 2050. The human welfare benefits offset the increased energy system costs from the additional investments in low-carbon technologies and the stranded assets. There are other potential benefits, for example, in terms of environmental impacts and agricultural productivity. Quantifying and highlighting these benefits to stakeholders – especially to the broader society – can assist in creating the necessary buy-in to enable the expediting of action to avoid stranded assets.

Action Areas

The following high-level action areas are proposed for consideration by policy makers. These are based on findings from this IRENA analysis.

Availability of finance

The investment demands for energy transition are significant. Where risk is not adequately priced, financial markets should make the necessary corrections. Governments should play a role through the use of particular instruments, tailored to specific country and sector needs.

Curtailing investment in upstream

Upstream energy investments face significant stranding under a Delayed Policy Action pathway. Almost USD 7 trln would be stranded, with a significant share of those stranded upstream assets taking place in the oil industry. Reducing upstream investments today will prove to be an important measure in reducing the total value of stranded assets in the future. The most direct way to influence today's investments will be for governments to re-evaluate their own upstream investments, as well as the licensing of listed companies that undertake such investments within their jurisdictions. Policy makers and regulators can also improve the transparency of the stranded asset risks of such investments, with a view to encouraging financial institutions to place pressure on companies to reduce upstream investments.

Coal phase out

While the total value of stranded coal-fired power generation assets would be significantly lower than the value of assets stranded in the other sectors considered here, coal has an out-sized impact on decarbonisation. Without phasing out coal-fired power plants, achieving a carbon budget that limits the rise in global temperatures to less than 2°C is difficult, since progress in the deployment of CO_2 capture and storage for coal-fired power plants has been lagging and a massive ramp-up is unlikely in the near future. The phasing out of coal sooner rather than later also will enable a reduction in the scale and pace of required decarbonisation in other sectors. Early action on coal also will reduce the total amount of stranded coal assets.

Energy efficiency retrofits and higher standards for new buildings

Buildings, particularly in developed economies, generate by far the largest quantity of stranded assets. Policies to enable the deep energy efficiency retrofits of residential and commercial properties in these countries are essential. Furthermore, introducing these mechanisms as soon as possible will yield significant benefits. Pay As You Save (PAYS) schemes, tax incentives, energy performance regulations and the provision of concessional finance have each demonstrated success in some jurisdictions for energy efficiency retrofits, providing valuable case studies for policymakers. In developing economies, where the quantity of new build relative to the existing building stock will be much higher between now and 2050 than in developed economies, adopting suitably ambitious building standards and regulations for new builds will be crucial.

Improving the efficiency of industry

Industry can benefit from the cost savings that derive from energy efficiency improvements. These savings will provide incentives for industry retrofits, aligned with decarbonisation pathways. Policy makers should further encourage industry to invest in retrofits and energy efficiency improvements by applying tax incentives, regulatory standards and concessional finance. Governments should also invest in the facilitation of infrastructure for industrial carbon capture and storage (CCS), particularly in relation to industrial processes that generate flue gas with high CO_2 concentration.

Stronger policy signals

For various reasons, companies and investors are likely not to act in the light of future stranded asset risk. As a result, a case can be made whereby policy makers should provide stronger signals and foreground these issues more clearly for stakeholders in an effort to prevent companies and investors from throwing good money after bad and further delaying action due to loss aversion, thus increasing the amount of stranded assets with delayed action.

Such policy signals will need to be stronger than what standard economic models suggest in order to take account of this phenomenon. They should include higher carbon prices and larger economic incentives or tighter regulation. Regulators should ensure transparency on such issues for decision makers, ensuring that investors have access to the necessary information when determining which companies to invest in. The same would apply for consumers when deciding which products to purchase. Company directors should also be responsible for systematically taking these issues into consideration.

1. STRANDED ASSETS: ORIGINS, CONCEPTS, AND DEFINITIONS

1.1 Introduction

This working paper examines the potential magnitude of asset stranding in the energy, industrial and property sectors on a worldwide basis, specifically as a result of accelerated renewable energy and energy efficiency deployment. This analysis will provide an understanding of whether or not and by how much the delays of policy action to fulfil the Paris Agreement will affect the amount of assets put out of action by energy transition. The analysis contained herein is part of a broader decarbonisation study that has been undertaken by the International Renewable Energy Agency (IRENA) and commissioned by the German government – the latter of which holds the 2017 G20 Presidency. It intends to inform the G20 Energy and Climate Working Groups (IEA and IRENA, 2017).

The issue of stranded assets, created by climate change and by the transition to a low-carbon economy, has escalated considerably on the international agenda in recent years.[2] Asset stranding and its implications are relevant to a wide range of investors, companies, policy makers and regulators, particularly in the following areas:

- Investment risk – Managing the exposure of investments to climate change-related risks across sectors, geographies and asset classes so that financial institutions can avoid stranded assets (Financial Stability Board, 2015; Caldecott, Dericks and Mitchell, 2013; Generation Foundation, 2013; Carbon Tracker Initiative, 2011; Caldecott, 2011).

- Financial stability – Financial stability implications of stranded assets and what this means for macro- and micro-prudential regulations and financial conduct (Kruitwagen, MacDonald-Korth and Caldecott, 2016; Bank of England, 2015; Carbon Tracker Initiative, 2011; Caldecott, 2011).

- Just Transition – Reducing the negative consequences of stranded assets created as societies transition to more environmentally sustainable economic models by finding ways to effectively address unemployment, lost profits and reduced tax income that are associated with asset stranding (Caldecott, 2015).

- Management – Internalising the risk of stranded assets in corporate strategy and decision making, particularly in carbon-intensive sectors susceptible to the effects of societal action on climate change (Rook and Caldecott, 2015; Carbon Tracker Initiative, 2013; Ansar, Caldecott and Tibury, 2013).

- Carbon lock-in – Keeping track of progress towards emission reduction targets and understanding how “committed emissions”[3] should influence decarbonisation plans developed by governments, as well as companies and investors (Pfeiffer et al., 2016; Davis and Socolow, 2014; Davis, Caldeira and Matthews, 2010).

These are critically important topics that will likely increase in significance as societies transition towards a low-carbon economy. While much has been written about stranded assets in a short period, however, there remain significant gaps in the literature. Much of the existing research focuses on asset stranding facing listed upstream fossil fuel producers – particularly international oil companies listed on the New York and London stock exchanges – and how their fossil fuel reserves are incompatible with required carbon budgets (Carbon Tracker Initiative, 2011; Carbon Tracker Initiative, 2013).[4] This focus on listed upstream oil companies provides a limited perspective of the potential impact of stranded assets, as these companies own less than 5% of total global oil and gas reserves versus the disproportionate amount held by states through national oil companies and other

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[2] The issue that has been raised by prominent international figures, from the former UN Secretary-General Ban Ki-moon to Mark Carney, Governor of the Bank of England and Chair of the G20 Financial Stability Board (Carney, 2015).

[3] Defined as the future emissions expected from current worldwide fossil fuel-burning infrastructures (Davis, Caldeira and Matthews, 2010).

[4] Carbon budgets are the amount of CO_2 that can be emitted for a given probability (usually 50% or 66%) of keeping below an average global rise in temperatures of usually 2°C (or 1.5°C) above pre-industrial levels.

state-owned enterprises (Stevens, 2016). This focus on the stranded assets facing fossil fuel producers and power plants rather than on those end-use sectors facing those that use fossil fuels misses very significant impacts. Certain types of buildings, transport equipment and transport infrastructure, as well as industry installations, are also characterised by a long life span and stranded asset risks. This working paper argues that the value of assets at risk is higher in end-use sectors than in supply sectors.

This working paper furthers existing analyses of stranded upstream fossil fuel assets and undertakes a new analysis of asset stranding downstream, specifically in power generation, buildings and industry, three large sectors that are responsible for 25%, 6.4% and 21% of direct global energy-related greenhouse gas emissions, respectively (Allen, Barros, Broome, et al., 2014). Refined methodologies to estimate the potential magnitudes of asset stranding in these three sectors are applied, as well as for the global upstream fossil fuel production sector by 2050, which stems from accelerated renewable energy and energy efficiency deployment, using IRENA's REmap analysis. A breakdown of the scale of stranded assets facing individual G20 countries is also provided. As there is a dearth of analysis specifically targeting renewables and energy efficiency deployment as the key drivers of stranded assets, this will fill a significant gap in the current literature.

Based on the REmap 2050 analysis, this working paper examines two cases. The first relates to accelerated renewables and energy efficiency deployment from today until 2050 that deliver emissions reductions that have a two-out-of-three (66%) probability of maintaining global below-temperature change from rising more than 2°C above pre-industrial levels ("REmap"). Based on the REmap case, a carbon emission budget of 880 gigatonnes (Gt) CO_2 is defined for the period 2015–50. This includes fossil fuel and other (e.g. land use, industrial process) emissions. This case assumes action will begin soon as a result of new policy initiatives.

In the second case, business as usual continues until 2030 (represented by the Reference Case here). Following 2030, the deployment of renewables and energy efficiency accelerates sufficiently to ensure that the global energy system remains within the same emissions budget by 2050. This is the Delayed Policy Action case. Comparing these two cases allows for an understanding of whether or not the scale of asset stranding will vary should policy actions to achieve the Paris Agreement be delayed. It should be noted that in the Delayed Policy Action case, emissions during the period up to 2030 would be higher than in the Remap case. To achieve the objectives of the Paris Agreement, more investment (e.g. on bioenergy with CCS) would peraps be required to compensate for these higher emissions.

1.2 Defining stranded assets

There are several definitions of stranded assets in the energy context. The term "stranded costs" or "stranded investment" is used by regulators to refer to "the decline in the value of electricity-generating assets due to restructuring of the industry" (Congressional Budget Office, 1998). This was a major topic for utility regulators when power markets were liberalised in the United Kingdom and the United States in the 1990s.

Several organisations that work in the field of energy and climate have already examined what stranded assets could mean from their own perspective. The most commonly applied definitions are briefly discussed below:

- The International Energy Agency defines stranded assets as "those investments which have already been made but which, at some time prior to the end of their economic life (as assumed at the investment decision point), are no longer able to earn an economic return as a result of changes in the market and regulatory environment brought about by climate policy" (IEA, 2013, p. 98).

- While the Carbon Tracker Initiative also defines such economic loss in the same way, it indicates that the losses are a "result of changes in the market and regulatory environment associated with the transition to a low-carbon economy" (Carbon Tracker Initiative, n.d.).

- The Generation Foundation defines a stranded asset "as an asset which loses economic value well ahead of its anticipated useful life, whether that is a result of changes in legislation, regulation, market forces, disruptive innovation, societal norms, or environmental shocks" (Generation Foundation, 2013, p. 21).

- The Smith School of Enterprise and the Environment at the University of Oxford employs a 'meta' definition to encompass these (and other) definitions. It states that "stranded assets are assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities".

For the purpose of this analysis, stranded assets are defined as the remaining book value[5] of assets substituted before the end of their anticipated technical lifetime and without recovery of any remaining value to achieve 2050 decarbonisation targets. This definition emphasises that assets become stranded because of the requirement to reduce fossil fuel use to achieve a deeply decarbonised energy system by mid-century.

1.3 Evolution of stranded assets

While the climate change discourse has appropriated the term, asset stranding, in actual fact it occurs regularly as part of economic development. Schumpeter coined the term "creative destruction", and within this concept is the idea that value is created as well as destroyed, and that this dynamic process drives innovation and economic growth.

Recent research on stranded assets has focused on how the causes of asset stranding are increasingly related to the environment, through a combination of physical environmental change and societal responses to such change. This is in contrast to previous drivers of creative destruction. Moreover, such environment-related factors appear to be stranding assets simultaneously across all sectors, geographies and asset classes and perhaps more swiftly than in previous instances. Such trends, furthermore, are accelerating, and such a tendency represents a potential and unprecedented unknown factor (Caldecott and McDaniels, 2014b).

Carbon budgets and stranded assets

At the beginning of the late 1980s, individuals and organisations working on climate and sustainability issues began to acknowledge the possibility that climate change regulation could reduce the value or profitability of fossil fuel companies (Krause, Bach and Koorney, 1989; IPCC, 1999; IPCC, 2001; IEA, 2008). When the amount of fossil fuels already combusted plus the amount of carbon in reserves yet to be burned reach the limit of the carbon budget, the value of fossil fuel reserves would decline unless the amount of carbon were allowed to exceed the budget, thus generating a climate change that is dangerous. This concept of unexploited carbon reserves was dubbed "unburnable carbon" by the Carbon Tracker Initiative (2011) and was popularised in early 2010 by the U.S. environmentalist, Bill McKibben (2011), among others.

Unburnable carbon represents a significant difference between the current value of the listed equity of global fossil fuel producers and the reduced commercial value of their reserves under a strict carbon budget constraint (Carbon Tracker Initiative, 2011; Caldecott, 2011). The idea that "unburnable" fossil fuel reserves have the potential to become stranded assets has sparked a significant discussion on the risk of investing in fossil fuels (Ansar, Caldecott and Tibury, 2013). It has also helped spur a campaign aimed at forcing divestments in fossil fuels (Ibid).

In parallel, the idea of a "carbon bubble" also gained traction. This concept indicates that the existence of unburnable carbon would also signal that upstream fossil fuel assets are significantly overvalued. This would potentially create a financial bubble with systemic implications for the global economy (Carbon Tracker Initiative, 2011; Caldecott, 2011).

Recent studies on stranded assets

As part of the literature review for this working paper, 29 studies that have attempted to quantify the scale of asset stranding in different sectors and geographies have been examined (Table 1). One of these relates to 1989, while the others date from 2013 or later. Twenty-two reports are global in coverage, while seven are country specific. Seventeen address upstream fossil fuel production, four relate to power generation, two review upstream production and generation together, two are associated with agriculture, and four examine all sectors. None of the studies addresses, in any detail, the buildings or industry sectors.

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[5] Book value is defined here as the cost of an asset, minus accumulated depreciation.

Table 1: Studies reviewed that relate to stranded assets

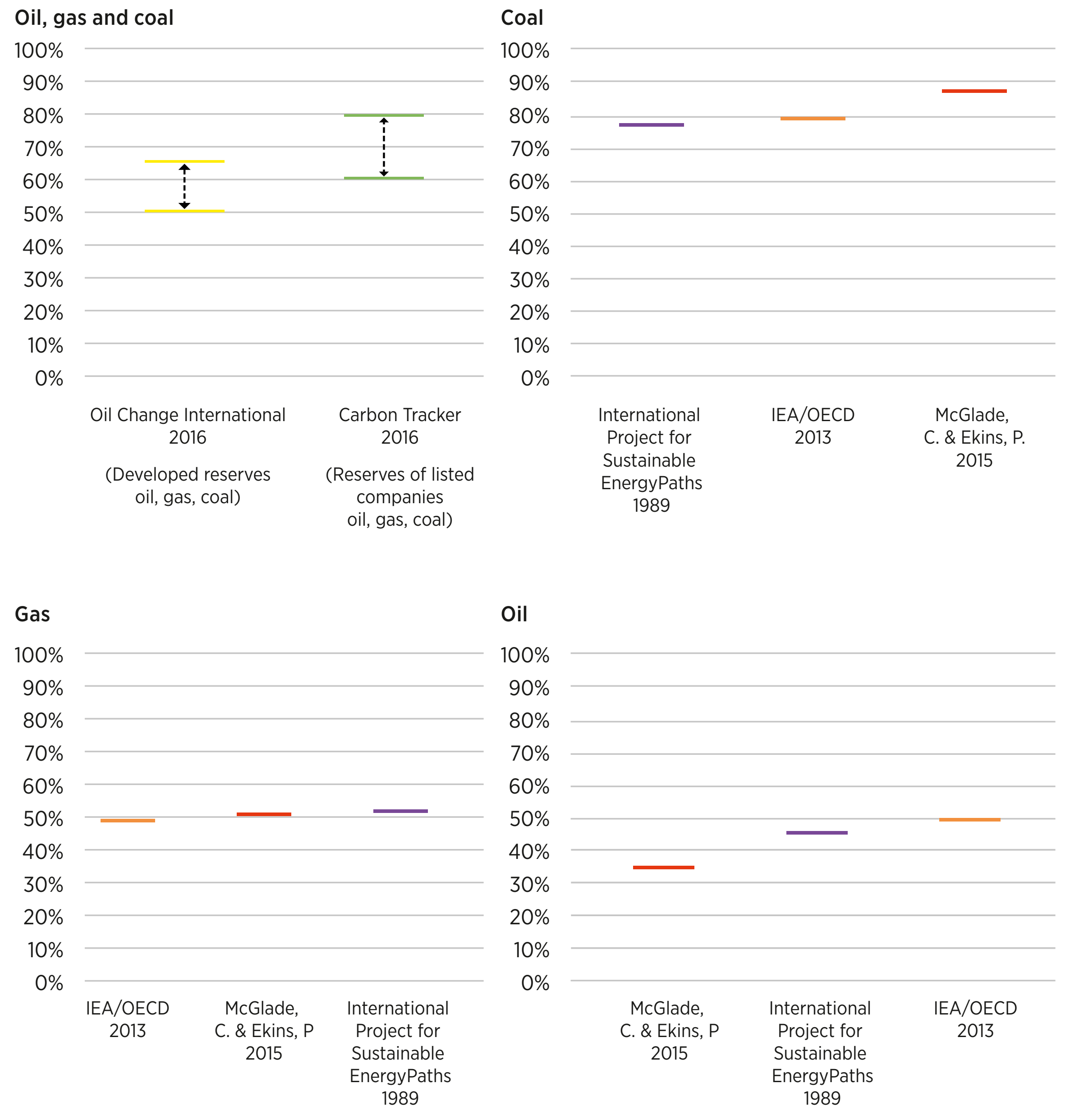
Authors	Title	Publisher	Year	Sector	Geographic Coverage
F. Krause, W. Bach and J. Koomey.	Energy Policy in the Greenhouse	International Project for Sustainable Energy Paths	1989	Fossil fuels	Global
M. Meinshausen, N. Meinshausen, W. Hare, S.C.B. Raper, K. Frieler, R. Knutti, D.J. Frame and M.R. Allen	"Greenhouse-gas emission targets for limiting global warming to 2°C"	Nature	2009	Fossil fuel reserves	Global
Caldecott, B. and G., Elders	"Bloomberg Carbon Risk Valuation Tool", White paper	Bloomberg New Energy Finance	2013	Oil & gas	Global
Carbon Tracker Initiative	Unburnable Carbon 2013: Wasted capital and stranded assets	Carbon Tracker Initiative	2013	Coal, oil, gas	Global
P. Spedding, K. Mehta and N. Robins	Oil and Carbon Revisited; Value at risk from 'unburnable' reserves	HSBC Climate Change and HSBC Global Research	2013	Oil companies	Europe
International Energy Agency	Redrawing the Energy-Climate Map: World Energy Outlook Special Report	International Energy Agency/ Organisation for Economic Co-operation and Development	2013	Power, coal, oil, gas	Global
B. Caldecott, N. Howarth and P. McSharry	Stranded Assets in Agriculture: Protecting Value from Environment-Related Risks	Smith School, University of Oxford	2013	Agriculture	Global
B. Caldecott, J. Tilbury and Y. Ma	Stranded Down Under? Environment-related factors changing China's demand for coal and what this means for Australian coal assets	Smith School, University of Oxford	2013	Coal mining	Australia
A. Ansar, B. Caldecott and J. Tilbury	Stranded assets and the fossil fuel divestment campaign: what does divestment mean for the valuation of fossil fuel assets	Smith School, University of Oxford	2013	Oil and gas	Global
Carbon Tracker Initiative	Carbon supply cost curves: Evaluating financial risk to oil capital expenditures	Carbon Tracker Initiative	2014	Oil	Global

Authors	Title	Publisher	Year	Sector	Geographic Coverage
Carbon Tracker Initiative	Carbon supply cost curves: Evaluating financial risk to coal capital expenditures	Carbon Tracker Initiative	2014	Coal	Global except China
M.C.Lewis, S. Voisin, S. Hazra, S. Mary and R. Walker	"Stranded assets, fossilised revenues"	Kepler Cheuvreux, ESG Sustainable Research	2014	Fossil fuels	Global
B. Caldecott and J. McDaniels	Stranded generation assets: Implications of European capacity mechanisms, energy markets and climate policy	Smith School, University of Oxford	2014	Gas utilities	Europe
Bank of England	The Impact of climate change on the UK Insurance Sector: A climate change adaptation report by the Prudential Regulation Authority	Bank of England	2015	All	Global
Carbon Tracker Initiative	Carbon Asset Risk: from rhetoric to action	Carbon Tracker Initiative	2015	Primary oil and gas	Global
Carbon Tracker Initiative	The $2 trln stranded assets danger zone: How fossil fuel firms risk destroying investor returns	Carbon Tracker Initiative	2015	Oil, gas, thermal coal	Global
Carbon Tracker Initiative	Carbon supply cost curves: Evaluating financial risk to gas capital expenditures	Carbon Tracker Initiative	2015	Liquefied natural gas	Global
Paul Griffin, Amy Myers Jaffe, David Lont, and Rosa Dominguez-Faus.	"Science and the Stock Market: Investors' Recognition of Unburnable Carbon"	Energy Economics	2015	Oil and gas	US
Mercer	Investing in a Time of Climate Change	Mercer	2015	Energy sector	Global
C. McGlade and P. Ekins	"The geographical distribution of fossil fuels unused when limiting global warming to 2 °C"	Nature	2015	Fossil fuels	Global
B. Caldecott, G. Dericks and J. Mitchell	Subcritical Coal in Australia: Risks to Investors and Implications for Policymakers, Working paper	Smith School, University of Oxford	2015	Coal utilities	Australia

Authors	Title	Publisher	Year	Sector	Geographic Coverage
The Economist Intelligence Unit	The cost of inaction: Recognising the value at risk from climate change	The Economist Intelligence Unit	2015	All sectors	Global
A. Pfeiffer, R. Miller, C. Hepburn and E. Beinhocker	"The '2C capital stock' for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy"	Applied Energy	2016	Electricity generation	Global
S. Dietz, A. Bowen, C. Dixon and P. Gradwell	"'Climate value at risk' of global financial assets"	Nature Climate Change	2016	All sectors	Global
G. Muttit.	The sky's limit: Why the Paris climate goals require a managed decline of fossil fuel production	Oil Change International	2016	Fossil fuels	Global
C. Shearer, N. Ghio, L. Myllyvirta, A. Yu and T. Nace	Boom and bust 2016: Tracking the global coal plant pipelines	Sierra Club, CoalSwarm and Greenpeace	2016	Coal	Global
B. Caldecott, L. Kruitwagen, G. Dericks, D.J. Tulloch, I. Kok and J. Mitchell	Stranded assets and thermal coal: An analysis of environment-related risk exposure, Working paper	Smith School, University of Oxford	2016	Coal utilities, mining and processing	Global
B. Caldecott, G. Dericks, D.J. Tulloch, L. Kruitwagen and I. Kok	Stranded assets and thermal coal in Japan: An analysis of environment-related risk exposure, Working paper	Smith School, University of Oxford	2016	Coal utilities	Japan
A. Morel, R. Friedman, D.J. Tulloch and B. Caldecott	Stranded Assets in Palm Oil Production: A Case Study of Indonesia, Working paper	Smith School, University of Oxford	2016	Palm oil	Indonesia and Malaysia

These studies apply various methodologies and quantify asset stranding over different time periods, making it a challenge to compare studies. The figures below present, nevertheless, the studies in a way from which a sense of the order of magnitude of the stranded assets can be determined. Moreover, studies often calculate cumulative asset stranding in a smooth or linear fashion over multi-decade

Figure 4: Estimated stranded oil, gas and coal reserves (percent of global total)



Source: IRENA analysis of cited reports

Note: The coal, gas and oil figures show range of estimated stranded oil, gas and coal reserves as a percentage of proven reserves for each of those commodities.

time periods. Asset stranding, however, may occur at a non-linear pace, which is that stranded fossil fuel assets have been hypothesised as contributing to financial instability. The timing and pace of asset stranding – not only in terms of its cumulative scale – determines the severity of impact on companies, investors and countries.

Figure 4 presents the range of estimated stranded oil, gas and coal reserves as a percentage of total reserves. The drivers of stranding across each of these studies reflect carbon budget constraints, and the studies tend to apply a 2°C target with a 50% or 66% probability. One study (Muttit, 2016) examined all listed and non-listed developed oil, gas and coal reserves. Carbon Tracker Initiative (2013) examined all oil, gas and coal reserves held by listed companies. Three studies (Krause, Bach and Koorney, 1989; McGlade and Ekins, 2015; IEA, 2013) examined all proven oil, gas and coal reserves. In this working paper, the three fossil fuels are distinguished to enable a fuel-by-fuel comparison. These studies estimate that 50–80% of total fossil fuel reserves could become stranded. Specifically, the studies estimate that 34–49% of oil reserves, 49–52% of gas reserves and 77–87% of coal reserves would be stranded to meet carbon budget constraints. The range of estimates around gas is very small (3 percentage points), followed by coal (10 percentage points) and oil (15 percentage points).

Other studies have attempted to quantify the impact of decarbonisation on financial assets, such as equities and bonds. Dietz et al. (2016) examined all financial assets, and two studies (Bank of England, 2015) reviewed global listed equities. Other studies investigatged different asset classes (investment-grade bonds, high-yield bonds, leveraged loans)[6] and separate sectors (oil, gas and coal; agriculture; oil and gas). There is a very large range in the estimates of equity value that might be stranded in upstream oil and gas. BNEF (2013) puts the range of stranded oil and gas equities from as low as 10% to as high as 90% of the total amount of such equities. Spedding, Mehta and Robins (2013) places the range for oil equities alone at 40–60%. The wide range of estimates from these studies shows that there is no clear answer regarding the magnitude of stranded financial assets. The explanation depends on a range of factors, which also include essential regional variations.

Some of the studies reviewed as part of this working paper mark down future income from specific assets under different carbon budgets and then compare valuations (e.g. IEA/OECD, 2013; Carbon Tracker Initiative, 2014). These studies each take varying views on the size of markdowns caused by different carbon budget constraints and on how swiftly the markdowns occur. They use separate datasets based on the sectors analysed, and these vary in terms of coverage and accuracy. Other studies apply a similar "bottom-up" methodology, although they focus on non-carbon, budget-related drivers of asset stranding, such as water stress and air pollution (e.g. Caldecott, Dericks and Mitchell, 2015; Caldecott et al., 2016a).

Several other methodologies have been employed to estimate the value of stranded assets. Lewis et al, (2014) take an aggregate "top-down" approach looking at sector-wide revenues. They calculate the net impact of a 2°C carbon budget on the projected revenues of the global upstream fossil fuel industry. They find that the difference in revenue (in constant 2012 U.S. dollar terms) between a 2°C scenario and business as usual is USD 28 trln in the period 2013–35. Of that, there would be USD 19.3 trln of unrealisable revenue in the oil industry, USD 4 trln in the gas industry and USD 4.9 trln in the coal industry.

Other studies have deployed "value at risk" (VaR) methodologies to estimate the potential impact of stranded assets. VaR is used to determine the probability of a defined loss. Dietz et al. (2016) calculate that the loss measured by the 1 percent VaR due to a business-as-usual emissions pathway is 16.9% of all global financial assets, or USD 24.2 trln (i.e. a 1 percent chance of the annual loss exceeding USD 24.2 trln). Caldecott, Haworth and McSherry (2013) focus on agriculture and calculate the VaR facing the sector from an extreme loss of natural capital. They find that the loss measured by the 1 percent VaR is USD 10.4 trln (i.e. a 1 percent chance of the annual loss exceeding USD 10.4 trln).

Other studies have employed Integrated Assessment Models that attempt to maximise social welfare under several imposed constraints. Using such models, McGlade and Ekins (2015) find that, globally, a third of oil reserves, half of gas reserves

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[6] Investment grade bonds have a credit rating of BBB- or higher from Standard & Poor's or Baa3 or higher by Moody's; high-yield bonds offer a higher rate of interest due to a higher risk of default. Leveraged loans are offered by banks and banking syndicates and they bear a higher risk of default. Therefore, a leveraged loan is costlier to the borrower.

and over 80 per cent of current coal reserves would remain unused from 2010 to 2050 to meet the 2°C target (Figure 4).

As drawn from the literature review, there are many viable methodologies to estimate the value of stranded assets. The review was used to inform the selection and refinement of methodologies employed in this working paper.

Methodology

The analysis compares stranded assets under two cases and uses a bottom-up analysis of the energy system of G20 countries (19 G20 countries, as well as in other European Union countries):[7]

- The "REmap" case assumes the world takes the path of timely decarbonisation as envisioned by REmap. This includes a 27% reduction in the primary use of fossil fuels by 2030 and more than a 60% reduction by 2050 compared to 2015 levels. This reduction is achieved by an increase in the renewable energy share in total primary energy supply of 65% by 2050 and by an accelerated energy intensity improvement rate of 2.5% each year between 2015 and 2050. Renewable energy and energy efficiency technologies represent 90% of the total emissions reductions that are needed to remain within the carbon budget for a decarbonisation of the global energy system. The remaining 10% comes from CCS deployment, material efficiency improvements and structural changes (e.g. industry relocations and transport modal shifts).

- The Delayed Policy Action case includes a business-as-usual outlook for the energy system until 2030 (referred to in this study as the Reference Case 2030) with an increase in the primary use of fossil fuels of 16% compared to 2015. After 2030, policy action is expected to accelerate and the same outcome for the energy system in 2050 as with REmap will be reached. Comparing these two cases allows an understanding of whether or not the scale of asset stranding will be different in the event that policy action to achieve the Paris Agreement is delayed. Based on this methodology, the value of stranded assets by sector from these cases has been estimated (upstream oil, gas and coal; power generation; industry; and buildings). Details of the definitions, methodologies, assumptions and data sources are in Annex A. To calculate stranded assets for each sector, an asset-by-asset, bottom-up approach has been followed, refining the methodologies employed in some of the studies contained in the literature review.

Upstream

In the upstream energy sectors, stranded assets are defined as the unrealisable value of existing and planned production assets for coal, gas and oil producers. These assets include reserves (i.e. crude oil, gas and coal) and capital assets (i.e. infrastructure to produce from these reserves). Initially, the aggregate value of coal-, gas- and oil-producing assets was estimated based on the current valuation of major producers. The valuation is adjusted by reducing cash flows due to reduced production in the REmap and Delayed Policy Action cases. The difference between this adjusted valuation and the current valuation provides an indication of the value of the stranded assets in terms of the oil, gas and coal reserves that are left in the ground as a result of decarbonisation. Adjusting valuations based on the unrealisable value of unburnable fossil fuel reserves due to decarbonisation is similar to the analysis carried out by Spedding, Mehta and Robins (2013), which estimates that as much as 40–60% of the value of gas and oil equities is at risk as a result of lower-than-anticipated demand and pricing. As a further step, the incremental capital expenditures in the Delayed Policy Action case that are avoided in the REmap case have been added. This approach is in line with that followed by the Carbon Tracker Initiative (2015), which found that USD 2 trln of planned upstream capital expenditures between 2015 and 2025 are not required in a decarbonisation pathway.

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[7] Economic data provided in this paper refer to real U.S. dollar terms in 2015. Stranded asset estimates have been provided in cumulative terms for the period between 2015 and 2050, and they have not been discounted to express an annual value. This choice was made based on the discount rate, which is the same concept as the period over which one would fully depreciate the asset. Here, the estimates are expressed in years over which the asset is fully depreciated (not in percentage terms), as well as for consistency with estimates of other organisations. A shorter period of depreciation would be a higher discount rate and a longer period, a lower one. Moreover, the analysis excludes any complex assumptions about cash flows from assets beyond 2015 when using inflation estimators and predicted growth rates.

Power

In power generation, stranded assets are defined as fossil fuel power plants that call for closure before the end of their anticipated technical lifetimes. Plants that need to operate at lower load factors to accommodate a higher penetration of renewables are not included. To estimate the plants that should be shut down before the end of their technical lifetimes, the current stock and age distribution of power plants have been taken into account and in a subsequent step, these have been retired by age (starting with the oldest), based on standard assumptions on anticipated technical lifetimes (50 years for coal and oil power plants, 30 years for gas-fired power plants).[8] Similar methodologies have been employed for country-level studies (Burton, 2016), and at a global level by Pfeiffer et al. (2016). The latter concludes that "even under the very optimistic assumption that other sectors reduce emissions in line with a 2°C target, no new emitting electricity infrastructure can be built after 2017 for this 2°C target to be met unless other electricity infrastructure is retired early or retrofitted with carbon capture technologies."

To estimate the value of the stranded power plant assets in a simple and transparent way, it is assumed that investment costs are recovered linearly over a plant's lifetime. It is also supposed that the carrying value, at the time of stranding, equals the plant's nominal value minus accelerated depreciation.

While accounting standards require impairment tests – with impairments generally occurring when the sum of expected future cash flows are less than the carrying value of an asset on the balance sheet[9] – no attempt was made to undertake these calculations. These impairments would ideally be accounted for, as the value of power plants that are shut down might be below their nominal value minus accumulated depreciation.

This choice was made because there is a large degree of uncertainty in estimating the carrying value (accounting for the impact of impairments) of power plants. Even for existing power plants, a lack of disclosure makes it very difficult to estimate their carrying value. Estimating carrying values into the future comes with an even larger degree of uncertainty. It requires detailed forecasts of wholesale electricity prices, input prices, technical efficiencies and other factors, on an annual basis, up to 2050 and beyond under various scenarios.

Industry

In industry, the identical approach as in power generation was used. The stock of industrial process heat equipment has been taken and, subsequently, the technical lifetimes of assets and rates of natural retirement were calculated, while estimating how much value is stranded due to the premature obsolescence of equipment. In the assessment of retired capacity, the selection was made based on the age of capacity, and no distinction was made between the capacity that is efficient and that which operates based on old equipment.

Buildings

Given data availability, a different approach for buildings is necessary. In addition, a number of assumptions has been required to account for the gaps in data.

Forecasted total building floor space and natural demolition rates were used to estimate the floor space of new buildings and the existing floor space for each year. New buildings were assumed to consume no fossil fuels after 2020 under REmap, and after 2030 under Delayed Policy Action. Subsequently, the floor space needed to be retrofitted to reduce fossil fuel consumption was estimated for each year in the REmap and Delayed Policy Action cases. When buildings are retrofitted, some of the original building materials and equipment need to be replaced, such as gas-fired boilers and/or single glazed windows. The value of these stranded assets is estimated by the difference between the cost of retrofit and the additional cost to construct a new energy efficient and fossil-free building in lieu of conventional buildings (Box 1).

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[8] These plants require significant mid-life efforts to maintain their operation. In order to assess the impact of shorter lifetimes on stranded asset estimates, a sensitivity analysis has been carried out.

[9] For more on this, see PwC (2011)

Cost assumptions are based on a comprehensive study of the Global Buildings Performance Network (GBPN) (2015). This study confirms that a new fossil-free building (which, on average adds a 23% premium to the construction cost of a conventional building) is generally less costly than constructing a conventional building and then having to retrofit it later (at an average cost of 49% of construction cost for conventional buildings). While this pattern holds true for all parts of the world, the turnover rates for building stock differ by region. For instance, in the United States and Western Europe, new builds are minute compared to total stock.

Box 1: Stranded assets and energy efficiency investments in buildings

Buildings have a low stock turnover. This is especially true in the United States and Western Europe, where the growth in building stock is slow. In Germany, for example, more than 85% of the expected residential building stock in 2050 exists today. As a result, the stranding of building assets (i.e. through tightened requirements for building envelopes and equipment, among others), will be high, even when all new buildings are constructed to the highest of standards in terms of energy efficiency and renewable energy use.

An example of stranded assets would be the additional costs of installing single-glazed windows and later replacing them with double-glazed windows versus installing double glazed windows in the first instance. Similarly, stranded assets would occur through the ambitious deployment of energy efficiency technologies in new and existing buildings. By comparison, investments refer to energy efficiency measures that either replace building equipment that has reached the end of its lifetime (e.g. efficient light bulbs) or that are implemented as an additional feature to buildings to reduce energy demand (e.g. wall insulation).

Conclusion

This working paper examines the potential magnitudes of asset stranding in the global energy, industrial and property sectors. It is based on the result of accelerated renewable energy and energy efficiency deployment, using IRENA's REmap analysis.

In this section, the origins, concepts and definitions of stranded assets were discussed. In addition, some of the current literature was reviewed and explained on how the new IRENA analysis is contributing to fill a significant gap in available knowledge.

Most of the work on stranded assets has focused on listed upstream fossil fuel reserves and their compatibility with carbon budgets. In contrast, the approach adopted here looks at upstream as well as downstream energy. It also examines industry and property, two sectors where there is a real absence of available analysis. The next section presents the results from this analysis.

2. RESULTS

This section presents the results from the IRENA analysis of potential magnitudes of asset stranding in the energy, industrial and building sectors, globally, resulting from accelerated renewable energy and energy efficiency deployment. It begins by comparing the scale of asset stranding under the REmap and the Delayed Policy Action cases. The section then examines the geographic distribution of this stranding across key countries and regions, as well as a sectoral distribution by fossil fuel type.

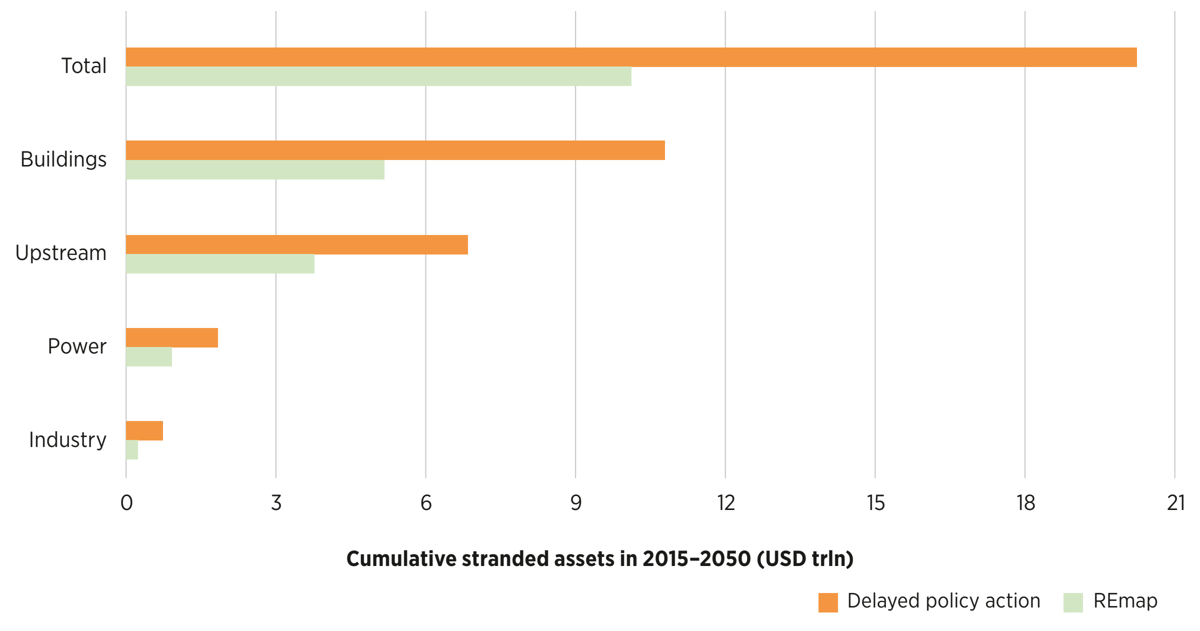
2.1 Impact on stranded assets of Delayed Policy Action

The importance of early action is crucial. Early action is called for not only in the deployment of renewables and other enabling infrastructure and supporting technologies but also in the development of solutions for sectors where no significant or economically attractive solution exists today. If action is delayed, total investment costs will rise, and costly negative emission technologies will be needed to limit planetary warming. Delayed Policy Action, where business as usual continues until 2030 before accelerated renewables and energy efficiency deployment takes place, would result in significant asset stranding in comparison to the REmap case, where accelerated deployment takes place immediately. The total value of stranded across upstream energy, power generation, industry and buildings under Delayed Policy Action is found to be USD 20 trln, which is USD 10 trln more than in the REmap case (Figure 5). To put this into context, USD 20 trln is approximately 4% of global wealth in 2015 (estimated at USD 250 trln, according to Credit Suisse, 2015).

2.2 Who will be affected most?

The sector that would experience the largest amount of asset stranding on a global scale is buildings, with approximately USD 10.8 trln stranded under Delayed Policy Action – twice as much as in the Remap case. The large difference between the two cases is due to the fact that about half of the building floor space in 2050 is yet to be constructed; the other half

Figure 5: Stranded assets by sector with REmap and Delayed Policy Action



Source: IRENA analysis

consists of buildings in existence today. The low stock turnover rate of buildings means that stranded assets (i.e. buildings with inefficient building envelopes and equipment, among others) cannot be avoided, despite the fact that all new buildings from today onwards may be constructed to the highest of standards in terms of energy efficiency and renewable energy use. This is especially true in the United States and Western Europe where the growth in building stock is slow, and new builds account for only a marginal share of the total stock. In Germany for example, more than 85% of the expected residential buildings stock in 2050 already exists.

In REmap, total building stock grows from approximately 140 billion square metres (m^2) to 270 billion m^2 between 2015 and 2050. It is important to distinguish between the share of buildings that will be new and the share that will need to be renovated. At the country level, an annual demolition rate, ranging from 0.1% (e.g. in European Union (EU) countries) to 1% (e.g. China, India and Indonesia), has been assumed based on average rates of demolition. At these rates, 184 billion m^2 of all building area in 2050 will be new. This represents about two-thirds of total stock. In REmap, it is assumed that by 2020, all new buildings will be free of fossil fuels. The remainder of the building stock would be from the existing building stock today. Assuming no additional effort for renovation, approximately 60% of this existing building stock in 2050 would continue to rely on fossil fuels. Thus, a share of this building stock needs to be significantly renovated to sufficiently reduce the demand for fossil fuels in buildings to remain within the carbon budget. The construction value that is lost due to the renovation of this building stock – or the stranded assets in buildings as defined in this assessment – is estimated at USD 5 trln in 2015–50 under REmap.[10]

Upstream energy is the second largest sector in terms of stranded assets, at approximately USD 7 trln under Delayed Policy Action – USD 3 trln more than in the Remap case. The large capital expenditures in upstream infrastructure until 2030 under Delayed Policy Action result in significant stranding in the period after 2030. This demonstrates the detrimental impact of Delayed Policy Action. Eighty percent (or USD 5.6 trln) of stranded assets are for upstream oil.

In 2015, total production of oil reached nearly 100 million barrels a day (mbd) worldwide. Six companies represent about a quarter of this total, namely Saudi Aramco (10.2 mbd), ExxonMobil (4.1 mbd), Shell (3.0 mbd), PetroChina (2.7 mbd), Sinopec (1.0 mbd) and BG Group (0.7 mbd). A large share of these companies' total market value is contained in their upstream activities. Accounting for the different shares of these six companies – where such information is publically available in this working paper – the total value of the upstream oil producers in 2015 was USD 12 trln. The upstream values for gas and coal producers have also been estimated at USD 1.3 trin and USD 0.8 trln, respectively, placing the total fossil fuel upstream sector market value at USD 14 trln in 2015. The total upstream value of fossil fuel producers is estimated to fall to USD 10.2 trln under REmap and USD 7.1 trln under the Delayed Policy Action, with crude oil production decreasing to 31 mbd and 2 mbd, respectively, in 2050. This level of oil supply could pose a challenge, since the technical substitution solutions are lacking in key oil markets such as petrochemicals and parts of the transportation sector. The stranded assets that would result would represent approximately 45–85% of the assumed valuation of today's oil upstream producers. This estimate is well within the range of HSBC estimates from 2013, which place the range at 40–60%. Falling stock prices of upstream oil producers in recent years may be a reason for this difference.

Power generation is the third largest sector in terms of stranded assets, at USD 1.9 trln under Delayed Policy Action – more than twice as much as in Remap, at USD 0.9 trln. The build-out of coal power plants in the developing world has a large impact: under business as usual, coal-fired capacity will be greatly expanded and will have to be stranded after 2030 to meet decarbonisation targets.

Under REmap, 40 gigawatts (GW) of coal capacity, worldwide, would be stranded on average each year between 2015 and 2050. Sixty GW of capacity would be stranded between 2015 and 2025. After 2025, it would average 50 GW a year until 2030 and then drop to approximately 30 GW a year until 2050. By comparison, the average worldwide gas capacity that would be stranded between 2015 and 2050 would be approximately 20 GW a year.

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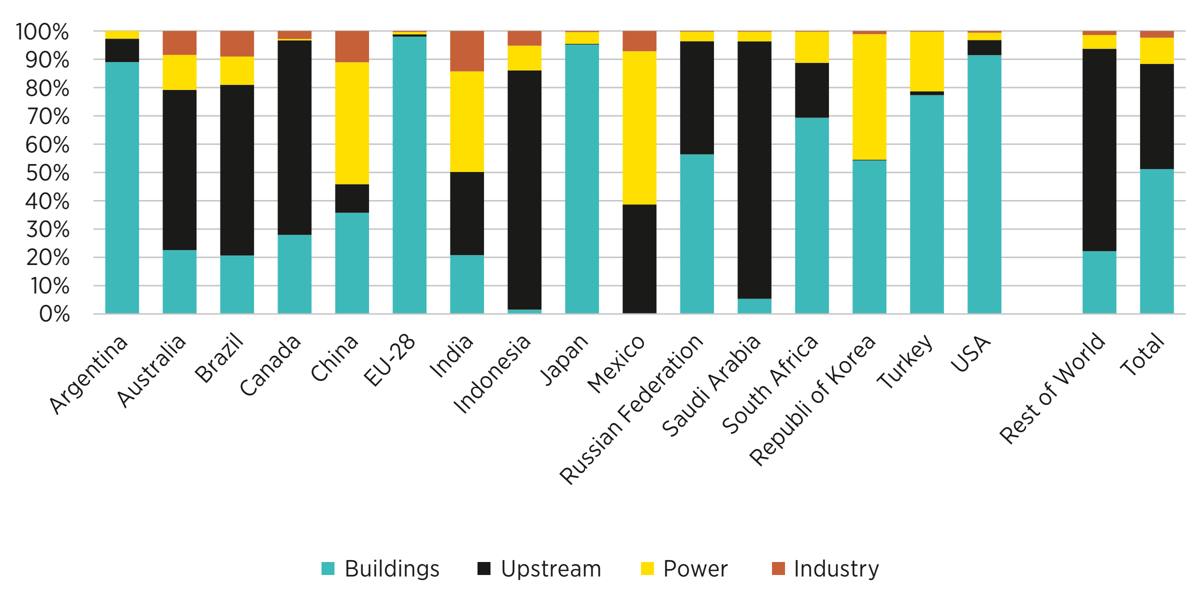
[10] This includes depreciation of the investment made prior to renovation. If depreciation is not included, the stranded asset value would be twice as high.

Figure 6: Stranded assets by sector and country with REmap



Source: IRENA analysis

Finally, stranded industrial assets with Delayed Policy Action are estimated at USD 740 billion (bln), three times higher than that estimated under REmap (USD 240 bln). Relatively lower capital expenditures for process heat equipment (compared to power generation) explain the lower order of magnitude.

There are very large differences in the total impact and sectoral distribution of anticipated stranded assets across countries and regions (Figure 6). In the EU, Japan and the United States, the value stranded is concentrated in buildings, with more than 95% of total value stranded under REmap being from that sector. This reflects the fact that these are advanced economies with well-developed property markets, extensive mortgage liabilities and high average property values. Buildings are also, on average, older and there are very low levels of building turnover (i. e. few new buildings).

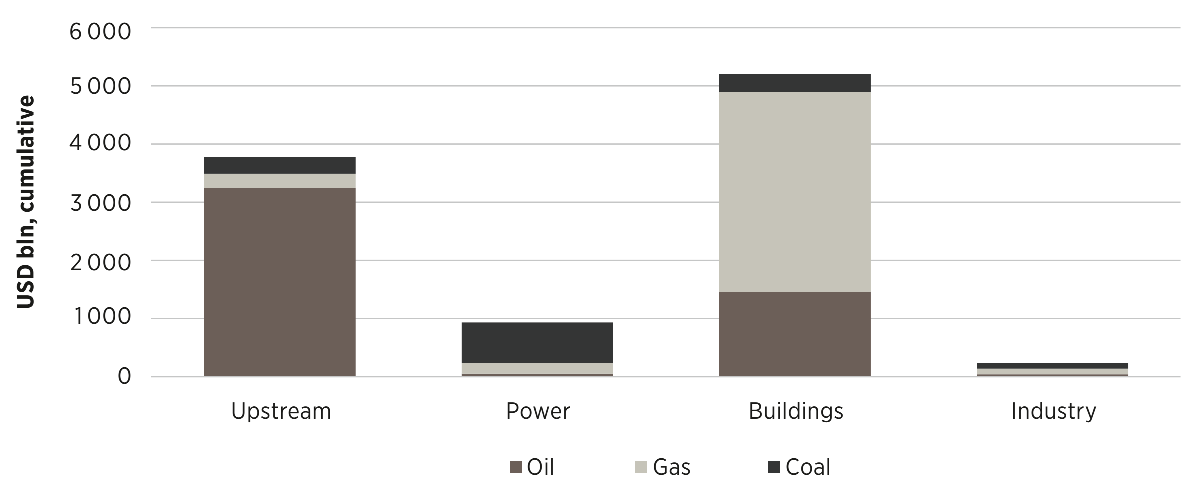
In China and India, power generation would be a much larger share of total stranded assets, at between 25% and 45% of total value. This reflects the large exposure of these countries to coal-fired power plants that are relatively new and not fully depreciated. These would absorb the brunt of efforts to decarbonise the power sector.

Countries such as Brazil and China would see significant stranding of industrial assets. This reflects the fact that they have large and inefficient industrial production facilities, particularly concentrated in heavy industry.

The countries in which the stranding of upstream energy assets would be significant are those with large oil, gas and coal reserves. Australia, Brazil, Canada, Indonesia, Mexico, the Russian Federation, Saudi Arabia and South Africa would see the largest proportion of stranded upstream assets.

In terms of stranding within upstream energy, the fuel types (oil, gas and coal) and the geographic locations of these fuel types make significant differences. In terms of value stranded under REmap, 7% is gas and 85% is oil, with only 8% being coal. Under Remap, the total value of stranded coal assets (USD 1.4 trln) is significantly smaller than values for gas (USD 4.0 trln) and oil (USD 4.8 trln). Yet, in terms of emissions benefit, the stranded coal assets are by far the most significant. Of the total reductions in direct CO_2 emissions in the REmap case versus a business-as-usual outlook for 2050, 48% come from the reduced use of coal, compared to only 29% for oil and 23% for gas.

Figure 7: Stranded assets by sector and fuel type with REmap



Source: IRENA analysis

The clear majority of stranded oil assets occur upstream, rather than in the power, buildings or industry sectors (Figure 7). Oil is primarily used in transport. As ultra-low emissions and electric vehicles reach maturity, oil demand and oil prices will drop, reducing the value of oil reserves. Relative to the demand from transport, the demand for oil from power generation heating in buildings and industry is minor.

Gas assets would be stranded across each of the four sectors. Stranded gas assets in buildings would be large. They result from replacing gas heating systems that currently are widely deployed, particularly in advanced economies in the Northern Hemisphere. Although gas is cleaner than oil and coal, it remains incompatible with the required levels of decarbonisation. As a result, significant gas stranding upstream and in gas-fired power generation are seen.

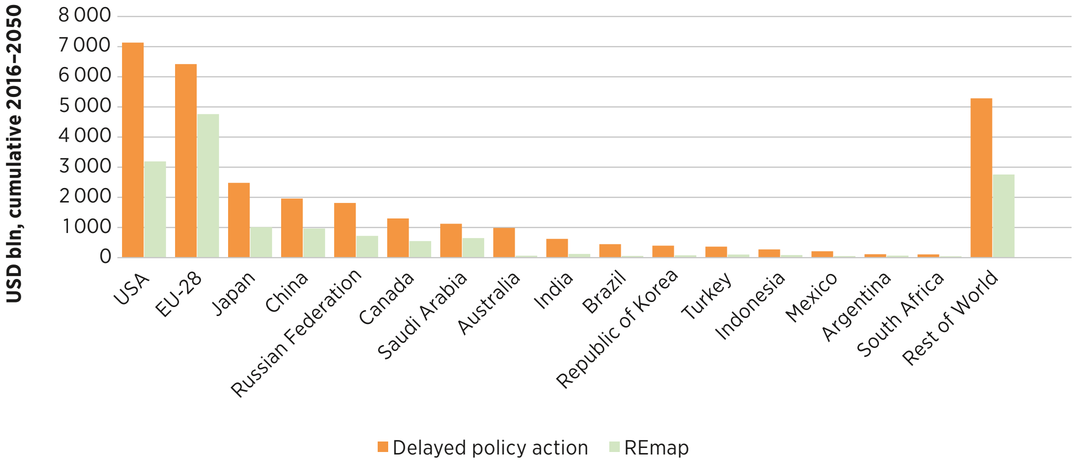
Coal assets would also be stranded across each of the four sectors, although the sector that would see by far the largest amount is power generation. Coal-fired power generation is a major source of direct CO_2 emissions (about 25% of the global total), and much of the policy effort has been focused on phasing out coal or limiting its growth, and this appears set to continue. For example, Canada, France and the United Kingdom have recently announced phase-outs of their coal-fired power plants (BBC News, 2016). Given the relatively modest value of stranded coal-fired power assets and the plants' high level of emissions, this approach is a cost-effective way of achieving decarbonisation. Furthermore, it is likely to contribute to avoiding "carbon lock-in".

The countries that appear to see disproportionately larger stranded assets under Delayed Policy Action are China, the Russian Federation, Saudi Arabia and the United States (Figure 8). In the case of the United States, this is due to relatively lower levels of ambition included in the Reference Case for 2030, based on modest anticipated renewables deployment, outlined in the U.S. Annual energy outlook 2017 with projections to 2050 (EIA, 2017). This means that the gap between business as usual and accelerated action is greater for the United States than for many other countries.

For China, the projected expansion of coal power plants up to 2030 in the Reference Case signifies that new power generation assets will be stranded prior to the end of their anticipated useful lifetimes after 2030, thus increasing the scale of asset stranding. For Saudi Arabia and the Russian Federation, significant additional upstream capital expenditures up to 2030 under Delayed Policy Action also result in significant asset stranding.

The United States and the European Union, combined, would account for more than 50% of the total global value stranded under REmap and Delayed Policy Action. The Russian Federation and Saudi Arabia would see approximately 10% of the total global value stranded, with China and India at 8% of total stranded assets.

Figure 8: Stranded assets by region/country – with REmap and Delayed Policy Action



Source: IRENA analysis

Box 2: The significance of technology lock-in: power sector case

In calculating the value of stranded power plant assets, a power plant's economic and technical lifetimes were assumed to be equal. Should a plant be shut down before it reaches the end of its lifetime, the nominal value (capital expenditure minus accumulated depreciation) is assumed to be lost.

The technical lifetime of an asset, however, is not the same as its economic lifetime. The economic life of a plant ends when marginal costs consistently exceed marginal revenues. This could happen due to market trends that cannot be perfectly foreseen at the start of operation (e.g. rising maintenance or input costs or lower than anticipated power prices). In practice, there also exists a grey zone of old plants that are mothballed or where operating hours are reduced significantly compared to new plants.

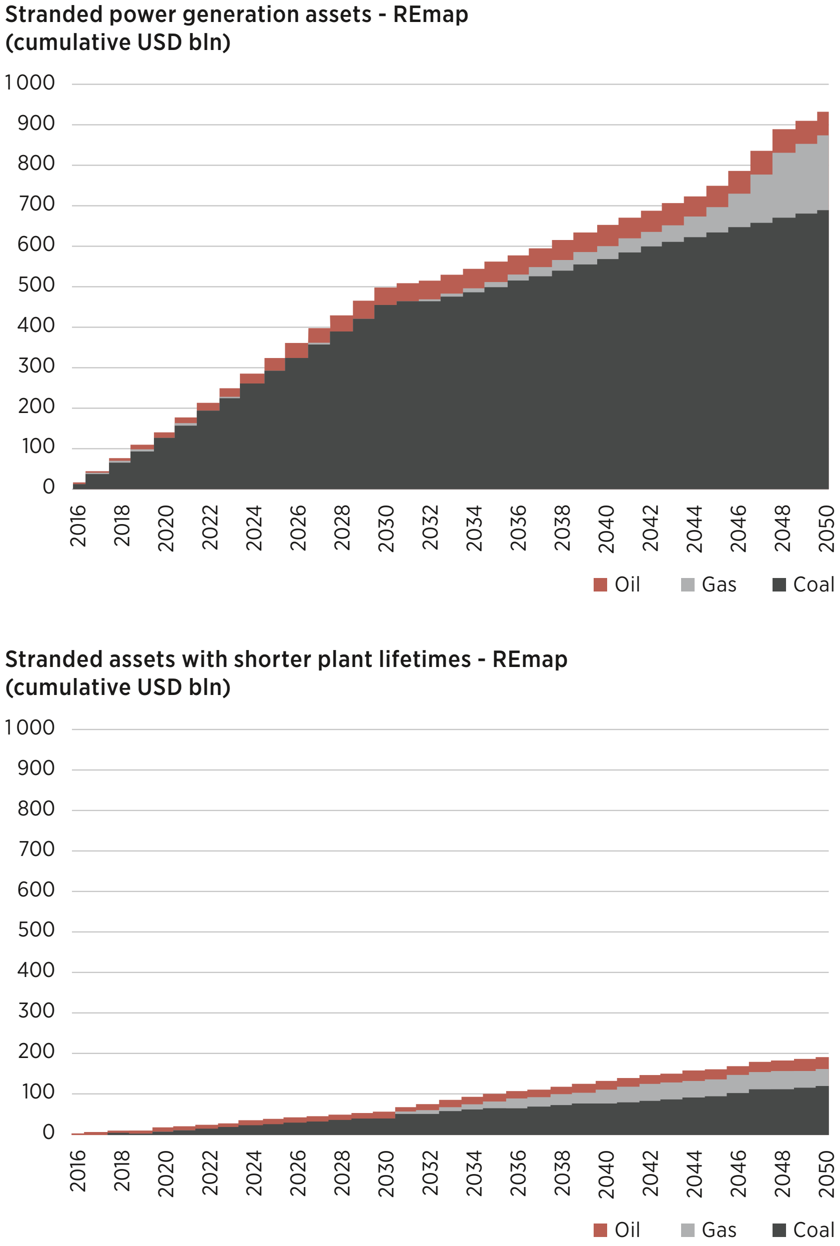
To account for the risk of reaching the end of an economic lifetime, companies might depreciate power plants over shorter periods than expected by their technical lifetimes. The assumed lifetime has significant implications on the stranded asset calculations in this study, in which the following technical lifetimes were assumed to be coal, 50 years; natural gas, 30 years; and oil, 50 years.

The resulting value of stranded assets in the REmap analysis is USD 940 billion (or about 3 800 gigawatts (GW)) (Figure 9). Were all companies to use these lifetimes to depreciate power plants on their balance sheets – and no asset impairments were to occur up to the point of stranding – then this is the value of asset impairments that could be expected up to 2050 due to decarbonisation.

Given that some companies, however, depreciate power plants over shorter periods of time or have already witnessed asset impairment in recent years for a variety of reasons, the impact of stranded assets might be more limited. In some cases, the assets that get shut down are those that have been written off and have little value left on the balance sheet.

If one assumes technical lifetimes of 50 years for coal and oil assets and 30 years for gas, rather than only the true economic lifetimes of 25 years for coal and oil and 15 years for gas, then 2 250 GW of 3 800 GW of total stranded assets in the REmap analysis would have economic value left at the point they are shut down.

Figure 9: Carbon lock-in through power generation assets, 2016–50



The remaining 1 550 GW (approximately 40% of the total) represents plants that are stranded with no remaining economic value, but that still have a remaining technical lifetime. With these assumptions, the value of stranded assets is USD 200 billion.

The balance sheet assumptions made by various countries and companies in valuing power-plant assets are difficult to assess. Shorter economic lifetimes, as assumed above, come with the risk of underestimating the magnitude of stranded assets. Electricité de France, for example, recently increased its depreciation period for nuclear plants beyond 40 years (UK Reuters, 2016). In some countries, plants run beyond their technical lifetime (recently, a 100-year-old, coal-fired power plant in Peru was decommissioned). Companies and countries would be well advised to report more transparently on the book value of power plant assets and, hence, their own exposure to the risk of stranded assets.

2.3 What do these findings imply for the various stakeholders?

The impact of asset stranding in upstream, power, industrial, and building sectors will vary significantly across the fossil fuels and the countries examined. The impacts are in no way evenly distributed.

There are some clear high-level implications based on this analysis. Developing countries, in particular, can reduce the value of future stranded assets by immediately accelerating policy action. Delaying action and continuing with the business as usual outlook means that future course corrections will result in significantly more asset stranding. Developed countries with low ambition plans for decarbonisation suffer from a similar problem and should seriously consider increasing their levels of intent to avoid stranded assets in the future which are accompanied by negative economic impacts.

In addition to these macro differences between fossil fuel sectors and countries, however, stranded assets will also affect a range of different stakeholders within countries in diverse and potentially significant ways. There are four key groups that will be affected: companies, investors, governments and workers. Each of these groups will be affected differently, and their capacity to take account of stranded assets will vary.

Companies

Corporations, whether listed, state-owned or non-listed, already suffer from stranded assets in key markets. The drivers of change are diverse and have multiple causes, although climate change concerns are a significant motivation in an increasing number of jurisdictions.

In the case of property, there are significant holdings through various corporate structures, such as Real Estate Investment Trusts. These could be particularly exposed to regulatory requirements that mandate energy efficiency improvements and retrofits.

In the case of power generation, thermal generators in Europe (often a guide to what might transpire in other power markets) have been suffering significant write-downs because of several interlocking factors, in particular, the unexpectedly rapid deployment of low-marginal-cost renewables which drive down wholesale electricity prices. In the United States, the shale gas revolution has resulted in a glut of cheap U.S. coal in Europe. The availability of this inexpensive, imported coal has undermined the competitiveness of brand new gas plants in Europe (Caldecott and McDaniels, 2014a). Together, these trends have significantly depressed the profitability of European power utilities, resulting in hundreds of billions of euros in lost market capitalisation (Ibid.).

Listed upstream oil and gas producers also face unprecedented challenges, with climate change concerns likely to exacerbate existing pressures. The limited availability of low-cost fossil fuel reserves due to competition from state-owned companies; the improvements in vehicle efficiency and changing transport modes that are reducing demand for transport fuels; and the faltering technical and financing advantages of oil and gas are cited as examples of factors that currently affect oil and gas company values and are stranding assets in that industry (Stevens, 2016).

Industrial companies, particularly large energy-intensive users, may need to upgrade to more efficient manufacturing or industrial processes or have CCS applications to be compatible with decarbonisation. In many cases, the cost of these changes could be completely or partially offset by reductions in energy costs, although this would depend on energy prices and a price of carbon, both of which are likely to vary significantly by country or region. While fuel savings may result in a neutral impact on value over the lifetimes of such capital improvements, this may also depend on access to low cost and suitably long duration financing, which may not be universally available.

Stranded assets in the transportation sector were not explicitly estimated in this study, although the automobile industry is experiencing structural change, with environmental concerns and rapid innovation as the key drivers. This is particularly relevant to future oil demand and the sectors upstream and downstream of automobile manufacturing.

Arguably the automobile sector is now experiencing its most significant period of change in at least 40 years, opening the industry to new entrants, radical innovation and potentially unprecedented transformation. Concerns about diesel pollution and carbon emissions from road transport have been growing for some time, particularly in Western Europe. The recent diesel scandal involving cheating on emissions testing, however, has elevated the issue significantly. This has called for stricter regulations and greater government incentives for cleaner alternatives, as well as a rethink of the development strategy in many car manufacturing companies.

These developments may have important ripple effects beyond car manufacturing, because changes in vehicle production and use have direct ramifications for the demand for natural resources in manufacturing (e. g. steel, aluminium, lithium), fuel (e. g. petrol, diesel, liquid natural gas, electricity, hydrogen) and products across the supply chain (e. g. batteries, furnishings), as well as for physical infrastructure (e. g. fueling, charging, intelligent sensors and computation), and financial services (e. g. demand for vehicle insurance). Developments in the automotive sector can significantly affect company and asset values in a wide range of other businesses.

Key challenges for companies to effectively manage stranded assets include perceptions of time horizons and the issue of sunk costs. Endemic short-termism is well documented, particularly among listed companies that report quarterly. Short-term outlooks could make it more difficult for companies and their executives to take pre-emptive action to avoid asset stranding (Generation Foundation, 2013).

Moreover, companies may suffer from deep-rooted reasoning and perceptions that prevent them from acting on sound evidence of the forthcoming of stranded assets. There is a well-documented behavioural tendency to continue with activities already invested in, despite such activities being not economically rational (Kahneman and Tversky, 1979). In the case of asset stranding, these sunk costs could be a very significant barrier to companies responding to policymakers' objectives on decarbonisation. Companies could be wedded to previous strategies (their sunk costs), despite the fact that maintaining the same course would be economically irrational. This could exacerbate the issue of stranded assets as companies throw good money after bad and further delay action due to loss aversion. It is also likely to result in companies actively lobbying to reduce the scale and pace of the low-carbon transition.

Financial institutions

As the analysis and the literature review in Section 1 indicate, the potential financial losses from stranded assets could be very significant, particularly if action is delayed. There are many participants in the investment chain, including but not limited to actuaries, asset owners, asset managers, accountants, banks, central banks, data providers, investment consultants, lawyers, multilateral development banks, ratings agencies and stock exchanges. Each of these groups, in mature and developing capital markets, could be affected by stranded assets in various ways.

Financial institutions, nevertheless, share common characteristics that make it hard to take account of risks, such as stranded assets, that are novel, non-linear and medium to long term (Kay, 2012; Thomä & Chenet, 2017). These include endemic short-termism, misaligned incentives and misinterpretations of fiduciary duty, among others (Kay, 2012; Carney, 2015). These are issues that make it hard for many financial institutions to engage with stranded assets and topics relating to environmental change on a broader basis.

Asset stranding is becoming a topic of greater interest to some financial institutions and finance practitioners. Stranded asset arguments have underpinned successful efforts to shift capital away from "brown" investments towards "green" investments, based on an enhanced understanding of environment-related risks (Caldecott et al., 2016a). These arguments also form the basis for a fossil fuel divestment campaign, the fastest-growing divestment campaign in history (Ansar, Caldecott and Tibury, 2013). The movement currently claims that 688 institutions with USD 5 trln of assets have committed to partially or fully divesting from fossil fuels (Arabella Advisors, 2016).

The Bank of England and other central banks, by showing sustained interest in stranded assets at the highest levels (Bank of England, 2015), have sent signals to the market and have encouraged functions within previously non-engaged financial institutions to become more engaged.

In addition to these developments, new products to address stranded assets are increasingly being launched. Examples include indices that are weighted away from the risk of stranded assets (Fossil Free Indexes, n. d.), exchange traded funds that employ such indices (State Street Global Advisors, 2016) and credit ratings that integrate stranded asset risks (Standard & Poor's, 2014; Center for International Environmental Law, 2015).

Government liabilities and reduced tax take

Governments (local, provincial, national and supra-national) are exposed to stranded assets in a wide variety of ways. Current or planned investments, made directly by government departments or via state-owned banks or investment vehicles, could also be at risk. So too could indirect exposure to such investments through loan guarantees or other contingent liabilities.

The impact is unlikely to be uniform and will vary significantly by country and government tier. Delayed action will potentially make the process of adjustment much harder for affected governments, whereas timely action to diversify the tax base could reduce the risk of fiscal shock. In addition to the tax base being affected, the ability to borrow from capital markets could be curtailed, with credit rating downgrades occurring as the implications of fiscal impacts become clearer.

This has significant implications for not only existing fossil fuel producers but also for countries that are developing and considering which sectors to develop. A fossil fuel export-led development model entails significant risk for the future.

Workers

Decarbonisation will result in asset stranding in carbon-intensive sectors (which has the potential to slow down transition and the realisation of Nationally Determined Contributions. The mere threat of stranded assets could cause groups that are potentially affected to attempt to delay or block low-carbon transition. Specifically, those groups that would lose employment because of asset stranding are likely to be most active. National governments and other stakeholders, however, can and should avoid such opposition through timely transition planning.

These issues are already being felt in different parts of the world. In 2016, China announced a USD 15 bln compensation fund for unemployed iron and steel workers and coal miners (Wood Mackenzie, 2016). The plight of Appalachian coal miners was a key issue in the 2016 U.S. Presidential election, with coal-mining counties playing a decisive role in battleground states. The challenges facing coal-mining communities in Germany and Poland have also become an issue for national and provincial governments, having an influence on burden sharing negotiations within the European Union (Krukowska, 2016).

The sectors most likely to generate the most political economy "friction" from asset stranding are those that are large employers where employment is highly concentrated. Upstream fossil fuel production and manufacturing are two sectors that share these characteristics. Stranded building assets are less likely to create labour disputes, although they are more likely to generate concern among property owners.

A growing literature explores the concept of "just transitions" underlining the equity issues that surround national decarbonisation strategies. This literature identifies the need for transition towards a low-carbon global economy; it also recognises the fact that developing and developed countries face different risks and opportunities, having varying levels of capacity for mitigation of and adaptation to environmental changes (Caldecott et al., 2016a).

This is a salient issue for developing countries whose right to development and access to affordable energy has to be aligned with low-carbon transition goals (Swilling and Annecke, 2010). This implies exploring the best possible outcomes for those whose livelihoods are affected by or dependent on a fossil fuel economy, and who will otherwise lose their jobs and communities (Newell and Mulvaney, 2013).

Reallocation of resources and provisions of transition assistance for those individuals and communities affected by climate change and related policies could facilitate a just transition (Caldecott et al., 2016b; Newell and Mulvaney, 2013). This might be more likely to occur in developed countries, where citizens tend to demand higher relocation costs and where stronger unions demand higher settlements for loss of earnings (Funk, 2014). Rosenberg (2010) suggests that job losses are not a direct result of national climate policies; rather, they are caused by a lack of social policies and by the anticipation of and investments in alternative mitigation measures. Thus, providing adequate support for sectors that are losing out in a low-carbon future and generating new employment opportunities in low-carbon sectors are critical to ensuring a just transition (Jagger, Foxon and Gouldson, 2013).

2.4 Are there ways to minimise stranded assets while achieving decarbonisation targets?

To avoid asset stranding caused by physical climate change impacts, polluting assets must be stranded before they emit the emissions that will irreversibly alter the climate. Fortunately, stranding assets to ensure timely decarbonisation can be done with significantly less cost if acted upon sooner rather than later.

There are significant co-benefits of acting early that are not shown here, although they are captured in IRENA's global REmap analysis (IEA and IRENA, 2017). There are the avoided cost of climate damages from limiting warming below 2°C, which is estimated at USD 1.5–3.3 trln a year in 2050 in IRENA's REmap analysis. There are also the avoided deaths and healthcare costs as a result of reduced air pollution from road transport and power generation. Those avoided costs are estimated at USD 2.3–6.5 trln a year in 2050. These human welfare benefits offset the increased energy system costs, which include the additional investments in low-carbon technologies and the stranded assets. There also are likely to be significant benefits to biodiversity and the natural environment, not the least from significantly curtailed coal mining operations and oil and gas exploration. Highlighting these benefits to stakeholders, especially the broader society, can help create the necessary buy-in for expediting action to avoid stranded assets.

As these benefits are assessed and the minimisation of the cost of action is considered, the difference between "temporary" and "permanent" asset stranding is important. An asset that is devalued due to falling commodity prices should be clearly distinguished from an asset that is closed and is no longer operational. To ensure decarbonisation and to achieve climate outcomes, polluting infrastructure has to be permanently closed, not temporarily mothballed (Caldecott et al., 2016a). Mothballing comes with the risk that assets may be reused, for example, when the market temporarily improves.

Policymakers will likely need to create frameworks and mechanisms that result in the permanent closure of carbon intensive assets, and they should do so in ways that are low cost and address the impacts of asset stranding on government budgets, communities, employment and financial institutions. This will require a range of multifaceted policy responses. The subsequent section explores the nature of these responses.

3. ACTION AREAS

This section identifies some high-level action areas for consideration by policymakers. They are based on the findings from this IRENA analysis.

3.1 Availability of finance

To avoid stranded assets by accelerating the renewables deployment and energy efficiency improvement under REmap, sectors will require appropriately low-cost and long-duration financing to realise the required investments and retrofits. Without this finance, particularly for buildings, power generation and industry, business as usual is more likely to prevail, whether or not there are strong macroeconomic incentives to make such investments. In some developed capital markets, this will be less of an issue; for smaller and less mature capital markets, however, the availability of low cost and long duration finance can be constrained.

Policy makers have a number of tools at their disposal to ensure that this necessary financing is available. In least developed countries, this may entail greater concessional finance (including subsidised loans, loan guarantees and credit risk insurance) with the support of developed countries, through overseas development assistance or through multilateral development banks, as well as the capitalisation of local public and private financial institutions.

In developed economies, ensuring the smooth refinancing of operational renewables and energy efficiency projects, particularly in the debt capital markets, is critical to enable the lowering of the average cost of capital for projects and to make it possible for equity to be recycled back into the earlier stages of project development. These markets are not yet functioning smoothly. Project bonds and asset-backed securities for renewables and energy efficiency could be kick-started through public institutions buying first-loss tranches or providing credit guarantees.

3.2 Curtailing investment in upstream energy

Upstream energy investments would face significant stranding in a Delayed Policy Action pathway. An estimated potential of USD 7.5 trln of these assets could be stranded, 85% of which would reflect the oil industry. Curtailing upstream investments today is a very important way to reduce the total value of stranded assets in the future. The challenge is that companies, together with governments, have the incentives to invest in upstream production and exploration. Governments have historically seen such developments as a way to support their fiscal position, increase energy independence and create jobs. Listed companies are incentivised through financial markets by ratios they are measured against, such as the Reserve-Production Ratio and the Reserve-Replacement Ratio.

Perhaps the most direct way of reducing these incentives is for governments to re-evaluate their own upstream investments and to establish how they license listed companies undertaking such investments in their jurisdictions. Policy makers and regulators can also improve the transparency of stranded asset risks facing such investments, which may encourage financial institutions to put pressure on companies to reduce upstream investments.

3.3 Coal phase-out

While the total value of stranded assets in coal-fired power generation is significantly lower than the value of stranded assets in the other sectors considered here, it has an outsized impact on decarbonisation. Without a very significant reduction of coal-fired power generation, achieving a carbon budget that limits temperature increase to 2°C is unlikely. There are also significant benefits from phasing out coal sooner, rather than later, which can help to reduce pressure on the scale and pace of required decarbonisation in other sectors. Early action on coal also reduces the total amount of stranded coal assets.

3.4 Energy efficiency retrofits and higher standards for new buildings

Buildings, particularly in developed economies, generate by far the largest quantity of stranded assets. Policies to enable deep energy efficiency retrofits of residential and commercial property in these countries thus will be essential, with a significant benefit associated with introducing these mechanisms as swiftly as possible. PAYS schemes, tax incentives, energy performance regulations and the provision of concessional finance have demonstrated success in some jurisdictions for energy efficiency retrofits and they provide important case studies for policy makers.

In developing economies, the quantity of new build relative to existing building stock is much higher up to 2050 than in developed economies. Thus, having suitably ambitious building standards and regulations for new buildings will be crucially important.

3.5 Improving the efficiency of industry

Industry can benefit from the cost savings that come from energy efficiency improvement. These savings would provide incentives for industry retrofits, aligned with decarbonisation pathways. This self-interest alone, however, may not be sufficient to deliver enough decarbonisation. Policy makers can further encourage industry to invest in retrofits and energy efficiency improvements through tax incentives, regulatory standards and concessional finance. Each industrial process will have different technical potentials and costs, and policy makers will have to tailor their approaches accordingly. Governments can also invest in enabling infrastructure for industrial CCS in processes that generate flue gas with high CO_2 concentrations.

3.6 Stronger policy signals

Companies and investors may suffer from cognitive biases that prevent them from acting on the evidence of forthcoming stranded assets. Policy makers should provide stronger signals and foreground these issues more clearly for stakeholders. This could help prevent companies and investors from throwing good money after bad and further delaying action due to loss aversion, thus increasing the amount of stranded assets under delayed action.

The required policy signals, which may need to be stronger than what standard economic models suggest, could include higher carbon prices and pricing of fair local air pollution and health impacts of fossil fuel use, larger economic incentives, and/or tighter regulation. Regulators may also highlight these issues for decision makers through appropriate transparency – requiring more information to be provided for investors deciding which companies to invest in or for customers deciding which products to purchase. There could also be duties placed on company directors to force them to consider these issues more systematically.

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ANNEX A. METHODOLOGY, ASSUMPTIONS AND DATA SOURCES

Sector	Definitions	Methodology
Upstream	Unrealisable value of existing and planned assets of upstream coal, gas and oil producers	1. Aggregate valuation of upstream coal, gas and oil producing assets was estimated, based on current market valuation of major listed producers and valuation of non-listed producers was also estimated. 2. Valuation was based on reduced net cash flows and adjusted due to a reduced production outlook with REmap and Delayed Policy Action cases: indication of stranded value of existing assets.[11] 3. Subtracted from valuation in Delayed Policy Action case is the incremental capital expenditure beyond the REmap case: indication of stranded value of planned assets.
Power	Unrealisable value of existing and planned coal, gas and oil power plants that will be shut down before the end of their projected economic life	1. Using the age of current stock, the required capacity for each year (as per REmap and Delayed Policy Action) and an anticipated economic plant lifetime for each year 2016–50 was estimated for the capacity that is naturally retired and that is stranded (i.e. shut down before the end of its anticipated technical lifetime). 2. For the capacity that is stranded each year, the remaining lifetime of this capacity was estimated as a share of the anticipated technical lifetime, and this was multiplied by the plant's capital expenditure to calculate the stranded asset value. 3. The sum of each of the year's stranded asset value was calculated to achieve the total stranded assets by country.

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[11] Assuming that current production outlook reflected in upstream valuations is represented by a business-as-usual outlook (as per the Reference Case).

Sector	Definitions	Methodology
Industry	Unrealisable value of existing and planned process heat equipment that consumes fossil fuels and will be shut down before the end of their projected economic life	1. Using an estimate for the age of current and required capacity for each year as per REmap and Delayed Policy Action, and an anticipated economic equipment lifetime for each year for the period 2016–50, the capacity that is naturally retired and that is stranded was estimated (i. e. shut down before the end of its anticipated technical lifetime). 2. For the capacity that is stranded each year, an estimate was made of the remaining lifetime of this capacity as a share of the anticipated technical lifetime, and was multiplied by the plant's capital expenditure to achieve the stranded asset value. 3. The sum for each of the years this stranded asset value to achieve the total stranded assets by country was made.
Buildings	Unrealisable building construction value due to required deep renovation of existing and planned inefficient building stock	1. Estimated forecasted total building floor space and natural demolition rates were applied to calculate the new building floor space and existing floor space for each year, 2016–50. 2. Estimates were made for the existing building stock the share of buildings not directly consuming fossil fuels, and assumptions were made for REmap and Delayed Policy Action that all new buildings do not consume fossil fuels, beginning in 2020 and 2030, respectively. 3. Estimated for each year was the building floor space that needs to be deeply retrofitted to achieve the REmap/ Delayed Policy Action cases. 4. For this retrofitted building floor space, the stranded asset value was calculated as the difference between the cost of deep retrofit and the additional cost to build a new energy efficient fossil-free building: indication of construction value that is lost due to retrofit. 5. The sum of the years this stranded asset value to achieve the total stranded assets by country was made.

Sector	Assumptions	Data Sources
General	• Stranded asset values presented are in real 2016 U.S. dollar terms. • REmap case: based on IRENA's REmap analysis for 2030 and 2050, by 2050: 30 gigawatts of fossil fuel power capacity, 90% reduction of fossil fuel use in buildings, 50% reduction of fossil fuel use in industry, 70% reduction in total fossil fuel primary energy use. • Delayed Policy Action case: based on IRENA's Reference Case 2030 analysis and REmap analysis for 2050.	
Upstream	• Aggregate valuation of existing upstream assets: oil (USD 11 900 billion); gas (USD 1 300 billion); coal (USD 795 billion, based on current (estimated) valuation of fossil fuel producers, their share in global production, and the share of company valuation related to upstream operations (as per the share of upstream in total operational income in recent years). • Assumed net cash flow per produced energy unit changes during 2016–50 by the implied annual price change of oil/gas/coal as per the IEA World Energy Outlook 2016 New Policies Scenario 2015–40; discount rate of 10% assumed to discount future net cash flows to arrive at current valuations. • Additional capital expenditure beyond REmap for the Delayed Policy Action case: oil (USD 158 billion/year), gas (USD 55 billion/year); coal (USD 15 billion/year). Approach in-line with previous analysis carried out by the Carbon Tracker Initiative (2015).	• Current market valuation of upstream producers: oil (Saudi Aramco, Sinopec, BG Group, Shell, ExxonMobil, etc.); gas (Gazprom, WPX Energy, Vanguard, etc.); coal (PwC, 2016). • Fossil fuel production for non-energy and annual fossil fuel price change (IEA, 2015). • Discount rate (Carbon Tracker Initiative, 2016). • Additional capital expenditure beyond REmap for the Delayed Policy Action case, based on IRENA estimates and Carbon Tracker (2015).
Power	• Plant lifetimes: coal (50 years), gas (30 years), oil (50 years) • Plant capital expenditure: coal OECD (USD 3 000/kilowatt (kW)), coal non-OECD (USD 1 300/kW); gas OECD (USD 1 000/kW), gas non-OECD (USD 1 200/kW), oil OECD (USD 1 200/kW), oil non-OECD (USD 1 200/kW)	• Distribution of existing fossil fuel power capacity stock based on Platts WEPP (2015). • Plant lifetimes based on (NREL 2010). • Capital expenditure assumptions based on NREL (2010) and IRENA (2016).

Sector	Assumptions	Data Sources
Industry	• Assumed 80% conversion efficiency and 75% capacity factor to estimate power capacity (in gigawatts) of fossil fuel powered industrial equipment • Assumed age distribution of current industrial equipment stock is same as distribution of total fossil fuel power capacity stock • Industrial equipment lifetime: 50 years • Industrial equipment capital expenditure: USD 500/kW	• Distribution of existing fossil fuel power capacity stock based on Platts WEPP (2015). • Equipment lifetime: based on IRENA estimates and Worrell and Biermans (2005). • Capital expenditure based on IRENA estimates.
Buildings	• Building floor space: increases from 130 billion square metres (m^2) in 2013 to 252 billion m^2 in 2050. • Natural building demolition rates: range from 0.13%/year (European Union) to 1%/year (China). • Share of existing buildings that does not directly use fossil fuels: 15–50% for residential buildings, 5–75% for commercial buildings. • Construction value by country: ranges from USD 169/m^2 to USD 180/m^2 for residential buildings and USD 273/m^2 to USD 658/m^2 for commercial buildings. • Cost of deep retrofit: average across countries at 46% of construction value for residential buildings (range of 23–71%), 52% of construction value for commercial buildings (range of 32–88%). • Premium of new fossil-fuel free building: average across countries at 24% of construction value for residential buildings (range of 11–47%), 21% of construction value for commercial buildings (range of 14–38%).	• Building floor space based on Navigant (2015) and Ürge-Vorsatz et al. (2015) for growth rates up to 2050. • Natural demolition rates: IRENA estimates based on various sources, including Housing Europe (2015); Kees and Haffner (2010); McArdle (2011); Shepard (2015); and GBPN (2015). • Construction value per country, cost of deep retrofit and premium of new fossil-fuel free building: IRENA estimates based on annexes to GBPN (2015); deep retrofit cost based on estimates per region for “advanced retrofit”; new fossil-fuel free building premium based on cost of “advanced new buildings”.

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