Quantifying stranding risk for fossil fuel assets and implications for renewable energy investment:

A review of the literature

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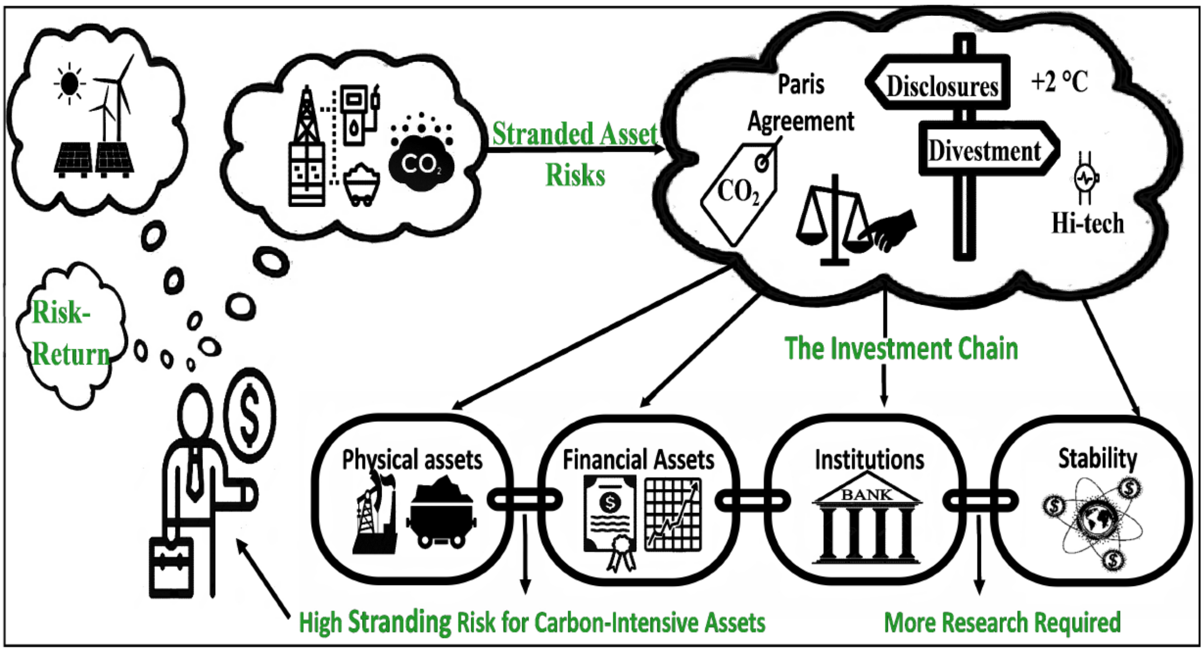
Abstract

Investment in sustainable and renewable technologies must be doubled if globally agreed climate targets are to be met. The ways in which stranded asset risk from climate change could impact the risk-return preferences and capital allocation decisions is therefore receiving increased attention. We develop an analytical framework to systematically review the literature on stranded asset risk across the investment chain: for physical assets, securities, investment portfolios, the creditworthiness of financial institutions, and the stability of the financial system. We find that there has been a strong focus on evaluating stranding risk for illiquid assets at the earlier points in the investment chain: fossil fuel reserves and the energy generation sector. These studies identify stranding risk for high cost or carbon-intensive reserves and for energy generation technologies dependent on these resources, in particular coal. There is also some evidence that owners of financial assets could also be exposed to stranding risk because the valuations of coal, oil and gas companies could be overstated, particularly for undiversified companies with high capital exposure carbon-intensive resources. Moving along the investment chain, there are fewer studies quantifying risks for the creditworthiness of counterparties, asset portfolio managers, financial institutions and the stability of the financial system. While there is some evidence that stranding risk may be an issue for financial institutions and investment portfolios, other studies find that risks to more liquid assets are less acute and can be managed by diversification strategies; and these are areas identified for further research.



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Highlights:

- *Stranded asset risk from climate mitigation affects capital allocation decisions*
- *Evaluating risks at earlier points in the investment chain has been the main focus*
- *High cost and carbon-intensive fossil fuel reserves are highly exposed*
- *Stranding risk could also affect financial institutions and investment portfolios*
- *Further research is needed to assess risks at later points in the investment chain*

Keywords: climate change; stranding risk; investment; renewable energy; fossil fuels

List of abbreviations:

2DII	2 Degree Investing Initiative
2DS	Two Degrees Celsius
CCS	Carbon Capture and Storage
CTI	Carbon Tracker Initiative
GDP	Gross Domestic Product
GHG	Greenhouse Gas
ICBC	Industrial and Commercial Bank of China
IPCC	Intergovernmental Panel on Climate Change
LNG	Liquified Natural Gas

1. Introduction

Limiting the rise in global mean temperature to well below 2°Celcius (2DS) would require an energy transition of "exceptional scope, depth and speed", and $3.5 trillion in renewable and sustainable energy-sector investments each year until 2050, which is about double the current level of investment [1].

Much of this capital will come from private sources. However, a combination of technological, economic, institutional and political barriers result in sub-optimal low-carbon investments along the innovation cycle [2]. Over the last decade, investor perceptions of risk and return have become an important stream of research in the energy finance, energy policy and energy economics literature. The importance of the risk and profitability characteristics of investments are generally accepted to be highly influential over investor behaviour [3]. It is widely accepted that investors—whether electric utilities, insurance companies, pension funds, or even retail investors—compare opportunities according to perceived risk-adjusted returns [4]. Lower risk perception for renewable energy projects or higher risk perception for fossil fuel projects could therefore affect investors' cost of capital, which in turn is important for determining the rate of technology diffusion and the pace of low-carbon transition.

Much of this literature has focused on how investor perception may unjustly disadvantage renewable technologies, which are characterised by high uncertainty [5], long lead times and high capital costs [6]; the ways in which high carbon investments are therefore "locked-in" [7, 8]; or the manner in which past investments in fossil fuels may influence the risk-return perception of decision-makers [9]. However, the ways in which climate change could affect risk perception for energy sector investors has also been the subject of growing interest. Krause, Bach and Koomey (1989) first applied the concept of "stranded assets" to the climate policy arena by identifying the potential for "early obsolescence" of infrastructures built up around fossil fuels under low-carbon transition, which could pose risks for the value of stocks and financial markets [10].

This is a theme that has garnered greater analytical attention as international political momentum to address climate change has gathered pace over the past decade. Most notably, 193 nations at the Cancun Climate Conference in 2010 agreed to *"hold the increase in global average temperatures below two degrees"*. This objective was subsequently incorporated into the Paris Climate Agreement of December 2015. Article 2.1 c of this agreement also includes the objective "*making finance flows consistent with pathways towards low greenhouse gas emissions and climate resilient development*"[11].

A parallel scientific development was the increasing prominence given to carbon budgets: that is, the amount of cumulative greenhouse gas (GHG) emissions in the atmosphere consistent with meeting a particular climate objective. The first budget estimates were provided by Meinshausen *et al* (2009) and Allen et al (2009). Further estimates have subsequently been provided under different assumptions in a wide number of studies [12]. The concept was mainstreamed into climate policy analysis by the Intergovernmental Panel on Climate Change (IPCC)'s synthesis report of 2014, which provided estimates for budgets consistent with various levels of warming. Recent budget estimates have focused on achieving the 1.5 °Celsius target [13, 14]. These carbon budget estimates gave rise to the concept of "unburnable carbon", which refers to the fossil fuel reserves that cannot be burned which is consistent with staying within a particular carbon budget [15], an idea that has attracted considerable analytical and public attention [16-19], and has clear implications for investor risk perceptions and capital allocation decisions. However, it is an open question in the literature how perceptions of stranding risk could affect investment decisions.

If these assets are effectively "unburnable", their worth could be vastly reduced and they could therefore fail to produce the return hoped for [20]. In other words, these assets may become "stranded". While there are a number of possible definitions of stranded assets, we adopt the definition proposed by Caldecott (2014, p 7), that *'stranded assets are assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities.* Central to the question of stranding risk, therefore, is the extent to which climate risks are correctly integrated into the risk-adjusted returns by actors in the financial system, and therefore the extent to which these are risks are integrated into market and share prices. The premise of the stranding literature is that stranding risks may be mispriced for a number of reasons [21-23], although others have argued that stranding risk has been adequately integrated into market prices [24].

This concept of stranding risk has move from the fringes to the mainstream of debates in climate change financial community. In September 2015, for example, the Governor of the Bank of England, Mark Carney, warned that there was a danger that assets of fossil fuel companies could be left stranded by tougher rules to curb climate change, and that investors faced "potentially huge" losses because this action could make vast reserves of oil, coal and gas "literally unburnable". The Financial Stability Board, which reports to G20 governments and is chaired by Governor Carney, subsequently launched a Task Force on Climate-related Financial Disclosures (2017), which recommended that climate-related financial disclosure should be incorporated into mainstream public annual financial statements [19]. The European Commission, meanwhile has introduced a proposed regulation which introduces obligations on how institutional investors and asset managers integrate environmental, social and governance (ESG) factors in their risk processes.

It is therefore an open question in the literature how stranded asset risk impacts investors' capital allocation decisions, and the extent to which stranding risk could change investor behaviour in favour of sustainable and renewable energy investments. Within this context, the objective of this paper is, first of all, to develop a novel analytical framework to codify both the academic and grey literature studies that evaluate stranding risk for fossil fuel assets, and how this affects investors' risk-return preferences and capital allocation decisions. Second, we use this analytical framework to undertake the first comprehensive and systematic review of this literature, covering the first decade of research, assessing both the methods used and the results of this literature.

This paper therefore makes a number of contributions: it provides the first systematic and comprehensive stock-taking of this literature following a decade of research; second, it provides a high-level overview of the findings from this research; and third, it identifies literature gaps, limitations of current approaches and areas for further research.

2. Materials and Methods: The Analytical Framework

To identify studies of relevance we employed a systematic literature review approach (Section 2.1). In order to review and categorise the studies identified as relevant by this review, we developed an analytical framework using the typological approach set out in Sections 2.2 to 2.5 below.

2.1. Systematic literature review approach

To identify studies of interest, we employ a systematic literature review approach. Systematic literature reviews offer an established methodology for presenting summaries of empirical evidence from across a range of disciplines [25-27].

In order to ensure the scientific validity of a systematic literature review it is important to determine the type of primary studies the review is trying to locate by identifying inclusion and exclusion criteria. In this case, we include both *ex post* and *ex ante* studies employing both quantitative and qualitative methodologies, which seek to explore stranded assets posed to fossil fuel assets from the transition to a low carbon economy. We focused on studies related to financial assets and fossil fuel infrastructure (Section 2.2), and therefore excluded studies focusing on natural assets. We also excluded studies related to the physical impacts of climate change [28, 29], and instead focused on the risks posed by transitioning to a low carbon economy (Section 2.3). We then used Science Direct, Google Scholar, Scopus and Web of Science to identify academic studies of interest using combinations of the terms *"climate", "carbon" and "stranded asset"* (Table 1).

Table 1 Results of Database Searches

	Carbon + Stranded Assets	Climate +Stranded Asset
Science Direct	716	714
Google scholar	11,400	18,100
Scopus	40	42
Web of Science	31	40

In addition, we searched for grey literature following Siddaway (2010), using the Stranded Assets Research Network's bibliography,[1] curated by the Smith School of Enterprise and Environment at Oxford University, as a starting point. Furthermore, a number of key organisations including Carbon Tracker Initiative, the 2 Degree Investing Initiative (2DII), the United National Environmental Programme, HSBC and Mercer have undertaken much of the research into stranded assets. Reports by these groups were therefore reviewed as a starting point, and bibliographies were used to identify further grey literature studies that met our inclusion criteria.

2.2. Type of asset

Following Chenet, Thomä and Janci (2015), we first categorise relevant studies according to the type of assets they consider, looking across the entire investment chain. Stranding risk first affects physical assets which tend to be the most illiquid, including both the underlying fossil fuel reserves, and "downstream" infrastructures that rely on fossil fuels (power stations, transport assets, real estate etc.). However, asset impairment can also impact financial assets, which are more liquid. For example, it could affect the companies or countries that own these assets, and could therefore impact the share price or creditworthiness of these actors. This, in turn, could feed through to investment portfolios owned by institutional investors, or indeed the balance sheets of financial institutions. Finally, the value of portfolios and creditworthiness of financial institutions has the potential to feed into systems risk, and to undermine the stability of the financial system [30] (Table 2).

[1] Hosted at https://www.mendeley.com/groups/8139231/open-stranded-assets-research-network-university-of-oxford/

Table 2. Investment chain for stranded assets

Physical Assets	Companies and countries	Investors and Institutions	Regulators and policy makers
Fossil fuel reserves	Equities	Balance sheets	Systemic stability
Fossil fuel dependent infrastructure	Debt	Portfolios	

Increased liquidity

Source: Adapted from [31] & [32]

2.3. Risks

The focus of this study is on climate risks, excluding risks associated with the physical impacts of climate change. These have been described as "carbon risks" or "transition risks" [31]. Initially transition risk was understood to arise from the full implementation of a scientifically-derived carbon budget agreed at international level [16]. More recent work, however, has focused on a wider range of interrelated risks, including regulatory and policy risks (including carbon pricing), technological change and associated changes to the competitiveness of sustainable and renewable energy technologies [33], social norms, and legal considerations. Following Caldecott, et al (2013), we categorise studies according to the types of carbon or transition risks they consider (Table 3).

Table 3. Carbon and transition risks considered

Type of Risk	Carbon budget risk	Policy and regulation	Technological change	Social norms	Litigation
Examples	Implementation of climate target	Subsidies	Falling costs for renewables	Divestment campaigns	Liability for climate damage
		Carbon pricing	Lower demand and/or prices for fossil fuels	Product labelling	
		Disclosure requirements		Consumer preferences	

Source: Adapted from [34]

2.4. Scenarios explored

Scenario analysis is popularly used to prepare for multiple possible futures under conditions of uncertainty and complexity [35]. For this reason, multiple futures are commonly (though not universally) explored in the stranding literature to explore the potential magnitude of the impacts on asset values in different possible future worlds [20]. In many cases, scenarios with an emissions constraint are compared to a baseline case where there are no emissions constraints. Other studies combine an emissions constraint with economic, technological, political and regulator factors to develop more granular possible futures. However, not all studies formerly develop scenarios to evaluate risk (Table 4).

Table 4. Scenarios explored

Climate constraint	Hybrid	No Scenario

Two-degree target	Climate constraint combined with economic and technological factors	Scenario method not employed
Two-degree and other climate scenarios	Climate constraint combined with policy and regulatory factors	

2.5. Methods used

A wide variety of methods have been used to quantify the value of assets at risk of stranding [31]. In the case of physical assets, stranding risk to fossil fuel reserves are often measured by estimating the impact of a particular carbon budget constraint, in some cases integrating considerations of fossil fuel supply curves. Energy and economic systems modelling approaches have also been used. For downstream fossil fuel-dependent assets, exposure of power generation plant, transport infrastructure and real estate to climate risk have been determined through the development of qualitative and quantitative risk assessments.

In the case of companies and their shares, a variety of overlapping methods have been employed. Some studies explore fossil fuel supply curves under a particular constraint to determine risks for a particular company or sector. In other cases, a variety of financial/accounting tests are employed to determine the value at risk and/or the potential implications for market capitalization, share price, creditworthiness etc. (Sections 3). Other approaches include using a shadow price for carbon, qualitative risk assessments, or measuring emissions intensity. Finally, *ex post* studies have quantified historical asset stranding using historical case studies and event studies. In the case of debt, stranding risk to sovereigns has been evaluated using carbon intensity of Gross Domestic Product (GDP), which sovereign credit ratings and risk assessments under climate risk have been used to determine the creditworthiness of a country or company under a low carbon transition (Section 3).

When it comes to portfolios, economic/energy systems models have been used to assess the magnitude of risks to a variety or asset classes. The carbon intensity of portfolios and traditional stress tests have also been used to assess stranding risk. Finally, macro-prudential stress tests can be used to determine the implications of stranding risk for the financial system. The typology of methods used to value stranding risk, divided according to asset type, is provided in Table 5.

Table 5. Methods used

Physical assets	**Companies/equities**	**Debt**	**Portfolios**	**Financial system**
Global budgets with supply curves	Global budgets with supply curves	Company or sovereign credit rating	Energy systems modelling	Macroprudential stress test
Energy systems modelling	Financial tests	Carbon intensity of underlying asset	Balance sheet stress test	
Risk assessments	Shadow prices		Carbon intensity of portfolio	
	Carbon intensity			
	Risk Assessment			
	Historic analysis			

3. Results & Discussion

3.1. Physical Assets

3.1.1. Fossil fuel reserves

Many studies have explored stranding risk for total known fossil fuel reserves. The majority of this literature is forward looking, aimed at measuring potential future stranding risk under 2DS by comparing carbon budgets to known reserves. A strong consensus emerging from this literature is that in a tightly carbon-constrained future, a large quantity of known reserves could face stranding risk, especially carbon intensive-resources that are costly to exploit. These concerns become particularly acute in a low oil price environment, but have been alleviated with oil price increases beginning in 2016. Carbon Tracker Initiative (CTI), for example, estimated that up to 80% of declared reserves could become stranded [36, 37], while McGlade and Ekins (2015) estimated that one third of oil reserves, half of gas reserves and over 80 per cent of current coal reserves should remain unused from 2010 to 2050 [38]. Other studies have monetized this value at risk. For example, Linquiti and Cogswell (2016) found that the value of the global fossil fuel reserves in a business-as-usual case ($295 trillion) could decrease by 63 % [39], while Kepler Cheuvreux (2014) estimated that the fossil fuel industry could lose up to $28 trillion by 2035, and found that high cost producers tended to be the most carbon intensive ones, and that the oil sector had the greatest level of exposure [40]. CTI (2015) concluded that $2 trillion of capital expenditure may not be profitable under the 2DS scenario, and that no new coal mines could developed, Liquified Natural Gas (LNG) production would be curtailed slightly, while US shale oil, Canadian oil sands, Russian conventional oil and Artic could also be stranded [41].

Not all studies, however, agree with projections of stranding risk for fossil fuel reserves. For example, Newell et al (2016), which did not impose a particular carbon constraint, but rather used harmonization techniques to compile energy forecasts (from the International Energy Agency, Exxon, Shell, and Organisation of Petroleum Exporting Countries), estimated that fossil fuels will remain from 60% to 80% of total primary energy sources in 2040 [42]. Aside from the uncertainty associated with whether a particular constraint will be implemented in practice, other studies have sought to assess the potential implications of negative emissions technologies for stranding risk. For example, Caldecott et al (2016) estimated that negative emissions technologies (including afforestation, soil carbon sequestration, biochar, bioenergy with carbon capture and storage (CCS)) could extend the 2050 carbon budget by a modest 11-13%, and found that these technologies continued to be subject to considerable uncertainty [43]. A weakness of this literature is that results are, to some extent, determined by assumptions about the carbon constraint.

Other studies have focused more forensically on quantifying stranding risk for a particular type of fossil fuel reserve in scenarios with a tight carbon constraint. In the case of oil, McGlade and Ekins (2014) estimated that 45% of available oil could not be produced before 2035 without CCS, rising only moderately with CCS, and that Arctic, unconventional and “tight” oil were largely “unburnable” [44]. CTI (2014) found that oil projects above $75/barrel were likely to be incompatible with a 2DS, and that capital expenditure of $1.1 trillion dollars earmarked for projects requiring an oil price of $95 dollars were highly exposed [45]. HSBC (2015) compared project break even points for Russian Arctic, Canadian oil sands, US shale oil, the North Sea, Venezuelan heavy oil and Saudi Arabian conventional crude, concluding that only the latter two were profitable at low oil prices [46]. In the case of gas, CTI (2015) found that there were $283bn of high cost, energy intensive LNG projects in the US, Canada and Australia could be stranded in low demand and price scenarios [47].

A strong message from this literature, therefore, is that in future scenarios with a tight top-down carbon constraint, difficult to reach projects with high capital costs, along with carbon intensive reserves, face high stranding risk. However, a weakness is that results are highly dependent on input assumptions and methods used. The absence of *ex post* studies assessing stranding risk for fossil fuel reserves is also notable. There would appear to be opportunities for future *ex post* research focusing on stranding risk coal and shale oil assets, particularly in geographic locations where a low-carbon transition has begun.

3.1.2. Assets & infrastructure reliant on fossil fuels

Stranding risk for known fossil fuel reserves inevitably feeds into impairment risk for downstream assets that are dependent on these assets, therefore potentially enhancing the business case for investing in sustainable infrastructure. The majority of studies that explore stranding risk for downstream assets are forward-looking, however there is also an emerging *ex post* literature.

Several *ax ante* studies that have explored stranding risk for downstream assets have focused on assessing overall stranding risk for the power generation sector. For example, Green and Newman (2017) explored the potential impact of disruptive change in power generation from new technologies. They concluded that in the most optimistic future scenarios, 100% of power could be generated by sustainable and renewable energy by 2046, a scenario which posed stranding risks for fossil fuel-based power generating assets [48]. Pfeiffer (2016) estimated that the 2DS capital stock for power generation would be reached by 2017 based on current trends, and concluded that all new power generation infrastructure would need to be sustainable or it could face stranding risk [49].

A strong message emerging from this literature is that stranding risk may be particularly acute for coal-powered generation compared to gas. Farfan and Bayer (2017), for example, concluded that about 300 GW of the installed coal power plants may end up as stranded assets, most of it in China (59%) and India (22%), and that future coal investment was also likely to be stranded, but that the risk for gas generation capacity was likely to be lower [50]. Farfan and Bayer (2017a) estimated that 17 GW of coal capacities installed in Europe from 2010 onwards faced a shorter-than-expected operational lifetime and that gas and oil-fired capacities commissioned from 2016 onwards may be required to shift to sustainable and renewable energy sources to avoid future stranding [51]. Caldecott et al (2015) identified a particular exposure for subcritical coal generation technologies, finding that Indian, former Soviet and Chinese companies' portfolios were particularly exposed due to high reliance on older technologies [52]. Caldecott et al (2016) and Coldecott et al (2017) explored stranding risk to Japanese and Chinese coal fired power generation respectively, finding considerable stranding risk in both cases, depending on the speed at which the risks identified materialized [53, 54]. In terms of mitigating climate risk for coal fired power generation, Johnson et al (2015) found that strengthening near-term climate policy (i.e. lowering the global greenhouse gas emission target in 2030) generally reduced the risk of stranded assets, and that an effective strategy for managing risk was to minimize the construction of new coal capacity without CCS [55].

A clear finding from the *ex-ante* literature, therefore, is that coal fired generation may face stranding risk in a carbon constrained world, and that this risk may be particularly prevalent in emerging economies. This conclusion is supported by an emerging *ex post* literature focusing on developed markets where the low carbon transition has begun. Ernst and Young, for example, have published a number of assessments of asset write-downs from climate risk to EU utilities over the past five years. Most recently, Ernst and Young (2017), estimated that €143 billion has been written off against assets that had lost value between 2010 and 2016, which they largely attributed to rapidly growing volumes zero marginal cost sustainable and renewable energy sources, carbon pricing and growing policy and regulatory pressure against coal-fired assets (in addition to poor overall economic conditions) [56]. Similarly, Caldecott et al (2017) explored the investment plans of the EU's 14 largest utilities in coal generation, finding more than a six-fold increase in write-downs had occurred since 2008. They concluded that in jurisdictions where coal expansions are being considered, stranding risk can be enhanced when a sector is experiencing significant technology, policy, and market innovation [57]. The weakness of the *ex post* literature is that it has focused exclusivity within the EU context, and is an opportunity for further ex post research exploring write downs to coal generation assets in other markets.

There have been fewer studies focusing on stranding risk for generation technologies other than coal. One exception is McGlade et al (2018), which found that without CCS, a 'second dash for gas' was unlikely to be the most cost-effective way to reduce emissions in the UK. With significant CCS deployment, however, they found that natural gas could remain at 50–60% of the 2010 level by 2050, reducing stranding risk [58]. Munoz and Bunn (2013) concluded that decarbonization of a wholesale power market, such as that of the United Kingdom, was associated with a progressive deterioration in the financial risk–return profile of all new *and* existing assets, irrespective of whether they were high or low carbon [59]. The stranding risk to gas generation is underlined by one ex post study: Caldecott and McDaniels (2014) assessed the impact of market contractions, fuel prices changes, climate and energy policies on gas-fired power assets in the EU, finding that stranding risk had significant and immediate consequences for company value, utility strategy and policy (next section) [60].

The majority of studies exploring stranding risk for fossil fuel assets therefore focus on the power generation sector. However, Lloyd's (2017) suggested that stranding risk could additionally affect property and transport assets [61] and Derricks et al (2018) found that the progressive tightening of environmental standards could limit the future exploitation of coal and steel reserves in Chinese "resource-based cities", thereby undermining real estate markets in these locations [62]. Moody's (2017) identified a number of factors which may pose stranding risk for European electricity and gas networks, particularly from self-supply and small-scale renewable energy generation [63]

These studies are reviewed under the analytical framework (Table 2, appendix).

3.2. Securities

3.2.1. Equities/companies

There is an extensive literature which explores how stranding risk posed to physical assets (previous section) can feed into risks for companies. In many cases, the intention is to establish if climate risks are fully reflected in company valuation, and the extent to which a "carbon bubble" could be said to exist [16].

This literature is again dominated by *ex-ante* evaluations, many of which explore the implications of a carbon constraint for coal, oil and gas companies. For example, CTI (2011) evaluated the link between reserves and share prices of listed fossil fuel, estimating that the reserves of 100 of the largest listed coal, oil and gas companies was greater than the total carbon budget for 2DS [36]. CTI (2017) ranked companies according to exposure to "carbon risk", finding that the majority of highly exposed companies were North American [64]. Moody's (2017) found that implementation of Paris Agreement pledges could bring price volatility and rising pressure on margins and cash flows, potentially leading to stranded assets, especially for companies with high-cost projects with long lead times [63]. In the case of oil companies, CTI (2014) (previous section) found that oil majors such as Petrobras, Exxon Mobil, Rosneft, Shell, Total, Chevron and BP had high capital expenditure on projects with breakeven of $80 [45]; HSBC (2008) found that ENI and Statoil faced the lowest carbon risk, whereas Repsol, OMV and Royal Dutch Shell and faced the highest potential carbon costs [65]; and Bloomberg New Energy Finance (2013) found considerable share price change for oil majors such as Exxon, Total, Chevron and Royal Dutch Shell, but results were dependent on the scenarios considered and assumptions applied [66]. In the case of gas, CTI (2015) found that Chevron, Shell, BG, Cheniere and Exxon have the highest total capital expenditure exposed and identified considerable stranding risk for capital expenditure on costly projects in the LNG sector [47].

However, not all studies find that a carbon constraint would necessarily impact company valuations. For example, HSBC (2013) found that "unburnable" carbon would have a limited impact on most company's value at risk. However, when possible lower oil process were also considered, the impact was found to be equivalent to 40-60% of the market capitalization of affected companies, including Shell, BP, Total, Eni, BG [28]. Heede and Oreskes (2016) found that stranding associated with existing reserves was minimal for private entitles (of which 70), but for 8 state-owned companies, stranding risk associated with existing reserves was apparent, especially those in high-cost environments and for carbon-intensive resources. They also concluded that new reserves would face stranding risk for both private and state-owned companies [67]. The finding of minimal stranding risk for oil and gas companies is supported by Griffin et al (2015), which used an *ex post* event study to evaluate the impact on stock prices of 72 oil and gas firms from media coverage of a possible carbon bubble during 2012-2013. They concluded that there was little evidence of a "carbon pricing bubble" for these stocks [17]. Suggestions of stranding risk have also been contested by industry studies like Exxon (2018), which estimated that there was little risk to its current reserves from a 2DS target [68].

In the case of coal mining companies, results of *ex ante* studies indicate exposure of some assets, but that these risks can be minimized through diversification strategies. Caldecott (2013), in an assessment of stranding risk posed to Australian coalmines, concluded that the coal price required for many of these projects to be economic was unlikely to be sustained given China's changing demand for coal, posing stranding risk for investors [69]. Cheuvreaux (2012) found that mining companies in Australia and South Africa (Xstrata, Anglo-American and BHP Billiton) were exposed to the implementation of a carbon price [70]. However, HSBC (2012), which explored the risk to four major UK-listed coal companies (Rio Tinto, BHP Billiton, Anglo American, and Xstrata), found that impacts would be relatively minimal for these companies because they were highly diversified [71] and BHP Billiton (2015) concluded that the low carbon transition posed minimal stranding risk to the company's diversified portfolio of assets [72]. A weakness in this literature is that there is little *ex post* evidence to draw upon. For example, there has been little analytical attention paid to examining the role of low-carbon transition in unanticipated write down of coal mining company valuations in North America. One exception is Byrd and Cooperman (2018), which concluded from an event study of CCS news events that coal investors had priced carbon risk into share prices [24].

In the case of power generation utilities, Credit Suisse (2007) estimated the impact of possible carbon prices for the largest 72 American utility companies [73]. Caldecott et al (2016) (previous section) found that all Japanese utilities considered faced stranding risk, Tokyo Electric Power Co had the highest exposure to asset in absolute value, whereas J-Power has the most exposure to asset stranding relative to total assets [53]. Coldecott et al (2017) (previous section), found that the five largest coal-fired utilities in China (Huaneng, Datang, Guodian, Huadian and State Power Investment Corp) all faced stranding risk in all scenarios explored [57]. The stranding risk for these utilities is supported by ex post evidence from Europe, which has moved further along the pathway of low-carbon transitioning comparison to China. Caldecott et al. (2014) found that between 2012-13 ten major EU utilities (E.ON, RWE, Statkraft, Vattenfall, EnBW, GDF Suez, Centrica, SSE, Verbund and CEZ) implemented and announced planned mothballing and closure actions of over 20GW of combined cycle gas turbine capacity, concluding that asset stranding had significant and rapid consequences for company value, utility strategy and policy [60].

When it comes to company valuations, therefore, many *ex ante* studies, in particular those employing a carbon constraint, find stranding risk for companies that rely on costly and carbon intensive resources, and for utilities dependent on these resources. This finding, however, is heavily caveated in other studies; for example, companies that are highly diversified appear less exposed to carbon risks. Several *ex post* studies find that carbon risk may already have been integrated into share prices in the case of some exploration companies, but *ex post* studies support findings of stranding risk for energy utilities.

3.2.2. Debt/Countries & Companies

The quality of the debt issued by companies and countries is also exposed to stranding risk, giving rise to greater risk of defaults and ratings downgrades [74]. Nevertheless, there are fewer studies focusing on the implications of carbon risk for sovereign debt, even though bonds make up a significant percentage of diversified investment portfolios, especially among institutional investors. The Global Footprint Network (2016) assessed the risk to sovereign debt to to a low carbon transition, using the carbon intensity per unit of GDP for countries as a starting point. They concluded that China could face higher risk given its high carbon intensity, but that findings were sensitive to choice of metric (e.g. production or consumption-based emissions) [75]. Malova & van der Ploeg (2017) found that a carbon constraint could lead to the Russian Government’s fiscal stance tightening by 5.5% of GDP [76]. In the case of companies, S&P (2013) adapted their standard risk assessment of fossil fuel company creditworthiness to include a “stressed scenario”, finding that companies with high exposure to Canadian oil sands and other unconventional fossil-fuel activities could see ratings pressure build. This tool, however, is typically intended to have a time horizon of three to five years, limiting its effectiveness [77]. The implications of stranded assets for creditworthiness is therefore an underdeveloped theme, and the methods are insufficiently developed, and it would therefore be premature to draw conclusions from the preliminary studies that have been undertaken.

These studies are reviewed using the analytical framework (See Table 3, appendix).

3.3. Investment Portfolios and Financial Institutions

As one moves along the investment chain, understanding of climate risk from a transition to a low-carbon economy, and how it can be managed, is less developed. This is perhaps because the risk is diversified across investment portfolios and balance sheets, and may therefore appear less prominent to investors at later points in the investment chain. Following a global divestment campaign, however, institutional investors are becoming more aware of stranded asset risk, and mangers of some $6 trillion of financial assets have committed to divest from carbon intensive sectors and companies [78].

There are, first of all, a number of general studies that attest to the potential materiality of climate risks for asset portfolio managers and financial institutions. For example, Dietz et al (2016) assessed how much the global portfolio of financial assets stands to lose from climate change, estimating that value at risk (without abatement) of 1.8% of total assets [79], while Mercer (2015) found that asset class return impacts could be material, but that 2DS would not necessarily have negative return implications for long-term diversified investors at a total portfolio level [80].

The concept of portfolio diversification as a means to manage investor risk is well established [81]. However, there are relatively few studies which evaluate, quantify and seek to manage climate risk at an individual balance sheet or portfolio level. In cases where this has been attempted, the focus has generally been on analyzing the emissions intensity of portfolios and balance sheets. For example, Credit Suisse (2015), undertook an analysis of a hypothetical portfolio comprised of 30 stocks and used tier 1 and tier 2 reported emissions. They found that the 10 equity positions with the largest footprint account for 90 percent of the total carbon footprint, meaning that portfolios contained carbon "hot spots" [82]. Blackrock (2016) developed a "Climate Score" as an aide to portfolio managers, which indexed companies' based on resource efficiency, exposure to climate risks and their position to gain from climate opportunities. They found that incorporating climate factors into the investment process could present investment upsides [83]. The Global Footprinting Network (2016) proposed that the carbon intensity of bonds weighed by each bond holding's position within the investor's total portfolio, and argued that this intensity approach can be applied to other asset classes [75]. Other approaches have involved focusing on the exposure of portfolios and balance sheets to fossil fuel exploration companies. For example, The Green European Foundation (2014) estimated the exposures of 23 large EU pension funds and the 20 largest EU banks to oil, gas and coal mining firms. The exposures were estimated at approximately 5% of total assets for pension funds, 4% for insurance companies and 1.4% for banks [84]. CTI (2014) (previous section) suggested that investors should understand their exposure to companies with the highest level of cap ex devoted to high risk (costly and carbon intensive) projects, and set thresholds for holding these assets [45]. These approaches are in their infancy, however, and are limited by a number of factors, not least by the absence of reliable reported information on climate risks.

Stress tests have also been adapted in some studies to evaluate climate risk under a low carbon transition. Industrial and Commercial Bank of China (ICBC) (2016) recommended that environmental stress testing should be used to assess the possible impact of environmental risk factors, and argued that this would promote the rational arrangement of bank loans and investment portfolio [85]. The Cambridge Institute for Sustainability Leadership (2016) stress-tested representative investment portfolios, concluding that climate risks could lead to financial tipping points that investors are not prepared for. They found that diversification strategies could offset approximately half of the negative impacts, but that climate risk is to a certain extent “unhedgeable” against [86]. Other studies that identify challenges associated with hedging against climate risk. 2DII (2014) warned that strategies that seek to diversify only at industrial sector level may be sub optimal [87], while Haslam et al (2018) warned that focusing only on carbon emissions embedded in investment portfolios is insufficient for managing climate risks [88].

There has, finally, been some analytical focus on exploring the extent to which climate risk is considered by financial institutions and asset managers. For example, in a survey of the European banking sector Weber et al (2006) found significant differences in integrating environmental risks between banks [89]. The Asset Owners Disclosure Project (2015) indexed the world’s 500 biggest pension funds, insurers, sovereign wealth funds, foundations and endowments on their success at managing climate risk within their portfolios. Oceania and Europe were found to be the most progressive regions, whereas US and China, were among the worst performers. Considerable diversity within regions, however, was also noted [90].

These studies are reviewed using the analytical framework (See Table 4, appendix).

3.4. Systemic risk

Some central banks and financial regulators have raised concerns that climate change may pose “systemic risk” to the financial system. In September 2015, Mark Carney, Governor of the Bank of England, declared that climate change—in particular “transition risk”—could threaten financial stability via a sudden and significant collapse in asset values. There are, however, few studies seeking to quantify the systemic financial risk posed by climate change. One exception is The European Systemic Risk Board (2016), which found that an abrupt and late switch away from fossil fuels towards sustainable and renewable energy investments could adversely affect systemic risk [91]. Several CTI studies considered the systemic implications of highly fossil fuel reserve dependent companies listed on global stock exchanges. CTI (2013), for example, found that the MICEX Index (Moscow) and Athens Stock Exchange General Index was the most intense and that some of the smaller exchanges (Brazil, Hong Kong, Johannesburg, India, Greece, Italy, Vienna and Budapest) were also found to have high fossil fuel dependency [37]. However, others have disputed the thesis of systemic risk. Yergin & Pravettoni (2016), for example, argued that an energy transition would unfold over decades and would not therefore pose a “Lehman-style” systemic risk to the global financial system, because 80% of the market capitalization for large oil companies reflected reserves reaching markets in the next 10–15 years [92].

In terms of managing systemic risk, ICBC (2016) found that environmental stress testing could reduce systemic risk [85], and the Task Force on Climate-related Financial Disclosures (2017) recommended that comprehensive climate-related financial disclosure reports should be incorporated into mainstream public annual financials [19].

These studies are reviewed using the analytical framework (See Table 5, appendix).

4. Conclusions And Future Prospects

The topic of “stranded assets” arising from the transition to a low-carbon economy with a greater dependence on sustainable and renewable energy sources, and how this might affect investor perceptions of risk and return and capital allocation decisions, has risen up the agenda of regulators, researchers and investors over the past decade. This has occurred against a backdrop of climate change and its impacts become increasingly notable [93-95], and the growing focus of policy makers and investors towards manage associated risks. In this paper, we systematically review the literature on stranded asset risk arising from the transition to a low carbon economy, focusing in particular on approaches used to value and manage these risks at different points in the investment chain. We have developed an analytical framework which has been employed to categorise studies according to the asset category they focued on, the risks they evaluated, the scenarios considered, the methods used and the results (see Appendix).

This systematic review suggests that there has been a strong focus in the literature at the earlier points in the investment chain: on fossil fuel reserves, the power generation sector, and companies that own these assets. This literature on fossil fuel reserves suggests that difficult-to-reach and carbon-intensive reserves with high capital costs face a high risk of stranding from a low-carbon transition, particularly when a robust emissions constraint is assumed. Much of this literature is, however, *ex ante* and there are few *ex post* studies to support these findings. When it comes to power generation assets, a clear finding to emerge from the literature is that stranding risk may be particularly acute for coal-powered generation compared to gas, and this is particularly the case for the older, less efficient technologies that are often deployed in emerging economies. Indeed, there is *ex post* evidence form markets where investment in sustainable and renewable energy sources has been advanced most rapidly (most notably the EU) that coal generation assets are highly exposed to stranding risk under low-carbon transition. However, there is an opportunity for further *ex post* research exploring write-downs to coal generation assets in markets outside of the EU. Furthermore, there has been little analytical attention paid to exploring stranding risk for real estate and transport assets reliant on fossil fuels, and this in another area perhaps meriting greater analytical attention.

The final area where there is substantial depth to the literature is exploring if stranding risks are fully reflected in company valuations, and the extent to which a "carbon bubble" in securities could be said to exist. Much of the ex-ante literature suggests that in a carbon constrained world, valuations of coal, oil and gas companies could be overstated, especially those with significant capital exposure to costly projects or carbon-intensive resources. However, this finding is contested by industry analysis and some independent studies, and companies that are highly diversified are generally found to be less exposed to carbon risks. Furthermore, the *ex post* literature suggests that, at least in some cases, investors may have factored stranding risk into company valuations.

The further along the investment chain one moves towards increasingly liquid assets, the increasingly sparse the literature becomes. This perhaps reflects a greater diffusion of risk for financial institutions and portfolio managers, which has been noted in previous studies [96]. There are fewer studies, for example, addressing the implications of stranding risk for creditworthiness of counterparties, asset portfolio managers, financial institutions and the stability of the financial system, and the methods used to quantify risk in these areas are considerably less developed. Stress tests under carbon risk and aids to efficient resource allocation under climate change (for example, quantifying the carbon intensity of an investment portfolio or a bank's balance sheet) have been proposed to manage stranding risk. While carbon intensity is used in many risk assessments to measure the exposure of securities, portfolios, or balance sheets to low carbon transition, this approach is made challenging and is limited by a number of factors. While there is some provisional evidence that stranding risk may affect financial institutions and portfolios, there is also some evidence that these risks can be managed by investors through diversification strategies. This highlights the potential importance for fossil fuel companies of investing in sustainable and renewable energy sectors. However, there are few studies exploring optimal diversification strategies under climate risk, and some studies point to the limitations of diversification strategies. The understanding and quantification of stranding risk for actors at later points in the investment is therefore an area that requires greater analytical consideration before definitive conclusion can be drawn.

The stranding assets literature is faced with a number of limitations and difficulties which are challenging to overcome. A lack of reliable reported data and accepted methodologies for measuring exposure to low-carbon transition makes managing these risks more challenging. Indeed inconsistent climate risk reporting is a major problem for global investors, and calls for harmonised reporting rules are therefore growing. Furthermore, the results of studies tend to be largely determined by which risks and scenarios are considered, and by the choice of method. Risks that are typically considered by financial market actors (such as market, inflation, or interest rate) are measured on a short time horizon (1-3 years) using familiar metrics such as volatility or value at risk. Climate risks generally demand longer-term (>3 years) measurement, and the integration of risks that come from outside the market (regulation, carbon-price developments, physical impacts etc.), factors that are generally outside of the average investor's experience. Even for *ex post* evaluations, the magnitude of stranding risk attributable to low-carbon transition can be difficult to differentiate from other factors, such as the macroeconomic backdrop or new electricity market rules, for example. These uncertainties add to the impression that the financial sector has yet to comprehensively grapple with the multiple dimensions of climate risk.

4.1. Practical implications

The practical implications that emerged from this review for policy makers, regulators and market participants are summarized in Table 5 below.

Table 5. Practical Implications of this Study

Asset Type	Physical Assets	Financial Assets	Investors and Institutions	Regulators and policy makers
	Fossil fuel reserves Fossil fuel-dependent infrastructure	Equities Debt	Balance sheets Portfolios	Systemic stability

Actions taken to date to quantify and manage stranding risk	Assets classes most at risk of stranding from low carbon transition have been identified Projects most at risk of stranding have been identified Some bankruptcies in exploration and mining companies have occurred in advanced economies Some financial institutions have stopped lending to the riskiest projects Some insurers have stopped underwriting sectors that face high stranding risk Some oil and gas majors have introduced shadow carbon prices when assessing project viability	Companies exposed to stranding risk have been identified Some evidence of a "carbon bubble" in securities, although this is contested Carbon-intensive companies have experienced considerable write-downs The implications of stranding risk for the quality of the debt issued is unclear, and a green bond market has emerged Rating agencies have begun to recognize the short-term threat of asset stranding, though medium-term concerns are more challenging to capture Accountants have developed and conducted asset impairment tests for fossil intense companies	Awareness of stranding risk among institutional investors is high in some markets Activist investors pushing divestment from fossil and investment in renewables Investment "hot spots" have been identified, which could affect portfolios Blackrock has developed a 'Climate Score' to aide portfolio managers Carbon intensity has emerged as an important metric, although quantification challenges remain	Systemic instability identified as an issue but challenging to quantify Indexes and exchanges with the greatest exposure to risks from fossil fuel reserves identified TCFD recommended comprehensive climate-related financial disclosures from financial market actors Some central banks have begun to consider stranding risk and how to manage
Further actions that could manage stranded asset risk	More *ex post* research required to assess materialization of stranding risk in advanced economies Knowledge and information dissemination to banks and insurers underwriting carbon-intensive investments in emerging markets required Risk to both property and	Event studies assessing the impact of climate policy in various jurisdictions could shed greater light on extent of a "carbon bubble" The role of energy transition in unanticipated write down of company valuations requires further *ex post* evaluation More effective carbon exposure metrics required	Dissemination of knowledge and best practice about stranding risk to markets all markets is required Onus on accounting profession to develop and agree standardized indicators and metrics Onus on regulators to require reporting on stranding risk from institutional investors and	Greater coordination and information sharing between financial regulators and central banks across jurisdictions is required TCFD recommendations on reporting to become mandatory in key markets National stock exchanges need to examine exposure to coal, oil and gas sectors in terms of

	transport assets requires greater analytical focus Implications of stranding assets for energy and electricity market design requires greater consideration	from rating agencies to assess creditworthiness of counterparties in light of stranding risk	financial institutions All banks should include climate related stress tests in capital adequacy provisions	total stock exchange valuation

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Appendix

Table 6. Studies evaluating stranding risk for physical assets

Study	Asset	Risk	Scenario	Method	Result
CTI (2011)	Fossil fuel reserves	Top-down target	2DS	Carbon budget compared to reserves	Stranding risk for up to 80% of declared reserves
CTI (2013)	Fossil fuel reserves	Top-down target	2DS considering prospects for CCS and non-CO_2 emissions abatement	Carbon budgets compared to reserves	Stranding risk for 60-80% of known fossil fuel reserves
Linquiti and Cogswell (2016)	Fossil fuel reserves	Top-down target	2DS	Carbon budgets compared to reserves	Stranding risk for 63% of known fossil fuel reserves
McGlade & Ekins (2015)	Fossil fuel reserves	Top-down target	2DS	Carbon budget compared to reserves	Stranding risk for one third of oil, half of gas 80% of coal reserves
Kepler Cheuvreux (2014)	Fossil fuel reserves	Top-down target	2DS	Carbon budget compared to reserves	Stranding risk for oil, coal and gas assets totaling $28 trillion by 2035
CTI (2015)	Fossil fuel reserves	Top-down target	2DS	Carbon budget compared to reserves (with supply curve)	New coal and LNG projects face stranding risk, as do investments in non-conventional North American oil, and Russian Artic oil.
Caldecott (2016)	Fossil fuel reserves	Top-down target	2DS with negative emissions technologies	Carbon budget compared to reserves	Negative emission technologies could extend the 2050 carbon budget by 11-13%
Newell et al (2015)	Fossil fuel reserves	No risks considered	Baseline energy demand forecasts	Harmonization of energy forecasts	Minimal stranding risk
McGlade & Eakins (2014)	Oil reserves	Top-down target	2DS considering prospects for CCS	Carbon budget compared to reserves	45% of oil reserves cannot be produced before 2035 without CCS, rising only moderately with CCS. Arctic, unconventional and "tight" oil largely "unburnable".
CTI (2014)	Oil reserves	Top-down targets (low oil price)	2DS	Carbon budget compared to oil reserves (using supply curve)	Projects with capital investment costs of above USD75+ at risk of stranding
HSBC (2015)	Oil reserves	Oil price in response to climate policy, renewables and gas sector innovation	N/A	Oil supply curve	Stranding risk for Russian Arctic, Canadian oil sands, US shale oil, the North Sea oil at low oil prices
CTI (2015)	Gas reserves	Top down target and demand/price risks	2DS combined with demand scenarios	Fossil fuel reserves with carbon supply curve	$283bn of high cost, energy intensive LNG projects in the US, Canada and Australia could be stranded in low demand/price scenarios.
Downstream Physical Assets					

Lloyds (2017)	Fossil fuel reserves, power generation and transport infrastructure	Top-down targets, policy, disruptive technology breakthrough and price changes	Eight sector-specific scenarios exploring different risk factors	Qualitative risk assessment	Risk of stranding to all assets under different scenarios
Green & Newman (2017)	Power generation assets	Risk of disruptive change from solar PV & battery technologies	Scenarios combining different rates of decoupling for GDP/fossil fuel demand, and growth rates of renewable power	Energy/Economic Systems Modelling	Rapid renewables deployment could stranding power generation assets
Farfan and Bayer (2017)	Power generations assets	Rapid decarbonisation of power sector	2DS	Energy/Economic Systems Modelling	300 GW of the installed coal power plants may end up stranded, most of it in China and India. Future coal investment likely to be stranded.
Farfan and Bayer (2017)	EU Power generation assets	Continued decarbonisation of power sector in EU towards zero emissions	Zero emissions power generation in Europe by 2050	Energy/Economic Systems Modelling	17 GW of coal capacities installed from 2010 faces a shorter-than-expected lifetime, and future gas and oil-fired capacities commissioned from 2016 need to shift to carbon-neutral fuels to avoid stranding.
Pfeiffer et al (2017)	Power generation assets	Top-down target	IPCC 2DS carbon budgets	Carbon budget compared to emissions from power generation fleet	Emitting electricity infrastructure built after 2017 faces stranding risk
Caldecott et al (2015)	Coal generation plant	Climate policy, local air pollution and water stress	N/A	Quantitative risk assessment	Indian, former Soviet and Chinese companies' portfolios were particularly exposed
Caldecott et al (2016)	Coal generation plant	Range of local and national environment-related risks	N/A	Quantitative risk assessment	N/A
Caldecott et al (2016)	Japanese coal generation plant	Range of local and national environment-related risks	Power stations are stranded over 5-year, 10-year, and 15- year periods	Quantitative risk assessment	Assets at risk of stranding of between \$61.6bn - \$80.2bn in value
Coldecott et al (2017)	Chinese coal generation plant	Range of local and national environment-related risks	Power stations stranded over 5-year, 10-year, 15-year, and 20-year periods	Quantitative risk assessment	Assets at risk of stranding of between US\$449-1,047bn in value
Caldecott et al (2017)	EU coal generation plant	N/A	N/A	Qualitative risk assessment (Case study)	Write downs in value of €6.9bn per annum
Johnson et al (2015)	Coal power generation assets	Top-down target	2DS and a range of GHG emission targets in 2030	Energy/Economic Systems Modelling	Stranding risk and associated cost for coal is heightened with lax climate targets for 2030. Restricting new construction of coal capacity without CCS reduces stranding risk.

McGlade et al (2018)	Gas generation assets in the UK	Climate policy	Range of emission reduction constraints by 2025 and 2050	Energy/Economic Systems Modelling	Stranding risk for gas generation dependent on availability of CCS technology
Derricks et al (2018)	Chinese real estate assets	Environmental standards and climate targets	N/A	Quantitative risk assessment	High stranding risk for real estate assets in China's resource-based cities with possible implications for global financial stability

Table 7. Studies evaluating stranding risk for securities

Study	**Asset**	**Risk**	**Scenario**	**Method**	**Result**
			Equities/Companies		
CTI (2011)[2]	Share prices for the top 100 listed coal, and top 100 listed oil and gas companies.	Top-down target	2DS	Reserves compared to budget	Reserves of listed companies greater than total carbon budget for 2DS, which could affect share prices
CTI (2017)[3]	Fossil fuel companies	Top-down target	2DS	Reserves compared to carbon budget/supply curve	Many highly exposed companies were found to be North American
Heede & Oreskes (2016)	78 fossil fuel companies	Top-down target	2DS	Reserves compared to carbon budget/supply curve	Stranding risk acute for state-owned companies, and for continued exploration by private companies.
Moody's (2017)	Oil and gas companies	Lower demand for oil and gas over time due to policy initiatives, changing consumer preferences and disruptive technological shocks	Scenario consistent with the nationally determined contributions (NDCs) maintained as part of the Paris Agreement that 197 countries had signed as 2017	Financial tests under carbon budget	Direct financial effects could be material by the 2020s. Low commodity prices, increased pricing volatility and weaker profitability and cash flow could arise. High cost projects with long lead times could become stranded.
HSBC (2013)	EU oil companies	Top-down target	2DS (IEA, 2012)	Financial tests under carbon budget	Value at risk could rise to 40-60% of market cap. Total and RD Shell had slightly lower exposure while Statoil had the highest.
CTI (2014)	Oil companies	Top-down targets resulting in low oil price	2DS	Reserves compared to carbon budget/supply curve	Petrobras, Exxon Mobil, Rosneft, Shell, Total, Chevron and BP had high capital expenditure on projects with breakeven of $80USD
BNEF (2013)	Oil majors	Price risk	5 scenarios for oil price and EBIT	Financial tests under carbon budget	Considerable risk for oil majors depending on assumptions for future oil prices and profitability

[2] http://www.carbontracker.org/wp-content/uploads/2014/09/Unburnable-Carbon-Full-rev2-1.pdf
[3] http://2degreeseparation.com/reports/2D-of-separation_PRI-CTI_Summary-report.pdf

CTI (2015)[4]	Gas companies	Top down target and demand/price risks	IEA 2DS, low demand scenario and baseline	Reserves compared to carbon budget/supply curve	Provided company and country exposure to LNG stranding. Found that Chevron, Shell, BG, Cheniere and Exxon have the highest total capital expenditure exposed.
Caldecott (2013)	Companies owning Australian coalmines	Low demand for coal	N/A	Risk assessment	12 companies that held mines faced stranding risk
Caldecott et al (2016)	Coal utilities in Japan	Wide range of environment-related risk factors	Three scenarios for speed of materialization of risk factors	Risk assessment	Largest utilities were all exposed to some stranding risk
Caldecott et al (2017)	Coal utilities in China	Wide range of environment-related risk factors	Four scenarios for speed of materialization of risk factors	Risk assessment	Largest utilities were all exposed to some stranding risk in all scenarios
Credit Swiss (2007)	US utilities exposure to carbon price	Regulatory risk	Four carbon price scenarios	Shadow price	Rating of NRG, ETR and EIX downgraded to Neutral. Most significant opportunities for FPL, CEG, and AYE
HSBC (2008)	Oil companies	Regulatory risk	N/A	Shadow price	ENI and Statoil faced the lowest carbon risk, whereas Repsol, OMV and Royal Dutch Shell face the highest
Cheuvreaux (2012)	Companies exposed to emissions trading schemes globally	Regulatory risk	Coverage by an emissions trading scheme	Shadow price	Xstrata, Anglo American and BHP Billiton potential exposure of USD180m, USD130m and USD210m p.a. respectively
HSBC (2012)	Four UK-listed coal companies	Top-down	2DS	Financial tests under carbon budget	Impacts relatively minimal because they are highly diversified
Exxon (2018)	Exxon exposure	Top-down target	2DS compared to baseline	Carbon budget compared to reserves	Little risk to Exxon from 2DS
BHP Billiton (2015)	BHP exposure	Top-down target	Four scenarios including 2DS	Carbon budget compared to portfolio	Given high portfolio diversity impacts not likely to be material
Caldecott et al. (2014)	EU gas generation assets	Market contractions, fuel prices changes and climate and energy policies	N/A	Historical case study	Asset stranding had been significant and rapid for utilities evaluated between in 2012 and 2013
Griffin et al (2015)	Oil and gas company share prices	Carbon bubble risk in share prices	N/A	Historical event study	No evidence of carbon bubble in share prices of 72 listed oil and gas companies, reducing stranding risk
Byrd and Cooperman (2018)	Coal reserves in North America	Possibility of technology breakthrough for CCS to reduce	N/A	Historical event study	Coal company shareholders have priced in stranded asset risk for coal-based

[4] https://www.carbontracker.org/wp-content/uploads/2015/07/CTI-gas-report-Final-WEB.pdf

		stranded assets risk			assets into share prices, reducing stranding risk
		Debt			
Global Footprint Network (2016)	Sovereign debt	Transition risk (carbon exposure), policy response and physical risk to climate impacts	N/A	Carbon intensity	Depends on metric chosen, but China shows high intensity by many metrics
Malova & van der Ploeg 2017)	Russian fossil fuel reserves	Top-down target	2DS	Carbon intensity of revenues	Russia is highly fiscally exposed to low gas and oil prices
S&P (2013)	North American oil and gas company	Top-down target with lower prices	Stressed scenario (IEA 2DS)	Risk assessment	Risk higher for companies exposed to oil sands and other unconventional fossil-fuel activities (Canadian Oil Sands Ltd. (COSL), Canadian Natural Resources Ltd. (CNRL), and Cenovus Energy Inc.)

Table 8. Studies evaluating stranding risk for securities

Study	Asset	Risk	Scenario	Method	Result
Weber (2008)	European Banks	Climate Risk		Risk management framework	Incomplete consideration of environmental risk factors
Asset Owners Disclosure Project (2015)	500 largest asset managers globally	Management of climate risk within portfolios	N/A	Scoring asset managers	Oceania and Europe were found to be the most progressive regions, whereas US and China were the least progressive.
Dietz et al (2016)	Global portfolio of financial assets	Growth rate, productivity growth, climate sensitivity, GDP losses and abatement costs	Multiple scenarios	Energy/Economic Modelling	Climate risk is material for many asset classes
Mercer (2015)	Equities in developing and developed markets, infrastructure, real estate, agriculture, sovereign bonds.	Disruptive technology, policy, physical impacts and resource availability	4 scenarios: transformation (2DS), Coordination (3DS), fragmentation (4 DS low); fragmentation (4DS bad).	Energy/Economic Modelling	Impacts could be material within sectors like coal or renewables. Class return impacts could also be material – varying widely by climate change scenario, diversified portfolio minimize risks.
Credit Suisse (2015)	Investor equity portfolio	Disruptive technology, policy, physical impacts and resource availability	N/A	Carbon intensity of portfolio using tier 1 and tier 2 reported emissions	Equity portfolios may contain emissions “hot spots”.
Green European	23 large EU pension funds	Exposure of portfolio to	2DS	Carbon intensity	5% of total assets for pension funds, 4% for

foundation (2014)	and the 20 largest EU	fossil fuel companies			insurance companies and 1.4% for banks in fossil fuel assets
CTI (2014)	Oil and gas equities in portfolio	Top-down target	2DS/Low prices	Carbon intensity (Exposure to high capital cost investments)	Investors should identify companies with the highest level of cap ex devoted to high cost projects, set thresholds for holding of these assets and require annual publication of stress tests
Blackrock (2016)	Investment portfolios	Physical impacts, technological, policy/ regulation and social change	N/A	Climate index based on resource efficiency, exposure to climate risks and position to gain from green economy	Incorporating climate factors into the investment process could present investment upsides.
Global Footprinting Network (2016)	Government bonds (and secondary focus on other financial assets)	N/A	N/A	Carbon intensity (country)	Carbon intensity of a portfolio can then be calculated by averaging the intensities weighed by each bond holding's position within the investor's total portfolio
CISL (2016)	Investment portfolios	Physical impacts, regulatory change and carbon pricing	Economic and market confidence shocks derived from climate change sentiment scenarios.	Stress testing	Some climate risk cannot be hedged against

Table 9. Studies evaluating systemic stability from climate risk

Study	Asset	Risk	Scenario	Method	Result
ESRB (2016)	Systemic stability	Economic and physical impacts	Soft and hard scenario	Risk assessment	Improve disclosure requirements
Dericks et al (2018)	Chinese real estate assets	Environmenta l standards and climate targets	N/A	Risk assessment	High stranding risk for real estate assets in China's resource-based cities with possible implications for global financial stability
CTI (2013)	Stock market stability	Top-down	2DS	Carbon intensity	Some indexes highly carbon intensive
Yergin & Pravettoni (2016)	Systemic stability	Risk to financial stability	N/A	Historical case study	Low risk to financial system from climate
Task Force on Climate-related Financial Disclosures (2017)	Systemic stability	Climate-related financial risk	N/A	N/A	Improve climate-related financial disclosures
ICBC (2016)	Systemic stability	Environment-related financial risk	High, medium and low stress scenarios	Case study	Improved environmental stress testing can improve system stability

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