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STRANDED ASSETS AND THE FINANCIAL SYSTEM

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Abstract

There has been a burgeoning interest and literature on the risks associated with stranded assets. This paper aims to present an overview of this literature with a focus on the risks to the financial system associated with stranded assets and why these risks need to be a concern to central banks. It considers various definitions of stranded assets and its expanding scope while focusing more narrowly on climate-related risks and how these affect the financial system. Two main channels of climate-related risks are discussed in depth: risks of physical impacts from climate change and risks associated with the transition to a low-carbon economy. Reasons why the financial system may inadequately account for these risks are presented along with corrective policies on the part of investors and central banks. The paper also considers the special challenges and threats to financial stability associated with the historically unique sustainability transition needed to achieve the targets set by the Paris Agreement.

JEL-classification: G2, Q54
Keywords: stranded assets, climate change, financial stability

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1. Introduction

There has been a burgeoning interest and literature on the risks associated with stranded assets. The idea of stranded assets is not new but its specific association with potentially unburnable fossil fuel reserves given our need to limit CO_2 emissions has struck the imagination and raised a concern that potential sudden devaluations of these assets could create shocks to the financial system. In this sense, 'stranded assets' became a rallying cry that large parts of the business community and the financial world (investors, companies, asset managers, and banks) need to wake up to the stark contrast between global political commitments to protect our planet from climate change and their apparent "business as usual" attitude. Many in the financial community have responded to this concern and along with international organizations, NGOs and the academic community have shed light on many aspects of this particular concern but also broadened the scope of issues that need to be addressed under the rubric of stranded assets. The fast expanding literature is still young and fairly limited in terms of peer reviewed academic publications.

This paper aims to present an overview of this literature with a focus on the risks to the financial system associated with stranded assets and why it needs to be a concern to central banks. The paper begins with a discussion of the various definitions of stranded assets. The first section points to the expanding scope of the notion of stranded assets to environment-related risks more generally before narrowing the scope to climate-related risks per se and how these affect the financial system. Two main channels of climate-related risks are discussed in depth: risks of physical impacts from climate change and risks associated with the transition to a low-carbon economy. The next section looks at potential reasons why the financial system may be unable to adequately account for these risks which provides the rationale for why specific actions and policies may be required to address these failures both on the part of investors as well as that of central banks. The final section takes a step back and looks at the big picture in terms of major technological transitions and the potential threats they raise to financial stability and what the special challenges might be from the historically unique sustainability transition that is before us.

1.1. Defining stranded assets

There are several definitions of stranded assets used in the literature depending largely on contexts. Accountants have used the term to refer to assets that become obsolete or non-performing but must be recorded as a loss of profit on the balance sheet (Deloitte, 2016). Regulators have used the 'stranded costs' or 'stranded investments' to capture the decline in value of electricity-generating assets resulting from the restructuring of industry. The power market liberalisation of the 1990s made this a major issue (Caldecott, 2017).

IEA (2013) provides a definition from an energy economist's perspective "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" IEA (2013, p. 98). The Carbon Tracker Initiative uses this definition and links the economic losses to those that are "a result of changes associated with the transition to a low-carbon economy" (Carbon Tracker Initiative, 2017). The Generation Foundation (2013) additionally specified the potential changes that could strand assets: 'legislation, regulation, market forces, disruptive innovation, societal norms, or environmental shocks' (Generation Foundation, 2013, p. 21).

Caldecott et al. (2013b) use a 'meta' definition to encompass all the different definitions and contexts: "stranded assets are assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities" (Caldecott et al., 2013b, p. 7). This definition avoids the explicit linking with environment-related risk factors that can strand assets and that has been the main focus of the recent climate change discourse. By doing so it allows potentially useful parallels with other contexts and indeed Caldecott et al. (2013) highlight the fact that asset stranding "in fact occurs regularly as part and parcel of economic development". They point to Schumpeter (1942) 'creative destruction' describing the dynamic process characterising capitalist economies where value is created and destroyed through innovation. In considering the challenges associated with a low-carbon transition there are many lessons to be learned by studying past technological transitions (Caldecott, 2017).

2. Climate-related risks of stranding

2.1. The expanding scope of environment-related risks to assets

The discussion on stranded assets has sometimes led to differences in the scope of term in the general context of climate change. Some have focused on the stranded assets created by international climate change policy, others on the risks that arise to assets from the range of societal responses to physical climate change impacts (Bank of England, 2015b) and some have included the risks associated with the physical environmental change as well (Bank of England, 2015a; Caldecott et al., 2013). The latter more comprehensive view allows many more sectors to be included like water risk and stranded water assets (Lamb, 2015), agriculture (Caldecott et al., 2013; Morel et al., 2016; Rautner et al., 2016). Figure 1 captures this more expansive interpretation with a typology for different environment-related risks that could cause stranded assets. The key distinction made by Caldecott et al. (2013) is that between *physical environmental risks* and *societal environmental risks.* In the first case the risks arise from direct physical damage associated with environmental problems while the second involves risks that result from how society reacts to address environmental issues.

The possibility that environmental policy and regulation could have a negative impact on the profitability of fossil fuel companies including the possibility that they could become impaired is acknowledged by individuals and organizations in the late 1980s (Krause et al., 1989). Furthermore, Krause et al. (1989) explicitly raised many of the issues that twenty years after his publication have recently come to the forefront of the stranded assets debate. Indeed, the initial proponents of the discourse in the early 2010s were unaware that their ideas had actually originated much earlier (Caldecott, 2017). Specifically, Krause et al. (1989) had pointed out that "tight carbon budgets implied by climate stabilisation greatly reduce the long-term value of fossil fuels" and that "any economic infrastructure built up mainly on the basis of fossil fuels risk early obsolescence" (Krause et al., 1989, p. 164). They also made the explicit link between this obsolescence and the implications for the financial markets as fossil industries confronted the risks that retrenchment from fossil fuels would have on the value of stocks. Finally, they highlighted the great gap between conventional wisdom in the energy industry as revealed in energy planning and the implications of climate stabilization. As Caldecott et al. (2013) point out, "unfortunately, these novel ideas for the late 1980s were largely ignored and then forgotten".

It should also be kept in mind that low-carbon transition risks may not always be associated with the fossil fuel industries. Some have argued that the support for certain forms of renewables along with the nature of that support brought about a 'renewables bubble' that also led to the stranding of substantial assets dedicated to renewable energy.

Caldecott (2017) argue that recent developments illustrate that environment-related risks in addition to those related to unburnable carbon can have a significant impact on assets today and that the significance will increase with time. Furthermore, these may be more material in the short to medium term than the risk of unburnable carbon or the carbon bubble

(Caldecott, 2017). Concrete examples include the threat to coal-fired power generation by air pollution and water scarcity in China. The changed coal demand has already affected global coal prices (Caldecott, Tilbury, & Ma, 2013). High-efficiency gas plants in Europe have been stranded by the downward pressure on coal prices resulting from the US shale gas revolution (Caldecott & McDaniels, 2014). Figure 2 provides some examples of physical environmental risks. The fossil fuel divestment campaign is an instance where social pressure is contributing to the potential stranding of assets and could lead to the increase of the targeted companies' capital costs. More generally there are many potential environment-related risks that derive from society's response to environmental issues and these need not be confined to climate-related environmental issues. Figure 3 provides some examples of societal environmental risks.

Physical environmental risks to assets can come from the many impacts associated with climate change such as droughts, floods and storms, sea-level rise, heat waves and extreme weather events. These impacts include direct damage to property, those that can arise indirectly like the disruption of global supply chains, as well as lower productivity of agriculture, human labor and physical assets. Again, in an expansive understanding of environmental-related risks, these can also be the result of other environmental problems like biodiversity and habitat loss, water pollution, air pollution and depletion of natural resources.

The stranded asset literature remains very recent and peer-reviewed academic literature is still very limited. Most of the work can be found in publications by international organizations, banks, insurance companies, NGOs, and working papers by academics. Numerous research topics have arisen in relation to 'stranded assets' and the way that these influence issues facing investors, companies, policy-makers regulators, and civil society in relation to global change. These are nicely summarised by Caldecott (2017):

> "Measuring and managing the exposure of investments to environment-related risks across sectors, geographies, and asset classes so that financial institutions can avoid stranded assets (e.g. see Carbon Tracker Initiative (2011), Caldecott (2011), Caldecott et al. (2013), Generation Foundation (2013), Financial Stability Board (2015)).
>
> Financial stability implications of stranded assets and what this means for macroprudential regulation, microprudential regulation, and financial conduct (e.g. see Carbon Tracker Initiative (2011); Caldecott (2011), Bank of England

(2015a), Kruitwagen et al. (2015), Caldecott et al. (2016a)

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 (e.g. see Caldecott (2015)).

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 (e.g. see Carbon Tracker Initiative (2013b), Ansar et al. (2013), Rook and Caldecott (2015)).

Underpinning arguments by civil society campaigns attempting to secure rapid economy-wide decarbonisation in order to reduce the scale of anthropogenic climate change (e.g. see (Ansar et al. 2013)).

Keeping track of progress towards emission reduction targets and understanding how 'committed emissions' should influence decarbonisation plans developed by governments, as well as companies and investors (e.g. see Davis (2014), Davis and Caldeira (2010), Pfeiffer et al. (2016))"

2.2. Climate-related risks to the financial system

To the extent that the literature has focused on climate-related risks of stranding assets rather than the more expansive environment-related risks (physical and societal), the standard classification has been between the essentially parallel concepts of climate-related *physical risks* and *transition risks*. Accordingly, the literature identifies two broad areas of climate-related financial risks. One is associated with the potential damages resulting from man-induced environmental changes that can adversely impact the economy (physical risk). The other broad area is associated with potential disruption resulting from the transition to a low-carbon economy and the policies implemented to support it (transition risk). Risks associated with climate change and society's response to it translate into existing categories like credit and market risk for banks and investors, or risks to underwriting and reserving for insurance firms.

In some ways the physical-transition classification reflects the standard way that timing and aggressiveness on climate action has been viewed in terms of striking a balance between the costs of mitigation (transition) and the damage associated with climate change. The asymmetry in the timing of these costs has been a big issue, i.e., that most damages from climate change will appear mostly in the future while the costs of transition appear mostly in the present and near future. When it comes to looking at the risks to the financial system a key feature is the element of surprise, the extent to which institutions and financial actors have not adequately accounted for potential risks associated with climate change or the transition to a low-carbon economy. The nature of uncertainty of both climate change and action to mitigate climate change makes such surprises more likely though this depends also on the extent to which the financial system develops tools to address such uncertainty.

The next two sections will provide an overview of the two channels for climate-related risks to the financial system starting with physical risks and then transition risks. Figure 4 provides a good overview of the relationship between climate risks and potential impact channels. There is also a small section on liability and other legal risks following a distinction made in the early work of the Bank of England (2015a) though this could also be subsumed in the two former categories.

2.3. Physical risks

Climatic change can lead to numerous disruptive phenomena such as coastal flooding, heavy precipitation, droughts, heat waves, and extreme weather events (IPCC, 2014a; IPCC, 2014b). The impacts on assets of households and businesses can be large, as well as on the balance sheets of the insurance companies and commercial banks from which they have borrowed funds (Batten et al., 2016; Dietz et al., 2016a). Large financial losses can result from direct and indirect physical impacts related to climate change like sea level rise, increased temperatures and catastrophic weather events. Uninsured households and corporations may shoulder the burden with asset values and the value of investments held by financial institutions being impaired. To the extent that losses are insured insurance firms will face the brunt of the impact through higher claims. Potential economic disruption, lower productivity and increasing sovereign default risk can also have wider systemic impacts (Scott et al., 2017).

Natural catastrophes have increased over recent decades leading to increases in both insured and direct overall losses. The average insured losses in the 1980s were around US$10 billion per annum (at 2013 prices) and are around US$45 billion per annum for this decade so far (Swiss Re 2014b). Over the past 30 years overall losses (insured and uninsured) have increased by about three times while the significant gap between insured and uninsured continues to widen (Schanz & Wang, 2014). The increasing value of property in high-risk areas (exposure) has been the primary driver of these losses. The trend in insurance losses derives mostly (85%) from economic growth and population migration to more coastal and urban areas. Weather and climate contribute to the remaining 15% (Aon Benfield, 2014).

By reducing the value of assets of households, banks and investors, e.g., property, and the profitability of firms, physical risks can lead to a deterioration of corporate balance sheets. The value of investments made by financial institutions may thus be impacted and the credit risk for banks may increase if the affected assets serve as collateral for bank loans. The financial impact could be further exacerbated if banks restrict lending as they suffer losses (Scott et al., 2017).

In some cases, damages resulting from specific events can be partially attributed to climate change. The estimated 20cm sea-level rise since 1950s at the Battery in New York contributed to a 30% increase in losses resulting from Superstorm Sandy according to Lloyd's of London (2014).

Caldecott and McDaniels (2014) develop three scenarios on how environmental issues could affect the stability of the global financial system. Bottom-up contagion refers to the case that mispriced environmental risks are repriced at sufficient speed and scale with possibly cascading effect that threatens financial stability. Capital flight could result from natural capital catastrophes resulting in negative capital outflows from an impacted country. Hazard globalisation refers to climate induced natural catastrophes and degradation of capital that significantly affect global markets and trade flows through price-based shifts, regulatory actions, or supply chain disruptions. For instance, global wheat prices doubled from 2010 to 2011 in response to supply shortages caused by shifting weather patterns. Both inflation and currency volatility can result from such changes and significantly impact countries dependent on imports.

There are a number of channels through which climate-related natural disasters could affect the soundness of individual financial institutions and the stability of the financial system. Figure 5 provides a nice overview of these channels. The way that losses are transmitted through the financial sector will depend on the extent to which losses are covered by insurance. In terms of total losses from the world's largest natural catastrophes from 1980-2015 only about 26% were insured (Batten et al., 2016).

2.3.1. The impact of insured losses on the balance sheets of insurers

If an event or series of events are sufficiently large and concentrated they can lead to distress or failure of insurance companies that cover the losses. Several insurance companies became insolvent because of Hurricane Andrew in 1992. Financial stability could be affected if critical insurance services and systematically important financial markets were disrupted. Asset prices of distressed insurers could fall through large-scale fire sales and this could adversely affect balance sheets of other financial institutions (Batten et al., 2016).

The extent to which insurance companies underestimate the risks is a key factor in determining the likelihood of distress or failures. The insurance industry has sophisticated approaches to modelling risk from catastrophes and other weather-related events. The combination of robust regulatory capital requirements, portfolio diversification, and the predominance of annual contracts means that insurance firms are fairly well equipped to handle the current level of physical risks to the liability (claims) side of their balance sheet (Scott et al., 2017). Climate change may lead to greater volatility and higher losses that could threaten the insurability of certain risks with important implications to the insurance industry and public insurance coverage (Bank of England, 2015a). There is some evidence that the insurance industry is underestimating catastrophe risks (Lloyd’s of London, 2014; Standard and Poor’s, 2014). While one issue is the potential underestimation of the likelihood of certain types of events an additional problem is that climate change may alter the correlation between individual risks with events like wind storms taking place in clusters. Correlated losses across business lines can also result from large catastrophes affecting multiple sectors which will reduce the benefits of diversification.

Insurers could collectively withdraw from covering risks that they deem uninsurable or they could respond by raising premiums. Reduced coverage could negatively impact collateral values in affected areas and accordingly tighten borrowing constraints for households and businesses (Batten et al., 2016).

2.3.2. The impact of uninsured losses on the balance sheets of banks

As already noted excessively high prices for catastrophic events could lead to underinsurance which could reduce collateral values. This in turn could reduce lending in the presence of borrowing constraints as has been shown to occur in poorly functioning catastrophe markets (Garmaise and Moskowitz, 2009). *Ex post*, higher levels of underinsurance would magnify the economic impact of natural disasters by constraining the financing of post-disaster reconstruction. Collateral values for securing loans may be reduced as reconstruction is delayed further tightening financing constraints. Uninsured losses have been associated with the negative impact on GDP after a natural disaster (Von Peter et al., 2012).

The reduction in collateral values will be larger after a disaster the less the risk of such disasters was reflected in the property prices and the more insurers avoid covering the affected region after the disaster. Reduction in output and employment can further weaken households' and corporates' balance sheets. This in turn could increase the loss-given-default (LGD) and the probability of default (PD) of loans potentially adversely affecting the banking system (Batten et al., 2016). A number of studies provide empirical evidence that natural disasters can affect the soundness of banks and that losses borne by banks is influenced by the structure of the financial system (Noth & Schüwer, 2017; Lambert et al., 2015; Noth & Schüwer, 2014; Landon-Lane et al., 2009; Klomp, 2014).

Domestic banks can also be impacted by major natural disasters in other countries especially if the economic disruptions lead to a sharp increase in sovereign default risk (Batten et al., 2016). Physical risk could also result in economic disruption at a national level if uninsured losses are significant with reductions in tax revenues and increases in fiscal expenditures. Sovereign default risk could increase with a negative impact on GDP. The widespread flooding in Thailand in 2011 had an estimated cost of $45 billion with only a quarter of that insured (Aon Benfield, 2011) and the Thai finance ministry reduced its 2011 growth forecast (HSBC, 2013).

2.3.3. The impact of the credit flow to the real economy and financial markets

To the extent that natural disasters lead to losses for banks this could lead to a drop in their lending to both affected and unaffected areas as they try to improve their regulatory capital ratios. Collateral values in affected areas could drop further and exacerbate the damage to households and corporates. There is also evidence that unaffected areas can be 'crowded out' of bank lending following the increased reconstruction demands of an affected area (Cortés & Strahan, 2017).

If there are disruptions in banking services caused by major natural disaster there may be an increase in precautionary demand for liquidity. This could potentially distabilize the financial system and economy in the absence of intervention by the central bank (Batten et al., 2016).

2.3.4. Global measures of physical risks to the financial system

Global economic losses from natural catastrophes could amount to US$1 trillion with a 1% annual probability (AIR Worldwide, 2015). Climate change is likely to significantly increase overall exposure to physical risks that extend beyond weather-related events such as food safety, global security and displacement of people (IPCC, 2014a; IPCC, 2014b) each with its own set of financial risks.

There has been little research to date on the potential impact of climate change to the financial sector with the exception of some kinds of insurance. Climate change can affect the value of financial assets directly by destroying or accelerating the depreciation of capital assets through its connection for instance with extreme weather events. It can also change the return on capital assets by changing the productivity of knowledge and/or labor. Integrated assessment models can be used to compute the value at risk (VaR) associated with climate shocks (Dietz et al., 2016b) under certain assumptions that are standard in neoclassical models. For instance, corporate earnings should grow roughly at the same rate as the economy as they account for a roughly constant share of GDP in the long run. Furthermore, according to the Modigliani-Miller theorem of corporate finance the future changes in capital structure will not change the expected value of today's aggregate portfolio. IAM forecasts of future global GDP growth with and without climate change can be used to provide an approximation of the climate VaR of financial assets. Dietz et al. (2016b) note that the problem of social discount rates is not relevant when looking at valuing a portfolio of privately held financial assets as these relate to opportunity cost of capital appropriate for the riskiness of the portfolio as assessed by the private investor.

The extended version of Nordhaus's DICE model (Nordhaus, 2008) is used and the authors' version (Moyer et al., 2014; Dietz & Stern, 2015) allows for a portion of the damages from climate change to fall directly on the capital stock in addition to the impacts on output from given capital and labor inputs. This means that the model can capture both the direct impact of climate change on capital assets as well as the indirect affect through productivity of inputs.

Dietz et al. (2016b) find that the expected 'climate value at risk' of global financial assets today is 1.8% along a business as usual emissions path. This would amount to US$2.5 trillion based on a representative estimate of global financial assets. There is a particularly significant tail risk for the VaR which amounts to 16.9% at the 99th percentile which in absolute terms would be US$24.2 trillion. To put these estimates in perspective the authors point to the fact that the stock market capitilization today of fossil-fuel companies has been estimated at US$5 trillion. Furthermore, given the global incidence of climate impacts and the potentially long holding periods required, the risk would be difficult to hedge fully. Most of the climate VaR arise in the second half of the century.

Dafermos et al. (2017) develop an alternative approach by using an ecological macroeconomic model that sheds light on the physical effects of climate change on financial stability. The key channels through which the financial system is impacted are (a) through the reduced profitability of firms and the deterioration of their financial position caused by climate change induced economic damages and (b) the impact on the confidence of investors leading to a rise in liquidity preferences and fire sales of financial assets. Instead of using an Integrated Assessment model (IAM) and a value at risk (VaR) framework they explicitly consider the balance sheets and financial flows in the financial sector allowing the portrayal of climate-induced fragility that can be caused in the financial structure of firms and banks. They also utilise a multiple financial asset portfolio choice framework allowing an explicit analysis of climate-induced effects on the demand of financial assets which lets them capture the implications of fire sale of certain financial assets. Finally, their model differs from the neoclassical growth framework in that it has a non-natural impact on economic activity so that the price of financial assets and credit availability affect economic growth and employment.

With simulations they show that a business as usual climate change scenario is “likely to have important adverse effects on the default of firms, the leverage of banks and the price of financial assets. Remarkably, this climate-induced financial instability causes problems in the financing of green investment disrupting the transition to a low-carbon and more ecologically efficient economy” Dafermos et al. (2017).

2.3.5. Looking at physical risks at a sectoral level

Beyond global estimates of climate related physical risks estimates can also be undertaken at the sectoral level. Climate change can lead to sudden reductions in both the quality and quantity of yields in agriculture as weather patterns shift (Morel et al., 2016; Rautner et al., 2016). Caldecott et al. (2013) note that environmental risk factors could cause material stranding throughout the global agricultural supply chain. The authors also explored a range of assets linked to the sector that could be stranded: natural assets (e.g., farmland water), physical assets (e.g., animals, crops, on-farm infrastructure), financial assets (e.g., farm loans, derivatives), human assets (e.g., know-how, management practices), and social assets (e.g., community networks). New insurance policies and government intentions may be required to protect interests and local communities to facilitate a just transition (Caldecott et al., 2016a).

In countries where nature-driven tourism is an important part of the economy, climate change could see service industry infrastructure stranded by physical changes. Climate change may strand individual tourist attractions as well as the industry in entire regions, e.g., ski resorts in the Alps. A growing number of reports point to potentially significant impacts to the Caribbean tourism economy though no research has explored the risks of stranded assets explicitly.

There has not been much exploration on the "stranding" of human capital resulting from climate change and society's responses to climate change. Caldecott et al. (2013) briefly explores how human and social stranding can come about by changing agricultural patterns.

2.4. Transition risks

An initiative from a coalition of investors, NGOs and universities led by Climate Change Capital in January 2012 called for an assessment of whether climate change could pose a systemic risk to the financial system. Governor Mervyn King responded to a letter from the coalition by specifying three conditions that needed to be met to consider carbon-intensive investments to be a threat to financial stability: 1) exposures of financial institutions to carbon-intensive sectors be large relative to overall assets, 2) the market is not already pricing in the impact of policy and technology either through lower expected returns or higher risk premiums, 3) any subsequent correction would not allow financial institutions to adjust their portfolios in an orderly manner (Caldecott et al., 2016a). A report that followed (Bank of England, 2015a) found that transition risks are relevant to financial institutions holding securities of firms that may be impacted directly by regulatory limits in terms of their ability to produce fossil fuels (e.g., coal, oil and gas and extraction companies) and securities of firms that are energy-intensive (e.g., forestry, paper, metals and mining, etc.).

The European Systemic Risk Board (ESRB, 2016) found that systemic financial risk could arise from either the macroeconomic impact of sudden changes in energy use or the rapid devaluation of carbon intensive assets. An abrupt low-carbon transition would lead to a restricted energy supply along with increased energy costs.

When it comes to disruption related to the low-carbon transition there are several layers of complexity (Campiglio et al., 2017). First, a large portion of existing reserves of oil, gas and coal will have to remain in the ground and thus become ‘stranded’ if the international community’s commitment to keep global temperatures below 2°C (UNFCCC, 2015) is realised. The concept of a global ‘carbon budget’ identifies the total amount of cumulative atmospheric CO_2 emissions allowable for specified amounts of anthropogenic climate change. A specific climate change target like not allowing global temperature to exceed 2°C can be translated into a measure of allowable accumulated CO_2 emissions and this in turn can be used as a basis to identify the extent of fossil fuels that must be left in the gourd or be ‘unburnable carbon’ as dubbed by (Carbon Tracker Initiative, 2011).

According to Meinshausen et al. (2009)’s calculations more than half of all economically recoverable fossil reserves should be left in the ground by 2015 if we are to achieve at least a 50% chance of not exceeding 2°C. Carbon Tracker Initiative (2013a) estimate that only about a fourth these reserves should be used up by 2050 if we are to remain below the 2°C threshold with an 80% probability. In their estimate 762 gigatonnes of CO_2 emissions are embodied in the reserves of listed companies. Approximately eighty percent of coal reserves, half of gas reserves and a third of oil reserves must remain unexploited according to the estimates of McGlade and Ekins (2015). Exxon Mobil and PetroChina are in the top ten listed companies by market capitalisation of the FT Global 500 list (FT, 2015). An additional three oil and gas companies (Petrobas, Royal Dutch Shell and Chevron) were in the top ten in 2011 before the large drop in oil prices. Given the many large unlisted oil companies, including Saudi Aramco considered to be the largest company in the world, one can imagine how stranded physical assets might have system wide implications (Campiglio et al., 2017).

A second layer of complexity relates to the fact that a large part of the economic system is deeply tied to the use of fossil fuels. Production of electric power, for instance, is predominately based on fossil fuels and it is a critical factor in production processes. About two thirds of global electricity generation has been coming from coal (37%), natural gas (24%) and oil (4%) (IEA, 2017). Approximately 23% of global energy-related CO_2 emissions come the transportation sector (IPCC, 2014c) and this is mainly from the combustion of oil-based products in automobiles, heavy-duty vehicles, airplanes and ships. Substantial amounts of fossil fuels are also implicated in heating of buildings and industrial processes. A low-carbon transition could negatively affect all these sectors as they would need to overhaul production technology and process and may be forced to write off a relevant portion of their high-carbon physical capital assets (Campiglio et al., 2017).

A third aspect of the implications of a low-carbon transition relates to the stranding of physical assets (natural resources and productive capital) that could in turn lead to sharp reductions in the valuation of companies owning them along with the financial assets they have issued. Unburnable fossil reserves have the potential to become stranded assets thus raising the risk of investing in fossil fuels and also spurring the fossil fuel divestment campaign (Ansar et al., 2013). To the extent that upstream fossil fuel assets are significantly overvalued there is a danger of a financial bubble (or ‘carbon bubble’) that could have systematic implications for the global economy (Caldecott, 2017). All investors holding devalued financial assets in their portfolios will suffer adverse wealth effects. Their distress will spread to others holding financial assets in the distressed group and so on with potential systemic ramifications and cascade effects through the whole financial network. By running a network-based climate stress test on the EU and US financial system Battiston et al. (2017) find that direct and indirect exposures to climate-relevant sectors represent a large portion of investors’ equity holdings portfolios, especially for pension funds (Campiglio et al., 2017).

2.4.1. Transition risk as a multiple equilibrium problem

A key element in the stranding of assets from societal responses to climate change is the extent to which investors are unable to adequately gauge this response. Batten et al. (2016) offer a very simple stylised ‘game’ between government and electricity companies in determining investment in low-carbon electricity generation that highlights the critical role of signalling on the part of government. The game has two periods. In the first period electricity companies must decide whether to invest in abatement technologies like CCS. In the second period the government decides whether to shut down those companies that have not invested in abatement. To make the decision the government weighs the environmental benefit of shutting down the unabated firms against the higher electricity costs for the population. This cost however itself depends on how much investment has taken place in the first period. If many firms have already taken action on abatement then shutting down unabated firms will not lead to great increases in electricity costs since clean supplies will be plentiful. In this sense there is a strategic complementarity among firms in their decision to abate. If many abate then the government is likely to shut down the unabated firms in the second term while if few abate then it will be too costly for the government to take tough action. In this game there are two equilibria, a ‘low carbon emission’ and a ‘high carbon emission’ equilibrium.

As long as the economy gets stuck in the high carbon emission equilibrium there is an increased chance that a transition to low-carbon economy will be abrupt and that the risk of stranded assets will rear its head. The government by committing early to a low carbon transition can signal its future intentions and bring about a virtuous cycle of increased investment in clean technology and a smooth transition. This shows the value of transparent, predictable policy on carbon emission in anchoring private investors' expectations. It also shows that the nature of the very game may mean that the potential for abrupt change is always present even when everyone is fully rational.

A potentially related literature looks at the broader question of how policy uncertainty impacts the economy. Baker et al. (2016) use a news-based index of economic policy uncertainty for the United States and 11 other major countries and find that elevated uncertainty may have harmed macroeconomic performance in the United States and Europe. They also find "sizeable effects of policy uncertainty on the cross-sectional structure of stock price volatilities, investment rates, and employment growth" Baker et al. (2016, p. 1634). Brogaard and Detzel (2015) also use a news-based index of economic policy uncertainty and find that increased uncertainty reduces asset returns. Baker et al. (2016)'s use of category-specific policy uncertainty indexes on health care and national security policy suggests that a similar methodology might provide a measure of how climate policy uncertainty affects carbon related asset returns.

2.4.2. Measuring the impact of stranded assets from a transition to a low-carbon economy

Rogelj et al. (2016) offer a review of the several methods used to estimate the cumulative carbon emissions that would keep global warming below a given temperature limit. They find that estimates for maintaining the global temperature rise below 2°C ('2°C carbon budget') fall within the range of 590 to 1,240 gigatonnes of Carbon Dioxide from 2015 onwards, for a 66% probability of limiting warming below 2°C relative to pre-industrial levels.

Heede et al. (2016) estimate the carbon potential of the earth's total reserves of fossil fuels to be around 2,750 $GtCO_2$. Coal represents 64.3%, oil and NGL 22.9% and natural gas 12.8% (values are for end of 2013). Depending on assumptions about the cost and availability of carbon capture storage (CCS) as well as the carbon budget used (and estimate) this could imply that up to two thirds of the stock of known carbon-based energy reserves could become unburnable. According to IEA (2017) transition scenario consistent with limiting warming below 2°C (Sustainable Development Scenario) coal demand peaks before 2020 and is cut by half in 2040 relative to the New Policies Scenario. Oil demand peaks soon after coal. Natural gas is the only fossil fuel that does not experience a pronounced peak and decline.

A recent report by the International Energy Agency and the International Renewable Energy Agency IEA/IRENA (2017) points out that it is important to distinguish between fossil fuels that will be left unexploited ("unburnable fossil fuels"), the capital investment in fossil fuel infrastructure which ends up not being recovered over the operating lifetime of the asset due to reduced demand or prices resulting from climate policy ("stranded assets") and the potential reduction in the future revenue generated by an asset or asset owner assessed at a given point in time because of climate policy ("carbon bubble") (IEA/IRENA, 2017).

Taking current reported fuel reserves and burning them would lead to three times more CO_2 emissions than would be allowed by the 66% 2°C Scenario (880Gt). This is the basis of the oft-quoted finding that two-thirds of today's fossil fuel reserves should be left in the ground. More relevant for the stranded assets analysis however is the outlook for each fossil fuel which varies markedly in the 66% 2°C Scenario: there would be a 65% drop in coal consumption between 2014 and 2015 while a 55% drop for oil and less than 20% for gas. Accordingly, the breakdown for unburnable fuels based on cumulative fossil fuel production would be around 40% of gas, 50% of oil and over 80% of coal (IEA/IRENA, 2017). Importantly, however, the world's proven reserves are not synonymous with those lined up for development and even in the absence of stringent climate policies today's current reserves would not be produced by 2050. Figure 6 shows this discrepancy.

'Unburnable' reserves are not the right measure of the extent to which a resource is stranded. To measure the potential value of stranded assets one needs to "recognise the difference between assets that are prematurely shut down because of adverse demand evolution, and assets that are prematurely shut down and lose part of the capital spent on their development" (IEA/IRENA, 2017, p. 108). The analysis on stranded assets undertaken by the International Energy Agency and the International Renewable Energy Agency IEA/IRENA (2017) focuses on those assets that may not recoup their capital due to the additional climate policies in the 66% 2°C Scenario. This requires a detailed modelling of investment and operating costs, utilisation and production rates, commodity prices and other potential revenue streams over the lifetime of an asset. Fossil fuel power plants that would need to be retired (stranded) prior to recovering capital investment would amount to a total USD 320 billion worldwide over the period to 2050. The vast majority would involve coal-fired power plants (96%) as many would be phased out. Gas-fired and oil-fired power plants would be far less affected. Three-quarters of the total stranded assets in the power sector are related to plants already in operation today.

A key message however is that the level of new power plants that would become stranded is limited by the assumption that the emission reductions are well-planned and scheduled so that market players know what to expect. If climate action is delayed and there is an abrupt and unexpected change in mitigation policy the stranding of assets can be much more severe. Such a sudden shift is modelled in a “disjointed transition case” and “this is hugely disruptive…for the energy markets and the abrupt change in 2025 would pose enormous challenges to the industry” (IEA/IRENA, 2017, p. 112). In this case the increase in upstream oil and gas stranded assets is much larger while coal assets are less affected (since most of these plants are already in production in less standard scenario). Total stranded assets would now be above USD 1 trillion with over USD 300 billion stranded in natural gas assets. See Figure 7.

In addition to global estimates of stranded assets in the upstream power sector calculations have been recently made for downstream fossil fuel assets (power generation), buildings and industry (IRENA, 2017). Estimating stranded assets in power generation requires a calculation of plants that will be shut down before the end of their technical lifetime. Current stock and age distribution of power plants are used and have been retired by age (starting with the olds) based on standard assumptions of anticipated technical lifetimes. Similar methodologies have been used for estimates at a country level (Burton et al., 2016) and at a global level (Pfeiffer et al., 2016). This approach was also used for power generation.

In the case of buildings, total floor space and natural demolition rates were assumed to consume no fossil fuel after 2020 under REmap and after 2030 under Delayed Policy Action. Retrofitting of buildings to reduce fossil fuel consumption was estimated in terms of floor space needed. Gas-fired boilers or single glazed windows may need replacing and the value of these stranded assets is estimated using the difference between the cost of retrofitting and additional costs of constructing a new energy efficient and fossil-free building. Cost assumptions confirm that the eventual cost of retrofitting a conventional building is greater than the initial additional costs of a new fossil-free building.

“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, compared to USD 10 trln in the REmap case" (IRENA, 2017).

Caldecott et al. (2017) look at both physical and transition risk and its implications for the insurance industry. Among the sectors they consider they also discuss the implications of transition risk for the shipping industry.

2.4.2.1. Additional approaches to measuring the impact of transition risk to the financial system

Dietz et al. (2016b) used and IAM approach to focus on the physical impacts of climate change on financial assets but their model was also used to assess the impact of mitigation to financial assets. By comparing the 2°C mitigation scenario with its counterpart along BAU, when mitigation costs are included, they find that the expected value of global financial assets is 0.2% higher along the mitigation scenario though 65% of the distribution lies below zero so that the present value of global financial assets is larger under BAU. This relates to the reduction in asset values including stranded assets resulting from abatement policy.

Instead of calculating aggregated financial losses derived from top-down estimated GDP losses due to physical risks Battiston et al. (2017) focus on transition risks and look at microeconomic data of listed firms in climate-related sectors and consider how shocks can affect their values and propagate through the financial system. They point out that this requires estimations of the likelihood of the introduction of a specific policy and that this likelihood is also dependent on the expectations of agents that it will be implemented. The intrinsic uncertainty of the policy cycle along with the fact that interlinkages among financial institutions can amplify both positive and negative shocks limit the use of traditional risk analysis for climate policies (Battiston et al., 2017). Battiston et al. (2017) adopt a complementary network approach to financial dependencies to look at how climate policy risk might propagate through all climate-policy-relevant sectors and spread through the financial system. In addition to the exposure of the fossil-fuels extraction sector they consider all sectors that are relevant to climate mitigation policies and they analyse microeconomic data for shareholders of listed firms in the European Union and in the United States. They find that the relative equity portfolio exposures of all financial actor types to the fossil-fuel sector are limited but that the relative equity portfolio exposures to all climate-policy-relevant sectors are large, e.g., 45.2% for Insurance and Pension Funds.

They apply a network-based climate stress-test methodology (Battiston et al., 2012; Battiston et al., 2016) on a sample of the top largest EU banks, taking into account the first-and second-round effects of shocks to their portfolios. European financial institutions holding direct ‘high-carbon exposures’ have been estimated to be, relative to their total assets, about 1.3% for banks, 5% for pension funds and 4.4% for insurances. For policy purposes, one of the advantages of their approach is that if offers granular information that with more refined data can help identify risk at the firm level. They conclude that if climate policies are uncertain, delayed and sudden, the large direct and indirect exposures of financial actors to climate-policy-relevant sectors could entail a systemic risk.

2.5. Liability and other legal risks

Claims for losses incurred from physical or transition risks could be made against those believed to have been responsible. If these claims are upheld losses will be borne by those deemed responsible or they could be passed on to their liability insurance providers. Bank of England (2015a) identified three primary lines of argument for establishing liability. First, failure to mitigate where the defendant is seen to have altered the climate to the detriment of the claimant through the release of GHGs. Second, failure to adapt where the claimant has been exposed to increased level of weather-related losses by goods or services supplied by the defendant of inadequate quality or fit for the purposes, or failure of companies to adapt to tighter regulations and thereby exposing claimants to increased levels of financial losses. Third, failure to disclose or comply whereby the claimant alleges that the defendant failed to sufficiently disclose information relevant to climate change or has not complied with climate change related legislation or regulation (Batten et al., 2016).

Given the present difficulty of attributing specific extreme weather events to climate change and the fact that GHG emitters are widespread it may be difficult to make GHG emitters legally liable for causing climate change (failure to mitigate).

Various types of liability insurance could be affected when it comes to failure to adapt, disclose or comply: directors’ and officers’ liability insurance (directors sued for a delay in taking action); professional indemnity insurance (claims against insured architects and engineers for building failures in the face of extreme weather conditions); public liability insurance (public authorities for providing inadequate infrastructure); employers’ liability insurance (liable for heat-related injury and illness); product liability insurance (product failure in extreme weather conditions) (Batten et al., 2016).

The risk to the macroeconomy or financial stability from the liability insurance market may be limited however as this market is relatively small in size. The liability market was worth US$160 billion, or 10% of global non-life premiums (Swiss Re, 2014a). The financial system could however be impacted if a series of successful climate-related liability insurance claims result in a distress of failure of a major liability insurer (Batten et al., 2016).

3. Market failure and the risk of stranded assets

An important question is the extent to which the financial industry acknowledges the existence of climate financial risks. In perfectly efficient asset markets as envisaged by the Efficient Market Hypothesis (Fama, 1970) asset prices would fully reflect the information available to rational profit-maximising financial actors. Stock prices of many companies operating in fossil fuel industries have been declining in recent years but this has been attributed to the large drop in fossil fuel prices in 2014 which itself has been driven by a number of factors: stagnation in demand, abundant supply (especially in view of the surprising success of fracking technologies in the US) and geopolitical reasons (Baumeister & Kilian, 2016). While the drop in stock prices may also be related to the growth in renewables, especially in Germany and its effect on utilities, there is not a sense that asset markets have actually priced in the dramatic implications of the low carbon transition needed to attain the 2°C target. One explanation that would be in line with the Efficient Market Hypothesis is that financial actors do not believe that policy makers will follow through with their commitments.

Many reasons have been offered in the literature for why the Efficient Market Hypothesis may not be an accurate model of the real-world financial markets and perhaps especially so when it comes to the nature of potential financial risks associated with climate change. Two recent articles consider some of the reasons why individuals operating in the financial industry may overlook or under-price low carbon transition risks (Silver, 2017; Weber, 2017). Low-carbon investment may appear to be a relatively unprofitable niche market given prevailing and widespread convictions and social norms in the financial industry. Due to their educational background they may have limited knowledge of energy and climate related issues so that they can only partially understand or even overlook the related news and empirical evidence. The structure of incentives faced by investment professionals may prevent them from investing in low-carbon assets. Asset managers' performance is evaluated on the basis of their short-term risk-adjusted returns as compared to that of their peers which makes them stick close to an established index. A decision to drop potentially stranded assets that are relevant in indices and have been relatively risk-free in terms of historical volatility, could be perceived as excessively risky and with possibly lower short term returns. Accordingly, asset managers may tend to prefer aligning with behavioural norms of their social group and shift the longer-term transition risks to asset owners.

Thomä and Chenet (2017) provide a theoretical account of potential reasons (market failures) that transition risks may be mispriced. They do not consider mispricing from other climate-related risks like physical risks or litigation risks. They start by discussing the Efficient Market Hypothesis that if empirically accurate would eliminate any concerns about mispricing by the financial market and consider reasons why the EMH can *in theory* break down. Bounded rationality (Simon, 1959) provides a strong criticism of utility-maximising models where agents are seen to use heuristics rather than optimise and as such price formation may not reflect all information and potentially become skewed. When it comes to transition risks, lack of historical data and the form of transition scenario lead to a breakdown of the normal distribution. Simplified assumptions are used by agents to reduce the complexity. Transition risks are particularly prone to complexity.

There is a vast literature often coming under the heading of behavioural and experimental economics that considers the many ways that human beings may deviate from the standard assumption of rationality assumed in economic models (including the EMH). This literature suggests many ways that humans may have limited rationality or behavioural biases (Tversky & Kahneman, 1974; Kahneman & Tversky, 1979; Simon, 1959) and that this can apply equally to investment professionals (Hirshleifer, 2001). In view of the many complex problems that humans confront, and that may be beyond their capacity to master, individuals may follow simpler 'rules of thumb' that can lead to systematic errors. A bias for the status quo may lead individuals to disproportionally prefer the current state of things (Samuelson & Zeckhauser, 1988). Confirmation bias may prevent individuals from registering new information that is out of line with their pre-existing system of beliefs and lead investors to be overconfident and ignore evidence that their strategies could lose money (Pompian, 2011; Hilton, 2001).

Asset prices may not fully reflect risks in a world of bounded rationality, limited information and deep uncertainty which is especially the case when it comes to climate change and a low carbon transition. The 'blindness' of financial experts and economists to the 2008 financial crisis has been attributed to biases such as 'irrational exuberance' that lead to an overvaluation of financial assets (Shiller, 2015). Critchlow (2016) has suggested that we may be facing 'irrational apathy' in the case of climate change. Accordingly, a number behavioural biases lead the financial system to disregard transition risks and overprice financial assets related to fossil or fossil-dependent industries. To the extent the financial community does not price in the risk of transition in the presence of a real low-carbon transition, there will likely come a time where the 'carbon bubble' will burst and the macroeconomic and financial implications may be grave.

Prospect Theory developed by Kahneman and Tversky (1979) suggests that investors appear risk-averse for small losses but are less impacted by large losses so that the level of risk aversion is partly dependent on the size of the loss. Similarly, Taleb (2007) discusses how the tail end of distributions are under weighted by the financial market models. To the extent that transition risks have fat tails (low but not insignificant probability of great damages) these may not be accounted for by the financial markets. The 2°C or lower, while being the official target, "remains on the lower end of the spectrum of climate roadmaps and far removed from the current business as usual" Thomä and Chenet (2017).

In addition to problems arising from the design of risk models in financial markets Thomä and Chenet (2017) also consider the role of time-inconsistent preferences and the role of institutions that can lead to departures from efficient pricing of risk. To the extent that agents' discounting resembles hyperbolic discount functions (Thaler, 1981) where agents have a 'present-bias' the immediate future is discounted highly while the long-term future is discounted at a progressively lower rate. As transition risks are likely to be long-term they are likely to be heavily discounted over the short term and thus even if investors believe the risks are real their financial impact will be discounted.

Two additional potential sources of financial market failure are presented by Thomä and Chenet (2017). One has to do with principle-agent problems where short-term asset managers externalise long-term costs associated with their investments to asset owners. The other relates to a potential herding behaviour where market participants prefer to move with the crowd than being right on their own. Such behaviour has been used to partly explain booms and busts (Bikhchandani & Sharma, 2000).

In one attempt to empirically gauge the extent to which investors are sensitive to climate risks Batten et al. (2016) use standard event study methodology to estimate the market reaction to news stories in major newspapers or energy specific investment press mentioning the words 'carbon bubble', 'unburnable carbon', and 'fossil fuel divestment' and data from climate organizations tracking divestment announcements. Specifically, they look at the changes in the market valuation of the firm's equity measures by abnormal returns following the event. They found that these events had a negative but statistically insignificant effect on abnormal returns for oil and gas companies but a positive and significant effect for renewable energy companies. The insignificant impact on market values of fossil fuel companies may be because investors remain uncertain about future climate policies or that they may choose to divest over several years rather than liquidating their portfolios as an immediate reaction to specific news. The results suggest tentatively that some investors may be beginning to incorporate expected changes in energy policy into assessment of firms Batten et al. (2016).

Another recent effort to measure the extent to which investors may be pricing in climate policy risk looks loan rate charged to fossil fuel firms relative to non-fossil firms. Delis et al. (2019) find no evidence that banks are charging significantly higher loan spreads to fossil firms with higher exposure to climate policies when looking at their entire sample from 2007-2016 but do find evidence of banks increasing their loan spreads after 2015. This suggests that the Paris Climate Agreement had an impact on perceived climate policy risk.[1]

4. Addressing climate-related risks to assets

4.1. Responses by investors

There are a number of strategies available for managing investment and portfolio exposure to stranded asset risks. The UK Law Commission (2014) and others argue that the investors' fiduciary duty should encompass ESG factors to protect the long-term interests of beneficiaries and other large scale losses. In this sense the risk of stranded assets should be accounted for in investment decisions. NGOs and legal groups have been campaigning and designing legal action against investors, companies and government that fail to consider long-term implications of stranded assets (Caldecott et al., 2016a).

4.1.1. Managing stranded asset risk investments

As mainstream investors are awaking to issues of climate change and carbon risk a number of new stock indexes, funds, bond ratings and investment tools are being designed to help. Two reports (UNEP FI, 2014; IIGCC, 2015) explore options for buying into low-carbon opportunities without expecting lower returns or the different climate strategies available to

[1] The methodology used by Baker et al. (2016, p. 1634) and Brogaard and Detzel (2015) could also be used to shed light on the extent to which investors are pricing in transition risk.

institutional investors to measure and manage stranded asset risk. A consortium of 2 Degrees Investing Initiative, UNEP FI and the World Resource Institute have highlighted two approaches and their related metrics and strategies entitled "Carbon risk" and "Climate friendliness". The first focusing on the potential financial risks and opportunities for portfolios of a low carbon economy, while the second relates to investors seeking to contribute to GHG reductions (Dupre et al., 2015).

4.1.2. Calculating exposure to stranded asset risk

A popular technique for assessing stranded asset risk within portfolios is the process of footprinting investments and portfolios. Another way to manage exposure is to use carbon intensity of capital as a proxy for a range of climate-related risks. There is also a growing movement to encourage managers to disclose portfolio-level exposure. France is the first country to require institutional investors to disclose how they consider ESG issues in decision-making processes including climate-related risks (Smart, 2015), while Sweden is considering a move to require asset owners and managers to report carbon footprints (Rust, 2016).

Caldecott et al. (2016b; 2015) highlight research at the University of Oxford that looks at the specific water, carbon, and other environmental risk that could affect assets owned by companies and this analysis can help investors identify companies at risk and undertake risk management actions like divestment, engagement, and hedging. Asset and company level analysis will help investors better assess the stranded asset risk within their portfolios though this analysis is still limited to specific sectors and geographic locations (Caldecott et al., 2016a).

4.1.3. Portfolio decarbonization and divestment

Decarbonization refers to the reduction in the carbon-intensity of investment portfolios. A range of investment tools can be used to achieve decarbonisation including selective divestment, screening, and investment in clean sectors. Divestment refers to the withdrawal of capital by investors from firms seen to be engaged in risky and reprehensible business (Ansar et al., 2013). This can be done by selling stock of market listed shares, private equities or debt. Decarbonization along with divestment are two strategies for reducing exposure to stranded assets that have gained momentum in the past decade. The Portfolio Decarbonization Coalition aims to mobilize a critical mass of institutional investors to commit to decarbonising their portfolios. Prior to the COP21 in Paris in December of 2015 over $100 billion had been committed. Similarly, campaigns for fossil fuel divestment have gained momentum. Hunt et al. (2017) provides an informative comparison of the anti-Apartheid and fossil fuel divestment campaigns.

4.1.4. Low carbon indices

Many of the major indices that are used in passively managed funds are underweight in renewable energy and overweight in fossil fuels and this has prompted some investors to use low-carbon indices to reduce their exposure to carbon-related risks. New "low-carbon" or "fossil-free" indices are among such indices that underpin the Exchange Trade Funds (ETFs). Other indexes for passive investors with exposure to environmentally driven companies include The FTSE Environmental Markets Index series, The S&P Global Eco Index and the MSCI Global Climate Index, MSCI Global Low Carbon Leader Indexes and MSCI ACWI Low Carbon Target Index. While there are numerous opportunities to invest through a range of indices focused on reducing carbon exposure many investors don't consider them comparable to mainstream indices (Caldecott et al., 2016a).

4.1.5. Engagement and voting

Engagement of investors and shareholder voting can play an important role in reducing the carbon intensity of large multinational companies. Such engagement with invested companies has increased in recent years (PRI, 2013). Besides encouraging low-carbon practices and investment engagement can enhance transparency and disclosure. Shareholder resolutions were filed against oil and gas giants Shell and BP in 2015, demanding greater disclosure and monitoring to stranded assets risks (Clark, 2015). Investors have filed a record number of shareholder resolutions mostly focusing on major US energy companies in the wake of the Paris Accord.

4.1.6. Screening

Exclusion from a fund or portfolio of certain sectors, companies, or practices based on ESG criteria is known as negative screening. In contrast, positive screening encourages investment on the basis of ESG criteria. Screening has been a popular choice especially among asset managers and banks. The largest sustainable investment strategy globally is negative/exclusionary screening ($15.02 trillion), followed by ESG integration ($10.37 trillion) and corporate engagement/shareholder action ($8.37 trillion) (GSIA, 2016).

4.1.7. Green bonds

In the past few years the market for green bonds has grown from $11 billion in 2013 to $41.8 billion in 2015 (Kidney, 2016). Green bonds are mostly “use of proceed” (proceeds earmarked for green projects) or asset-linked. In addition, there are green revenue bonds, green project bonds, and green securitised bonds. The Climate Bond Initiative is an international investor-focused NGO looking to encourage the issuance of $100 billion labeled green bonds in 2016 (Kidney, 2016).

4.1.8. Sovereign risk

Country sovereign credit ratings could be influenced by asset stranding both through direct, indirect and systemic effects. Sovereign bonds are one of the most important asset classes held by investors and represent over 40 percent of the global bond market (UNEP FI and Global Footprinting Network, 2012). Pressures from increasing global natural resource scarcity, environmental degradation, and vulnerability to climate change impacts are inadequately reflected in traditional sovereign credit risk analysis (UNEP FI and Global Footprinting Network, 2012). This has led to a growing literature on how to design methodologies and tools to better understand, map and reduce sovereign credit risks related to climate change.

Global Footprint Network and UNEP FI developed an Environmental Risk and Sovereign Credit methodology which aims to quantify natural resource and environmental risks for incorporation into country risk assessment (UNEP FI and Global Footprinting Network, 2012). The report applied the methodology to five countries and explored the resource balance, trade-related risk, degradation risk, and financial resilience of each economy. The increased volatility from rising resource scarcity and climate change was found to particularly expose exporters of natural resources (fossil fuels, timber, fish and crops). Future climate change and the associated ecosystem degradation and water scarcity was also found to lead to higher and more volatile food prices with potentially significant impact on countries’ risk credit and risk exposure of sovereign bond holders (UNEP FI and Global Footprinting Network, 2012). The same report provides examples of banks and asset managers adopting metrics for ESG risks including labor rights and environmental damage as a way to supplement sovereign credit risk.

4.2. Responses by central banks

Central banks and other institutions have increasingly looked in to the issue of financial risks associated with low-carbon transitions. These include the Bank of England (Carney, 2015), Netherlands Central Bank (Schotten et al., 2016), Bank of Italy (Signorini, 2017), Bank of France (Villeroy de Galhau, 2015), Bank of Canada (Lane, 2017), the Swedish Financial Supervisory Authority (Bowen & Dietz, 2016), the European Systemic Risk Board (ESRB, 2016), and the G20 group (GFSG, 2016). Some of these organizations have started developing methodologies to stress test their financial systems climate-related shocks and are involved in research on stranded assets and the potential role of central banks.

The Bank of England is currently deepening its activities in insurance and initiating an internal review of impact of climate change on PRA-regulated institutions. It is also looking at ways of supporting an orderly transition to a lower-carbon economy in order to enhance the resilience of the UK financial system. So far this has been advanced through engagement with international initiatives like the FSB's private sector Task Force on Climate-related Financial Disclosures, co-chairing the G20 Green Finance Study group and co-ordinating with other insurance regulators through the Sustainable Insurance Forum (Scott et al., 2017).

The European Systemic Risk Board (ESRB, 2016) suggested that to manage climate-related risks the ESRB could perform dedicated climate stress tests in the medium term. It suggests four potential policy options: (1) building systemic capital buffers to protect against adverse climate shocks with macroeconomic implications; (2) regulatory loss absorbency requirements; (3) capital surcharges based on carbon intensity of individual exposures; (4) large exposure limits to assets likely to be at risk from low-carbon transitions.

UNEP (2015) suggest a number of ways that central banks can promote resilience in the financial system. These include conducting environmental stress tests to evaluate the impacts of environmental scenarios on portfolios, institutions, and finical markets. Other tools include refinancing like establishing dedicated credit lines for green investments, liquidity operations like adapting the requirements for collateral in repurchase agreements to include low-carbon assets, interest rates, balances sheet management like incorporating ESG into asset allocation process, quantitative easing like giving greater weight to green assets in special asset purchase programs, and transparency an reporting.

4.2.1. Stress testing

Stress testing against climate-related risks would be one way to examine the resilience of the financial system to adverse scenarios. However, identifying the relative scenario that would likely lead to substantial loss in the financial sector is a key challenge. One would need to formulate a plausible scenario that would lead to large economic losses whether these result from direct physical damages in the domestic economy or to other economies that could impact banks and insurers. Information arising from stress tests of this nature could help financial market participants in their assessment of climate-related risk exposure of particular institutions Batten et al. (2016).

Developing scenarios for stress testing against transition risk may be more straightforward. Looking at different paths of carbon price would be one way to test the exposure of the financial system to fossil fuel related industries. There are data gaps, however, in undertaking such an exercise. Most of the data about exposures through bonds and loans are not available even to regulators (Battiston et al., 2017). Climate-related disclosures at a company level would help inform stress test exercises.

4.2.2. Macroprudential regulation

The financial sector can influence physical risks in a number of ways. It can contribute to climate change by funding activities that are intensive in CO_2 emissions or it can play a role in mitigation by funding technologies that reduce emissions. The standard way to deal with such externalities is to ensure that markets adequately price emissions through some instrument like taxes or emission permits. Given the existence of a possible threat to financial stability from climate change there has been some discussion about incorporating environmental considerations into macro prudential regulation. This could both protect the financial system from climate-related risks as well as help low-carbon investments which are ultimately key to a smooth transition. Rozenberg et al. (2013) has suggested the use of differential reserve ratio requirements so that they favour green sectors. Accordingly, the reserve ratio for banks that direct loans to low-carbon sectors should be lower. This should give banks an incentive to direct large amounts of lending toward green investment. However, according to Batten et al. (2016) prudential regulations are fairly blunt instruments for dealing with climate-related externalities. For instance, capital requirements are designed to mitigate prudential risks so adapting these to reflect externalities could undermine their primary purpose. Relaxing regulations to encourage climate friendly activities like reducing risk weights used for calculating regulatory capital ratios could jeopardise the safety and soundness of financial institutions. Alternatively, tightening regulations on financial exposures to carbon-intensive firms could increase the cost of finance for those borrowers and thus reduce their ability to invest in emission reducing technologies (CCS or renewables) (Batten et al., 2016).

Another option to protect against climate-related risks to financial stability would be to incorporate environmental, social and governance (ESG) criteria into asset risk assessment for risk-weighted capital requirements. This would mean that low-carbon infrastructure projects would appear less risky on banks' balance sheets. Nonetheless, caution should be used in implementing such tools in order to avoid the formation of a 'green bubble' (Campiglio et al., 2017).

4.2.3. Disclosure

Disclosure helps remove asymmetric information between a firm's management and investors. Depending on their objectives investors may be interested in different types of climate-related disclosures. Some may be interested in their exposure to financial risks associated with climate change, mitigation policy or divestment campaigns and others for ethical reasons may be concerned about the potential damage caused by firms. Effective disclosure could facilitate a low-carbon transition by encouraging firms and investors to adopt strategies that lower their exposure to risks of tighter policy on carbon emissions. It could also help institutions and government by better informing them about ways they can influence transition risks.

For disclosure to ensure efficient outcomes there are a number of considerations that need to be taken into account. If there are multiple frictions or market failure then removing one friction may not lead to the best outcome. For instance, having firms disclose the current emissions could make them focus on technologies with immediate short term emission reductions rather than ensuring more substantial long term emission reductions.

"The existing literature suggests that climate-related disclosures are more likely to benefit a wider range of investors, and hence be more effective, if they are based on forward looking information that is simple to interpret, and relevant for assessing financial risks and returns" (Batten et al., 2016, p. 22).

The Financial Stability Board (FSB) proposed the establishment of an industry-wide disclosure and this led to the formation of the Task Force on Climate Related Financial Disclosures (TCFD) in December 2015 chaired by Michael Bloomberg. Its final report was published in June 2017 (TCFD, 2017) and the four core elements of recommended climate-related financial disclosures related to governance, strategy, risk management and metrics and targets. See Figure 8. "Through widespread adoption, financial risks and opportunities related to climate chain will become a natural part of organizations' risk management and strategic planning processes. As this occurs, organizations' and investors' understanding of the potential financial implications associated with transitioning to a lower-carbon economy and physical risks will grow, information will become more decision-useful, and risks and opportunities will be more accurately priced, allowing for the more efficient allocation of capital (TCFD, 2017, p. 42).

4.2.4. Lowering risk by supporting the low carbon transition

Beyond protecting against stranded asset risks, there is a growing literature on ways that central banks can help the low carbon transition. In addition to some of the measures already discussed like green macroprudential regulation, climate related stress testing, disclosure requirements, green differentiated reserve and capital requirements, there are also policies like accepting carbon certificates as part of commercial banks' legal reserves, green quantitative easing and reserve management, green finance guidelines and frameworks and soft power (UNEP, 2017). One can think of many respects that such strategies can help avoid the climate risks associated with the financial system. Clearly to the extent that the low carbon transition is assisted the likely potential damages associated with climate change will be reduced. These policies will also likely better prepare the financial system against the risks of a low carbon transition either by directly diminishing banks' reliance on stranded assets relative to low carbon assets through climate-aligned financial regulation, or by making the financial risks associated with stranded assets more apparent while also altering the incentive structure in favour of the transition.

5. Sustainability transition

In this final section we will take a step back and look at the big picture in terms of major technological transitions and the potential implications for stranded asset risks.

5.1. The oil endgame

There is one prominent critic of the whole debate on 'stranded assets' and the transition risk when it comes to fossil fuels that is worth considering. Helm (2017; 2015) is critical of the simple identification of the quantity of stranded carbon assets based on the implementation of a carbon budget that will achieve the 2°C or even 1.5°C.[2] In particular he argues that it does not take into account the investor perspective on valuation which incorporates the price of the resource as well as the discounted cost of capital. Long before the carbon constraint bites, a falling price of oil in the medium and long run may have much more momentous implications for investors. We have already seen the impact of the price crash without any quantity adjustment or serious change in the cost of capital. The oil price crash means that oil in mid-2016 is simply worth half as much as it was in mid-2014. Much money has been lost by oil investors. This loss has nothing to do with climate change. Price changes happen all the time and can have important implications for the value of assets. "There is nothing 'stranded' here: it is just how markets work" (Helm, 2017).

Physical constraints matter for fossil fuel industries primarily because this means they are doomed in the long run (Helm, 2016). This also means that the reserves-to-production ratio will not matter as a measure of value for investors. A critical issue is the speed of the decline for each of the fossil fuels. Major oil companies do not seem to believe that the constraint will be much of a threat before the mid-century if judging by their forecasts. This may partly reflect their beliefs on policy developments but their seeming unconcern also draws from the fact that decarbonisation will not have much of an impact on the demand for oil in the next decade or so. With their typical discount rates the long run doesn't much matter. Importantly for the stranded argument debate "The fact that as a result they might slowly wither away over the next decades is not an investor problem: investors can gradually switch too, benefiting from the dividends as the companies decline" (Helm, 2017).

Helm (2017) also takes aim at the divestment campaigns for both mistakenly buying into the 'stranded assets' theory and for believing that the campaigns can help in the transition to a low-carbon economy. Divestment campaigns aim to influence the 'social license to operate' by turning the oil companies into the bad guys and to persuade investors to divest or avoid investing on grounds of ethics. To the extent that big pension and endowments are persuaded and override the narrow focus on returns, this could hurt the wider public. Global oil production will not drop because of divestment because National Oil Companies that account for the vast majority of oil reserves will simply step in as International Oil Companies are hit. Furthermore, those that ignore the moral arguments will profit with higher yields. Finally, Helm (2017) doubts that social responsibility issues really

[2] As noted before it is not correct to measured stranded assets simply on the basis of existing reserves anyway, but Helm's argument is not based on the measurement question.

affect the boardrooms in major investment decisions like whether to drill in the Arctic. Shell stopped Arctic drilling not because of eco warriors but because of costs.

Helm (2017) sees the challenge to fossil fuel coming from the low price of oil as a result of significant technological development in renewables rather than from global action on climate change from governments. To put his projections into perspective the International Energy Agency's *World Energy Outlook 2017* (IEA, 2017) sees oil prices rising back to $83-$111/barrel by 2040 according to their New Policies Scenario which serves as their baseline and assumes that government will broadly follow their present policy commitments including national pledges to reduce GHG. Helm (2017), on the other hand assumes a long-term price of $40-60 per barrel, this is even lower than the IEA's Low Oil Price Scenario with a long term equilibrium range of $50-70/barrel (in real terms). The assumptions underlying this scenario are a doubling of the estimated size of the resource base for US tight oil, accelerating technology learning across the upstream sector (reflecting potentially widespread application of digital technologies) and a more rapid switch to electric passenger cars.

The IEA's Low Price Scenario is similar to Helm's in that it relies on a rapid technology transition that is not the result of aggressive climate policy. This highlights a potential difference between oil prices responding largely to technological developments versus them responding to policy changes. Depending on the pace of these developments or their abruptness the concomitant stranding may differ. Moreover, fast technological developments in renewables implies a much less costly transition than a policy driven one that confronts technology constraints. This was also highlighted in Batten et al. (2016) simple stylised game. It is also related to the key message of the IEA (2017) report that the abruptness and unexpected change in mitigation policy can make asset stranding much more severe. In the big picture the extent and severity of stranding is largely a function of the underlying pace of technological developments and the interplay with transition policy.

5.2. Crises, socio-economic transitions and sustainability

As discussed by Caldecott (2017) in the beginning of this paper and reiterated with a different slant by Helm (2017) stranded assets are an inevitable part of 'creative destruction' associated with technological change and transitions. It is also true that many of the major technological transitions or revolutions have been associated with major upheaval and crises. Though some stranding may be inevitable this doesn't mean that something can't be done to avoid many of the risks associated with stranding or find ways to avoid or overcome potential crises related to transitions. It would seem that a better understanding of both the likelihood of stranding of assets, the potential severity of stranding, as well as the potential to overcome many of the risks of stranding, would come by looking at past technological transitions as well as the interplay with policy. In that regard it is worth considering the debate on major technological transitions and their relationships to economic crises.

A strand of literature on financial-economic crises sees these within a framework of Kondratieff long-wave dynamics.[3] Driven by new pervasive technologies, five techno-economic paradigm shifts (or long waves) are distinguished over the last 200 years by Freeman and Perez (1988) and Perez (2002). Figure 10 provides a quick overview of the five techno-economic paradigm shifts. Each techno-economic paradigm shift goes through a number of phases or periods. In the 'installation periods', when new technologies emerge in specific sectors, financial capital and speculative investment tend to drive the dynamics. The wider diffusion of these new technologies confronts barriers in the existing socio-economic framework. In order for the new technologies to spread and find wider deployment institutional adjustments are required. Socio-economic crises are seen as the normal and even necessary aspect of broader transitions in the socio-economic framework, overcoming the 'mis-match' between the requirement for new technologies to flourish and the socio-economic framework. Perez (2009; 2013) and Gore (2010) view the financial crisis of 2008 as precisely this kind of mis-match for the ICT-paradigm. In order that the information communications technologies realize their full potential finance needs to be disciplined and reoriented toward more productive long-term investments in the real economy. Drawing on these ideas a number of authors (Bradfield-Moody and Nogrady 2010; Allianz Global Investors 2010; and Gore 2010) have proposed that "the current crisis also signals the 'installation period' of a sixth green wave, carried by renewable energy, resource efficiency, green nanotechnology, and green chemistry" Geels (2013). A way out of this crisis could come from the convergence of the ICT-paradigm and the green Industrial revolution Perez (2013). If finance can be disciplined and reoriented toward greening the economy than the crisis may be the tipping point towards the next green wave. The idea of successive long waves suggest that the whole process is driven by some internal logic that may not be susceptible to human agency. Some theorists Gore (2010) have argued however that crises may create opportunities for agents to make the necessary policy and institutional changes that will lead to a sustainability

[3] This section and the next is taken with some small modifications from Papandreou (2015)

transition.

5.3. Sustainability transitions

A particular challenge for sustainability transitions is the presence of strong path-dependencies and lock-ins in existing sectors (e.g., IEA (2011), Safarzyńska (2013)). "Established technologies are highly intertwined with user practices and life styles, complementary technologies, business models, value chains, organizational structures, regulations, institutional structures, and even political structures" (Markard et al., 2012, p. 955). For this reason, established socio-technical systems undergo incremental rather than radical changes. The sustainability challenges we presently confront cannot be addressed with incremental changes.

The issue of how to promote more fundamental transformations in the modes of production and consumption (as well as in the energy systems) has been receiving increasing attention in the policy (OECD, 2011; UNEP, 2011) and social science research arenas. There are a broad range of theoretical approaches that have focused on many aspects relating to transitions. Four theoretical frameworks (transition management, strategic niche management, multi-level perspective socio-technical transition, technological innovation systems) that focus explicitly on transition studies from a perspective of systemic far-reaching transformation processes of socio-technical systems have recently achieved some prominence (Markard et al., 2012).

Socio-technical systems consist "of (network of) actors (individuals, firms, and other organizations, collective actors) and institutions (societal and technical norms, regulations, standards of good practice), as well as material artefacts and knowledge (Markard et al., 2012, p. 956). This systems approach highlights the tight interrelationship and interdependence among the broad array of elements and has critical implications for the dynamics of system transformations. A socio-technical transition involves a fundamental shift in socio-technical systems "through far-reaching changes along different dimensions: technological, material, organizational, institutional, political, economic and socio-cultural. Transitions involve a broad range of actors and typically unfold over considerable time-spans (e.g., 50 years and more)...The emergence of a transportation system with the automobile technology at its core, for example, required a complementary development of road infrastructure, fuel supply systems, traffic rules, services (e.g., maintenance, insurance), user practices, etc. In fact, socio-technical transitions do not just change the very structure of existing systems...but they also affect related societal domains, such as living, housing and working, production and trade, and planning and policymaking" (Markard et al., 2012, p. 956).

Sustainability transitions are then socio-technical transitions that involve shifts toward more sustainable modes of production and consumption. In principle, these transitions could take place at different scales (in time and space) as more or less guided responses to pressures or environmental bottlenecks, and attain different levels of sustainability. History certainly provides many examples of socio-economic transitions emanating from environmental pressures (man made or not)[4] . The sustainability challenges we face today are many and involve several domains. The energy sector is challenged by greenhouse gas emissions and air pollution, nuclear risks, security of supply, rapid resource depletion and energy poverty (IEA, 2011). The water sector confronts challenges of insufficient access in low income countries, extreme events, scarcity. Similarly critical challenges are confronted in the transportation sector (congestion, local air pollution, CO2 emissions), the agricultural sector, etc. All of these challenges require multi-dimensional responses and governance of sustainability transition. The climate change challenge is special in that it pervades nearly all sectors in terms of potentially devastating impacts and requires fundamental non-incremental changes (mitigation of emissions and adaptation) in most sectors many of which have been fundamentally moulded by the fossil fuel energy system of the twentieth century. It is also special in that only a global and comprehensive response within a very short time frame can adequately protect us from taking on unfathomable risks.

So while the energy system confronts numerous challenges, the climate change challenge dominates all others in terms of the extent and speed of required transition. The demands on globally coordinated comprehensive action are unprecedented. In terms of a transition to sustainable energy systems it is important to note that historical regime transitions were rarely if ever explicitly guided by long-term, socially deliberated goals like sustainability (Smith et al., 2010). The nature of transformation demanded to achieve a low carbon energy system means that great institutional, economic and political commitments are needed against the incumbent regime.

[4] For some more recent accounts of major transitions that include environmental pressures as drivers see (Morris, 2013; Morris, 2010; Diamond, 2005; Acemoglu, Aghion, Hemous, & Bursztyn, 2012).

6. Conclusion

Despite the growing interest in the risks associated with stranded assets the fast expanding literature is still young and quite limited in terms of peer reviewed academic publications. This paper attempts to provide an overview of this literature with a focus on climate related risks associated with the financial system and why it needs to be a concern to central banks. It is useful to note that stranded assets can be defined very broadly allowing us to draw lessons from historical transitions and important parallels with the dynamic nature of economic development or what Schumpeter called "creative destruction". Within this very broad context the recent discussion has focused on the potential stranding of assets from environment-related risks and more narrowly on climate-related risks and how these affect the financial system. Two main channels of climate-related risks have been discussed: risks of physical impacts from climate change and risks associated with society's response to climate change (transition risks). Risks of physical impacts from climate change encompass the many ways that disruptive phenomena such as coastal flooding, heat waves, droughts, and extreme weather events, will impacts assets of households and businesses as well as balance sheets of insurance companies and commercial banks. Transition risks encompass the many ways that society responds to climate change through mitigation and adaptation and how the form and pace of these responses will affect the risk of stranding assets.

An important aspect of the stranded literature discussion involves efforts to quantify the potential physical and transition risks. Dietz et al. (2016b) have used an integrated assessment model to provide some measure of global physical and transition risk while Dafermos et al. (2017) develop an alternative approach using an ecological macroeconomic model that sheds light on the physical effects of climate change on financial stability. There have also been efforts to quantify transition risks if society is likely to achieve the target set by the Paris Climate Agreement both at the global level but also at the level of sectors and firms. This literature is also recent and very limited but the issue of developing better measures of these various risks will form a critical part of society's capacity to better understand and respond to the risks of stranded assets.

We already know that markets are inherently incapable of addressing the climate change challenge on their own. Indeed, climate change represents the biggest market and institutional failure that humanity has faced. In focusing on the problem of stranded assets the question turns to the narrower issue of whether the financial industry is adequately aware of the nature of climate risks. There are many reasons why the financial industry may misprice both physical risks of climate change and society's response to climate change. Some of the literature looks at why individuals operating in the financial industry may fail to account for these risks while there is a much broader theoretical and empirical literature related to behavioural and experimental economics that provides explanations of how humans may deviate from the assumptions of rationally commonly assumed in economic models. The literature that actually attempts to measure the potential extent of mispricing of climate risks by the financial market is still very limited.

There are a number of ways that the financial industry can respond to climate risks and there is also a growing discussion about what central banks and financial regulators can do to improve the financial industry's response or to address its failure to respond adequately. As mainstream investors are awakening to issues of climate change and carbon risk a number of new stock indexes, funds, bond ratings and investment tools are being designed. Central banks and financial regulators are increasingly looking at the financial risks associated with climate change and they are discussing numerous means of enhancing the resilience of the financial systems from climate-related shocks. These include conducting environmental stress tests, dedicated credit lines for green investments, setting rules for transparency and reporting and even quantitative easing like giving greater weight to green assets in special asset purchase programs. As Campiglio et al. (2018) point out, much work still needs to be done to develop methodologies and collect data for evaluating climate-related risks that companies and investors are exposed to. Models that enable a forward-looking assessment of climate-related risks and their social impacts must also be developed. Central banks can play an important role in facilitating the exchange of practices across modelling communities (Campiglio et al., 2018).

The final part of the paper tries to put the stranded asset debate in the historical context of major socio-technical transitions that have taken place in the past. There are common features in past transitions that can guide us to what we might expect in the future but there are also critical differences that we must be aware of. While most of the focus has been on the worry that the sustainability transition will not be fast enough to address the challenge of climate change or that the policy response will be too slow leading to a rude awakening at some point, others have suggested that we may be surprised by the speed of technological developments. While the latter is a hoped-for surprise, both can lead to stranding of assets with damaging implications for the financial system. The challenges of a sustainability transition suggest that while it would be hoped that (a) climate change policy could give clear and consistent signals about where it is headed, (b) the technological and societal transition will be smooth and fast enough to address the climate change challenge but also to accommodate the energy demands of the economy, (c) the financial community will find means of handling the several novel risks associated with the sustainability transition, there are very good reasons to expect some of these conditions will not be met. The nature of deep uncertainty inherent in the sustainability transition and in climate change itself will heighten the need for vigilance against physical and transition risks and for better understanding these as well as finding the means of response at various levels of governance.

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Figures

	Class	Description
PHYSICAL	Environmental challenges and change	For example, climate change, water stress, and biodiversity loss.
	Changing resource landscapes	Price and availability of different resources, such as oil, gas, coal and other minerals and metals. For example, Peak oil and the shale gas revolution.
SOCIETAL	New government regulations	Introduction of carbon pricing (via taxes and trading schemes), subsidy regimes (e.g. for fossil fuels and renewables), air pollution regulation, disclosure requirements, the 'carbon bubble' and international climate policy.
	Technological change	For example, falling clean technology costs (e.g. solar PV, onshore wind), disruptive technologies, and GMO.
	Evolving social norms and consumer behaviour	For example, fossil fuel divestment campaign, product labelling and certification schemes, consumer preferences.
	Litigation and changing statutory interpretations	For example, court cases, compensation payments, and changes in the way existing laws are applied or interpreted.

Figure 1
Source: Caldecott et al. (2013)

Physical environmental risks

Risks	Issues	Consequences	Examples
Environmental change	Climate change	Increased extreme weather events, such as: droughts, floods, and heat waves	A temperature increase of 2.5ºC above pre-industrial levels by 2100 could result in annual damages of 1-2% of world GDP[16]
		Sea level rise	By 2050, US$66-106bn worth of existing coastal property will likely be below sea level in the US[17]
	Biodiversity and habitat loss	Loss and degradation of ecosystem services such as water retention, and soil formation and protection	Goods and services provided by ecosystems are estimated to amount some US$33 trillion per year[18]
	Land degradation and desertification	Deforestation and forest degradation	From 2000 to 2012, the world lost over 2.3 million km² (230 million hectares) of forest[19]
		Loss of agricultural areas	52% of the land used for agriculture is moderately or severely affected by soil degradation worldwide[20]
	Water pollution (biological or chemical)	Decreased water availability Health hazards	In a recent paper, 53% of the companies surveyed on the FTSE Global 500 Index reported that they had suffered water-related business impacts in the past five years[21]
	Air pollution	Decreased air quality, leading to health problems	In 2012, around seven million premature deaths resulted from air pollution, more than double previous estimates[22]
Resource landscape	Availability of natural resources	Depletion of non-renewable resources	Long-term exhaustion of phosphorus reserves[23]
		Reduced natural flows of renewable resources	Water scarcity for agriculture[24]
	Price changes of natural resources	Impacts on business value	Farmland value reduction in Iowa caused by crop price falls in 2014[25]

Figure 2
Source: Caldecott, Dericks, Pfeifer, and Astudillo (2017)

Societal environment related risks			
Risks	Effect	Response	Result
Government regulations	Climate change	Limit increase in global average temperatures to 2°C	Reduction of global emissions, fossil fuel reserves could remain unburned
	Stratospheric ozone layer loss	Prohibition of substances that deplete the ozone layer	Reduction of the ozone layer, factories of CFCs closed
Technological change	Climate change	Development of electric cars	Combustion engine infrastructure could be left unusable
	Air pollution	Elimination of leaded petrol	Lead production infrastructure affected
Societal norms change	Climate change	Divestment from fossil fuels	Reduction of investment in the fossil fuel industry
	GMOs	Product labelling	Changes in consumer preferences and behaviour
Litigation and statutory interpretation	Pollution	International lawsuit against Chevron-Texaco by Amazon communities	Potential judicial rule against the company. Payment of compensation for damages
	Climate Change	EU greenhouse gases emission for international air travel	Interference to free trade. Positive discrimination for low-carbon products

Figure 3
Source: Caldecott, Dericks, Pfeifer, and Astudillo (2017)

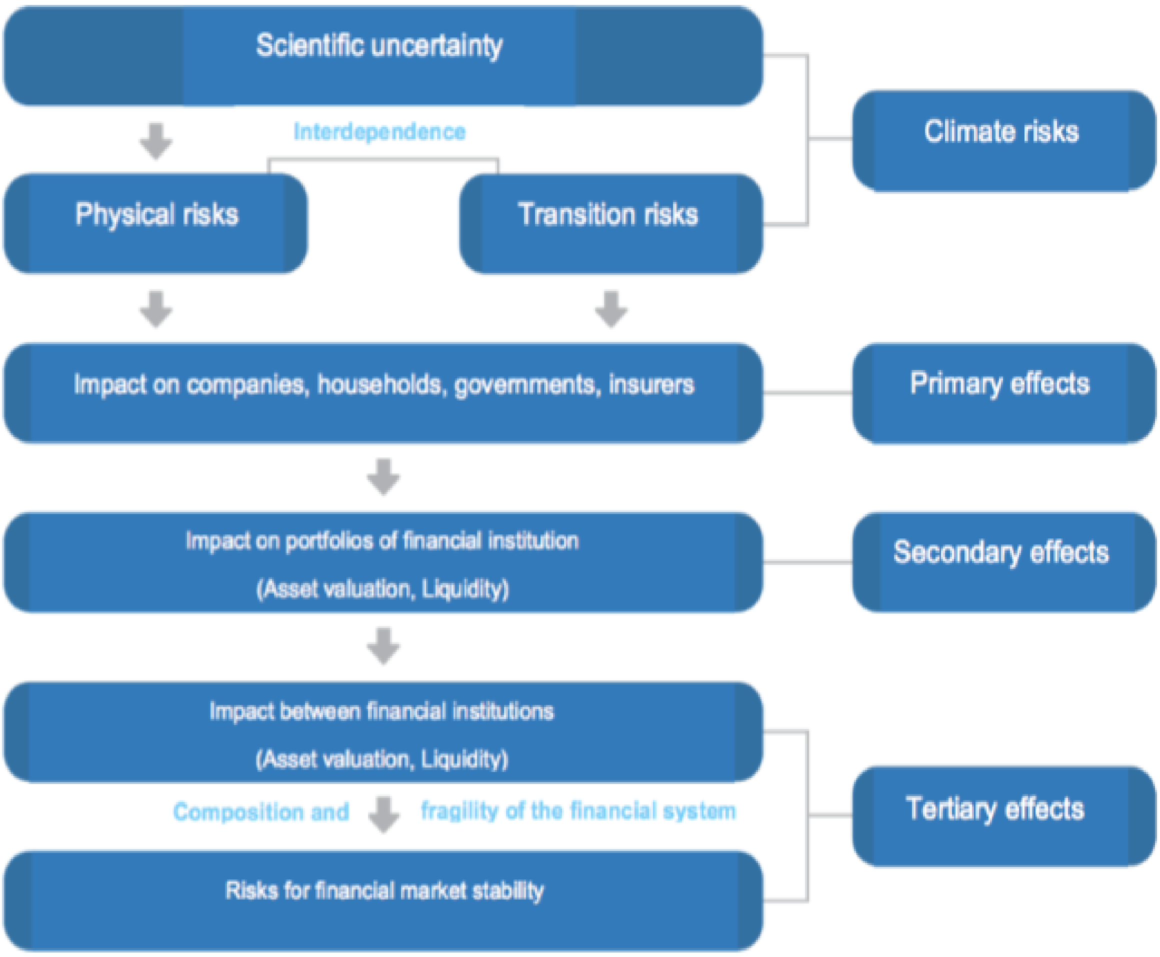

Figure 4
Source: South Pole Group (2016)

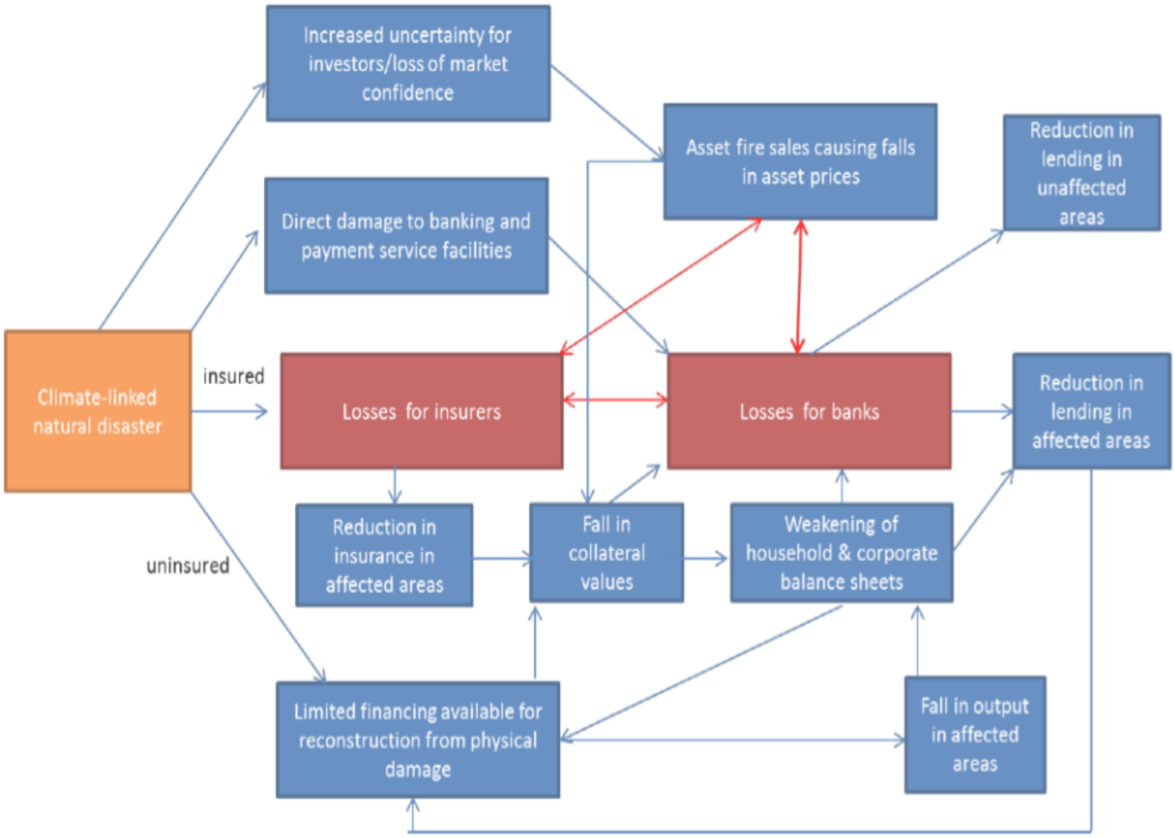

Figure 5
Source: Batten et al. (2016)

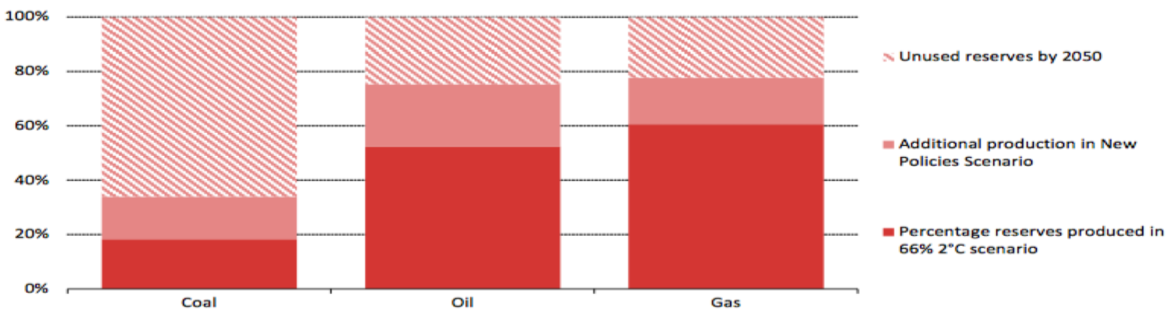

Figure 6
Source: IEA/IRENA (2017)

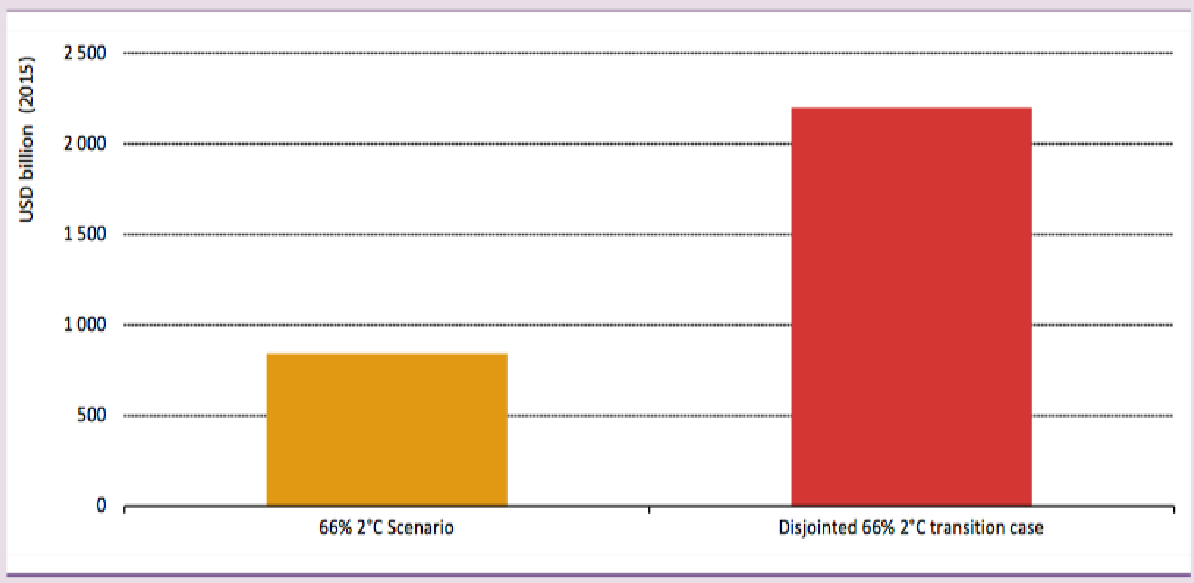

Figure 7: Cumulative stranded assets in the 66% 2°C Scenario and the disjointed 66% 2°C transition case
Source: IEA/IRENA (2017)

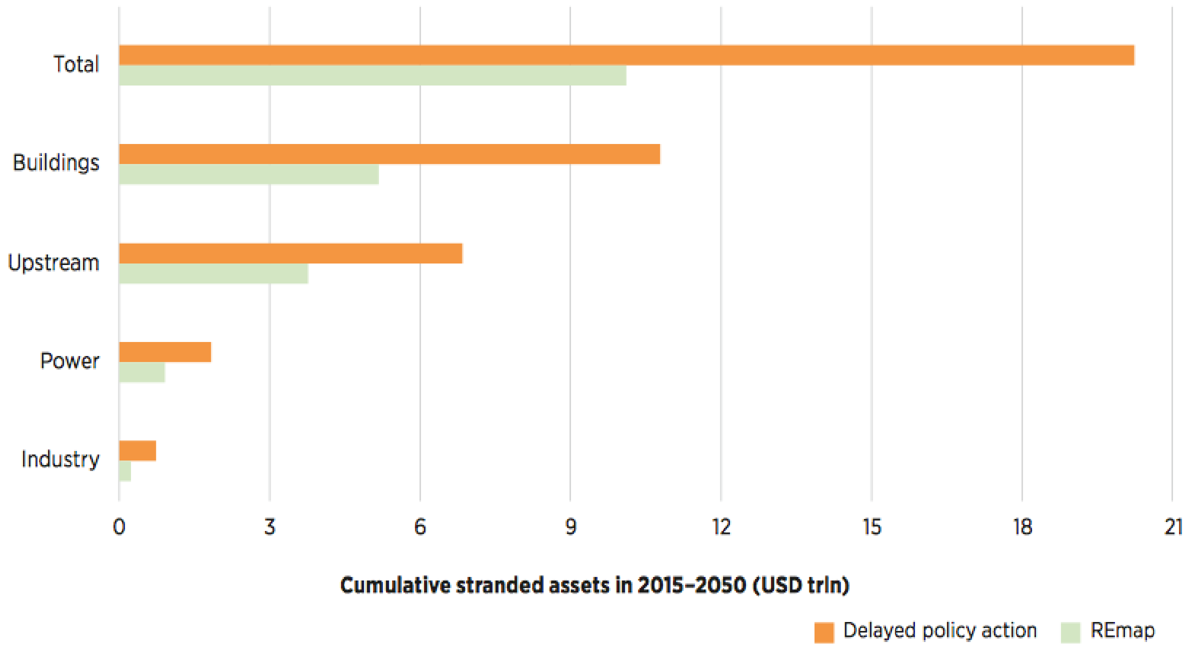

Figure 9
Source: IRENA (2017)

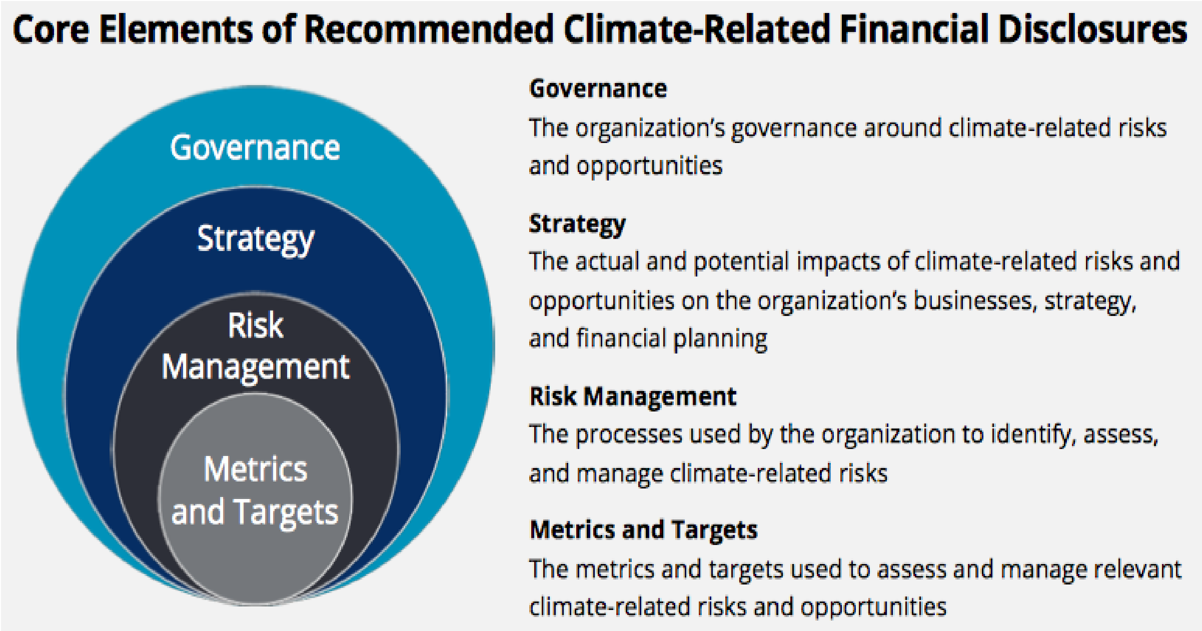

Figure 8
Source: TCFD (2017)

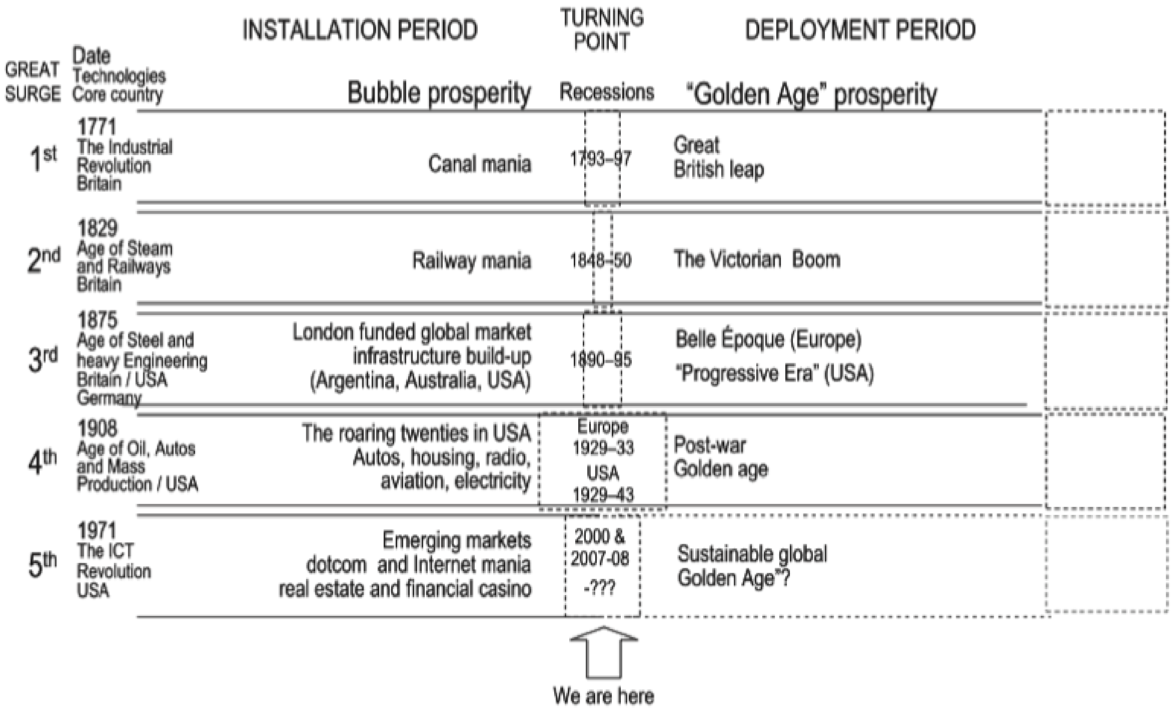

Figure 10
Source: Perez (2013)

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