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STRANDED ASSETS IN THE TRANSITION TO A CARBON-FREE ECONOMY

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Abstract

Assets in the fossil fuel industries are at risk of losing market value due to anticipated breakthroughs in renewable technology and governments stepping up climate policies in the light of the Paris commitments to limit global warming to 1.5 or 2 degrees Celsius. Stranded assets arise due to uncertainty about the future timing of these two types of events and substantial intertemporal and intersectoral investment adjustment costs. Stranding of assets mostly affects the 20 biggest oil, gas and coal companies who have been responsible for at least a third of global warming since 1965, but also carbon-intensive industries such as steel, aluminium, cement, plastics and greenhouse horticulture. A disorderly transition to the carbon-free economy will lead to stranded assets and legal claims. Institutional investors should be aware of these financial risks. A broader definition of stranded assets also includes countries reliant on fossil fuel exports and workers with technology-specific skills.

Keywords: de-carbonisation, policy tipping, technology, stranded assets

JEL codes: E62, F41, G11, O33, Q33, Q34, Q35, Q40, Q54

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1. Introduction

The Paris commitments to limit global warming to 2 degrees and aim for 1.5 degrees Celsius relative to pre-industrial temperatures imply a cap on cumulative emissions of only a couple of hundred Giga tonnes of carbon and that substantial amount of fossil fuel reserves must be locked in the crust of the earth forever. This cap is called the global carbon budget. Total proven fossil reserves amount to over 600 Giga tonnes of carbon at current economic conditions (BP, 2017). If all the proven or probable reserves reported in the annual accounts of the big fossil fuel companies are added up, McGlade and Ekins (2015) suggest that the carbon that were to come free if global fossil fuel reserves were burnt is a factor 3 to 10-11 times bigger than the global carbon budget. They suggest that one third of all oil reserves, half of global gas reserves and 80% of global coal reserves must be left unburnt if the safe threshold of 2 degrees Celsius for the global mean temperature is not to be exceeded. Such calculations suggest that the future of the big fossil fuel companies and of the industries that substantially rely on fossil fuel may be under threat and the end of fossil fuel is nigh (e.g. Helm, 2017; van der Ploeg, 2016a). This has led to heated discussion among activists, central bankers and the industry itself on the possibility of stranded financial assets in industries that depend heavily on fossil fuel and the repercussion of such stranding for the wider economy.

Stranding of assets and sudden changes in market valuation are likely to occur during a disorderly transition from a fossil-fuel to a carbon-free economy if two conditions are met. First, there must be an *unanticipated* future change in conditions affecting the profitability of fossil-fuel assets. Second, it must be costly or impossible to shift around the underlying capital stocks in the carbon-intensive industries to productive use elsewhere after the energy transition. One cause of stranding of carbon-intensive assets is when the government suddenly wakes up and steps up climate action to limit the total amount of cumulative carbon emissions and the private sector was previously unaware of that change in policy. Similarly, expectations about climate policy can shift (e.g. carbon pricing is moved forward by 10 years but has not yet been implemented). Another possible reason is the sudden occurrence of a breakthrough technology in renewable energy (e.g. a significant and sudden drop in the cost of batteries or perhaps in fusion energy). Such technological breakthroughs also directly threaten the sustainability of the fossil-fuel business model and can lead to stranding of coal-, oil- and gas-based financial assets if they cannot easily be shifted and used productively in the low-carbon or carbon-free economy.[3]

In the course of this review we will, therefore, introduce four types of asset stranding: first, a substantial part of fossil fuel reserves is simple never to be touched if temperature is to stay below 1.5 or 2 degrees Celsius. We call this stranded carbon. Second, some of the infrastructure and capital invested in the fossil fuel industry (up- and downstream) will become useless once the economy switches to renewable energy sources. This is stranded physical capital and speaks to the end of the carbon era just like stranded carbon. However, prices of fossil fuel assets (both carbon and infrastructure) respond long before their industry closes shop or climate policy is enacted. Hence and third, the valuation of these assets changes once the unanticipated future changes become known. However, not all policy changes are known with certainty and announcements today could be subject to doubt about their actual implementation. If this is so, the initial revaluation blow at the time of announcement will soften and a fourth point of stranding can occur, once this doubt is removed. All these types of asset stranding have further repercussions in financial markets.

The outline of this review is as follows. Section 2 discusses climate justice, presents moral arguments for climate policy, points the finger at the key emitters in the global economy, and shows what a fair global policy to keep within the safe global threshold might look like. Depending on the moral argument, owners of carbon-intensive assets can expect either compensation or litigation. Section 3 reviews how climate scientists translate Paris-style temperature caps into cumulative carbon budgets and how this

[3] Caldecott et al. (2016) argue that the stranding of assets might occur for a much wider set of reasons and can be related to much broader environmental challenges than global warming. Apart from the aforementioned unanticipated new government regulations (e.g. carbon pricing or air pollution regulation) and falling clean technology costs (e.g. solar photovoltaic, onshore wind or electric vehicles), sudden and unanticipated changes in the perception of environmental challenges (e.g. realisation of positive feedback loops in the climate system that accelerate global warming or degradation of natural capital such as the soil or water quality), in the natural resource landscape (e.g. scarcity of phosphate or shale gas abundance), in evolving social norms or social tipping and consumer behaviour (e.g. Greta Thunberg) and in litigation (e.g. carbon liability) and changing statutory interpretations (e.g. fiduciary duty or disclosure requirements) can lead to stranded assets too.

translates into the notion of unburnable fossil fuel deposits. This is relevant, since most economic models for the integrated assessment of climate and the economy do not take account of the most recent insights of climate scientists and have a much too sluggish response of temperature to changes in the stock of atmospheric carbon, thereby artificially inflating the viability of the fossil fuel industry. Section 4 emphasises that oil, gas and coal have become abundant resources and that reserves have relentlessly increased over the past fifty years in sharp contrast to the scarcity of carbon that the world can still afford to emit without violating the Paris commitments. Section 5 outlines the drivers of the transition to a carbon-low economy. Section 6 discusses the types of assets that are at risk of being stranded, what they are and where they come from. Section 7 discusses how fickle government climate policies can lead to stranded carbon assets. Section 8 discusses how technological breakthroughs might lead to stranded carbon assets. Section 9 discusses systemic risk, contagious and financial supervision. Section 10 concludes.

2. Climate justice and nationally determined carbon budgets

Climate change is a global problem and impacts everyone and everything across generations and across the globe. The first problem is that future generations are not sitting on the table where the negotiations are taken place, but more importantly current young generations are asked to make sacrifices by paying higher energy prices and may not be alive to enjoy the benefit of curbing global warming in the distant future. The questions is how a win-win situation can be created where early generations are compensated for the introduction of climate policies and future generations have to foot the bill for this (e.g. Rezai et al., 2012; Kotlikoff et al., 2019). The second problem is how to overcome the international free-rider problems that are associated with global warming as this is a truly global externality. This requires rich countries to compensate poor countries to implement a tough climate policy with uniform carbon prices throughout the global economy (Chichilniski and Heal, 1994) and negotiations where everyone is willing to sign the climate deal (e.g. Barrett, 2006). In addition, one might have a Coasian supply-side policy where poor countries are "bribed" not to cut down forests in order to preserve carbon sinks (e.g. Harstad, 2012; Asheim et al., 2019), despite such policies coming with the legacy cost of the bribe, reneging on previous commitments, and cutting down forests nonetheless (Belfiori and Iverson, 2019). For both problems the question is how those who gain from climate policy can compensate those who lose from it. Practice shows that it is frustratingly difficult to achieve a welfare-improving deal that is attractive for all generations and for all countries. From a climate justice perspective, it is important that the rich countries have been mostly responsible for carbon emissions, whilst developing countries suffer the main costs of global warming.

Let us consider in some more detail the intergenerational issues associated with the first problem. Why should we today invest into divestment and make an intangible future better off? The answer is for the same reason that we invest and bequeath to the future already. Due to missing price signals, we leave behind the wrong composition of capital and climate. The standard economic approach to the question of climate change identifies it as the result of an externality (Chichilnisky and Heal, 1994; Stern, 2007; Nordhaus, 2008; according to Stern (2007) the largest externality we ever faced). Microeconomic textbooks suggest that climate policy should limit climate change by forcing emitters to face the true (social) costs of their actions, correcting and internalising the externality. Given that in the absence of climate policy, there is excess pollution and the excess damage that comes with it, the correction of the externality leads to an increase in overall welfare large enough to make everybody better off. Pricing carbon gets prices right and incentivises the investments in low-carbon and low-energy technologies. It also discourages the holding of dirty assets, which are those who are prone to become stranded in the transition and which we will discuss in detail in section 6. This redirection of investment from carbon-intensive to carbon free industries under socially optimal policy, which leads to the correct composition of capital and the optimal level of global warming, has led some to proclaim an ongoing bubble in carbon-intensive sectors which bursts once climate policy hits: the so-called carbon bubble.

Returning to climate ethics, climate policy can grow the welfare pie by removing the inefficiency of free carbon emissions, thereby creating the possibility of a Pareto improvement (Rezai et al., 2012; Kotlikoff et al., 2019). The cost-benefit analysis underlying first-best climate policy trades off the benefits of the future versus the costs of today, giving importance to the discount factor applied. However, a more challenging question to the idea of Pareto improvements arises if one moves beyond the assumption of a representative infinitely lived household or of dynasties with perfect altruistic bequest motives. If agents do not strive for the "warm glow" arising from intergenerational altruism, real bargains must be struck and the Pareto possibility becomes elusive (Karp, 2017). Bovenberg and Heijdra (1998) propose government debt as a way of spreading out the climate rent smoothly across generations. Taxes and transfers have also been proposed as more targeted policy instruments (Kotlikoff et al., 2019; Dennig et al., 2019).

Regional disparities are at the core of the second problem of getting at a successful climate policy. Who should abate how much? From a climate justice perspective, one could argue that rich countries should shoulder more of the burden of a climate policy, but with a uniform carbon price, poor countries will be hit harder. Chichilnisky and Heal (1994) argue that getting poor countries to sign up to climate policy requires substantial cash transfers. Without these carbon prices will differ, which is inefficient. An additional argument put forward is that climate change hits the poorest countries hardest who are usually the ones who are least capable to protect themselves against climate change. Dennig et al. (2015) show that climate policy needs to be much more ambitious if within-country variations in income and vulnerability are taken account of. Nearly 50% of carbon emissions are caused by consumption decisions of the richest 10% households, but the poorest 50% are responsible for only about 10% of emissions (Oxfam, 2015). Considering that the richest 10% live in those countries which historically have contributed the most to climate change (especially when based on per capita emissions), the moral case for more ambitious climate policies in rich countries is further strengthened.

The implications of these arguments for the debate on stranded assets is not clear and depends on whether one looks forward or backward. One could argue that "bygones are bygones" and, looking forward, that owners of assets whose value will decrease due to a shift in (climate) policies need to be compensated by those who gain from the new policies. The recently proposed transfers to owners of German coal plants, due to a moratorium on coal-based power plants by 2038, are based on this line of reasoning, although critics view the payments as ransom and the outcome of successful albeit unproductive rent seeking. Looking backward and taking a historical perspective, the owners of carbon-emitting assets are responsible for significant amounts of damage. Legal action could focus on this aspect and hold owners liable for this damage, a liability that continues to grow. One could argue on basis of their own internal reports that the big oil and gas majors were fully aware of the dangers and risks of global warming from early 1960s onwards and yet continue to invest in large-scale fossil fuel exploitation. The legal case here is akin to the one against tobacco producers who knew for many decades about the dangers smoking posed to health, but nevertheless continued their business model. Legal philosophers have argued that "might makes right" and that the economic power of fossil fuel producers is such that this overwhelmed the moral case against extraction of so-called "blood oil" (Wenar, 2015). A similar case might be made against fossil fuel producers for their contribution to global warming.

The discussion so far was based on normative considerations of why climate policy should be imposed. Given the world political system's slow response to tackling the problem, investors in fossil fuel industries might expect no climate policy to occur for an extended period, despite the moral imperative. However, there are further reasons to expect that climate policies will be introduced: air pollution and its harm to local health. These are called the "collateral benefits" of global warming (Parry, 2015). While scrubbers and filters are solutions to the latter, many governments (especially in developing nations) are abandoning fossil fuels altogether and aiming for renewable energy sources instead. Together with (and reinforcing) the learning-by-doing driven reductions in the cost of carbon-free energy alternatives, these are further threats to economic sectors that depend for their livelihood on fossil fuel.

3. From temperature caps to unburnable fossil fuel deposits

With the Paris agreement politicians finally committed to 2 degrees Celsius global warming with the aim to limit it to 1.5 degrees Celsius. The new climate science suggests that global warming over this range temperature is remarkably well described by a linear function of cumulative emissions (Allen, 2016; van der Ploeg, 2018; Dietz and Venmans, 2019). Temperature caps therefore directly map into the amount of carbon we are still allowed to burn (i.e. the carbon budget). Most integrated models of economy and the climate have detailed models of the carbon cycle and a sluggish response of temperature to the stock of atmospheric carbon (Dietz et al., 2019), artificially inflating the carbon budget. In contrast, the new climate science suggests that temperature responds quickly to cumulative emissions.

A risk tolerance of 1/3 gives a safe carbon budget for 2°C from 2015 onwards of 335 GtC. Tightening risk tolerance to 10% or 1% curbs the safe carbon budget to 271 GtC and 209 GtC, respectively. Less risk tolerance increases the odds of achieving the temperature target and, thus, implies that less carbon can be burnt in total (van der Ploeg, 2018; Aengenheyster et al., 2018). If peak global warming is kept below 1.5°C, the safe carbon budget drops dramatically from 209 GtCO2 to a mere 65 GtC if the risk tolerance is 1% (van der Ploeg, 2018). In that case, if current emissions stay unchanged, there are only 20 or 6.5 years left (or 16 and 2.5 years from 2019 onward) before temperature exceeds the cap.

Similarly, climate scientists and the IPCC have argued that to limit anthropogenic global warming to at most 2 degrees Celsius relative to pre-industrial temperatures with a probability of 66% requires that cumulative emissions from 2011 onwards have to stay below 1 trillion tonne of carbon dioxide or 270 GtC to keep global warming below 2 degrees Celsius (e.g., Meinshausen et al., 2009; Allen et al., 2009; Millar et al., 2017). This amounts to only about 19 years of current fossil fuel use from 2019 onwards, less if fossil fuel use continues to rise but longer if annual fossil fuel use can be curbed. This can be achieved by a ramping up of renewable energy over the next two decades, although switching from oil to less carbon-intensive gas might increase the window of opportunity. To cap temperature in time the world must thus quickly lock up large deposits of global fossil fuel reserves by keeping them in the ground.

Rogelj et al. (2018) consider institutional speed limits on the road to the carbon-free era (e.g. due to slow displacement of fossil fuel or slow uptake of new technologies) and show that these imply that we cannot decarbonise before the mid-century, which increases the carbon budget. To hit the 1.5°C target by the end of century nonetheless, we need to rely on unprecedented energy savings in all regions of the world in the short term and massive deployment negative emissions technology deployment in the long run in the second half of the century to make up the previous over-shoot. This faith in negative emissions increases the carbon budget. Still, the fact that the world must lock up large deposits of global fossil fuel reserves by keeping them in the ground remains inevitable.

Using differences in the costs of extraction and production and in carbon intensities of the various types of oil, gas and coal across the globe, McGlade and Ekins (2015) break these carbon budgets down by region and fuel type by computing the socially optimal distribution of stranded carbon assets across regions and carbon assets. They find that a third of global oil reserves, half of global gas reserves and over four fifths of global coal reserves should be left unburnt to keep global warming below 2 degrees Celsius. Table 1 splits these figures up for the various regions of the world. Carbon Tracker Initiative (2011) and Millar et al. (2017) give similar numbers for the proportion of fossil fuel reserves carbon that must be less in the crust of the earth to cap global warming in line with the Paris commitments. These are stranded assets to be left untouched at the end of the fossil fuel era.

Fossil fuel reserves of international companies (excluding state-owned reserves) are 3 times and resources are 10-11 times the carbon budget compatible with maximum 2 degrees Celsius global warming.[4] Hence, fossil fuel companies risk undertaking exploration and exploitation projects that would be uneconomic when governments around the globe finally manage to put policies in place that limit global warming to 2 or even 1.5 degrees Celsius.

While the analysis of McGlade and Ekins (2015) makes several restricting assumptions (e.g. regarding supply and transportation constraints, limiting the period under consideration to the year 2050, the development of demand, the possibility of technological breakthroughs), it nevertheless highlights the insights that a substantial

[4] According to BP (2017) total proven readily accessible oil and gas reserves report a much smaller number than McGlade and Ekins (2015), 300 GtC in 2017; including coal, this figure doubles.

amount of oil, gas and coal reserves should be left unburnt and that the burden of abandoning existing natural wealth will be felt differently by different regions.

Turning to fuel types, we note that not all carbon is created equally. Coal has a higher carbon content and large health costs than gas. When considering multiple carbon sources, the Herfindahl rule states that the cheapest deposits get depleted first. This rule does not carry over to environments where deposits need to be priced according to their carbon content (e.g. Chakravorty, et al., 2008). Ordering of extraction need not be determined by whether a resource is clean or dirty if costs are uniform across the non-renewable resources. Coal may be used first, followed by natural gas, and again by coal. However, along an optimal transition to renewable energy, the dirtiest carbon source, i.e. coal, is typically displaced first, followed by oil and gas.

These limits on the amount of oil, coal and gas use have consequences for the private sector and investors. E.g. while in the end, all carbon has to be phased out, relative carbon intensities create a window of opportunity for some of the less carbon-intensive energy carriers to step up production in tandem with intermittent renewable energy, softening the blow of carbon pricing and possibly even creating a brief hiatus (Coulomb and Henriet, 2018; Coulomb et al, 2019). Similar considerations apply for the regional distribution of carbon sources and the costs of their extraction and production. Carbon pricing will force out the least efficient producers first, giving infra-marginal firms the opportunity to expand market share. In the case of OPEC, this would imply an increase in market power relative to its fossil competitors, while overall facing the threat of rising renewable energy giants. Millar et al. (2018) shows that physically based engagement principles can be used to assess whether an investment is consistent with long-term climate goals. We return to these questions in section 6.

4. Relentless increase in fossil fuel reserves must stop

Hubbert's "peak oil" hypothesis states that at some point the world will run out of oil and gas, which would imply that fossil fuel is scarce and that the climate eventually benefits (e.g. Priest, 2014). However, this hypothesis has become wholly irrelevant.

Discovery of natural resources has increased relentlessly over the last four decades and, despite steady growth in demand for fossil fuel, fossil fuel reserves have been growing at roughly 2% per year. The reasons for this are manifold. Firstly, many developing countries have been catching up due to the improvement in the quality of their institutions and rule of law and due to learning from liberalisation experiences of neighbouring oil- and gas-rich countries, not by higher demand from South-East Asia or rising extraction costs as less easily accessible reserves have to be depleted (Arezki, et al., 2019). Better institutions have also lowered the risk of expropriation of oil and gas revenues once investments have been made. This has reduced hold-up problems in exploration and exploitation investment by the big fossil fuel companies and led to the discovery and opening of new oil wells and gas fields. Second, there have been spectacular improvements in exploration technology. Countries like Norway have led the way in offshore exploitation. Even more important are inventions like horizontal drilling which has led to an enormous take-off of shale gas exploration. This has made the U.S. an exporter rather than an importer of fossil fuel, and thus has contributed to making the U.S. withdraw from the Paris commitments on limiting global warming. Countries such as Poland and the U.K. have become potential producers of shale gas.

Hubbert's "peak oil" hypothesis has, therefore, been displaced by the "peak demand" hypothesis: reserves are too high for global warming already and are growing faster than ever before, yet the transition to the green economy implies that most of these reserves should never be used (cf. Helm, 2017; van der Ploeg, 2016a). What is relevant in the coming years and what the market increasingly anticipates is that the historical steady growth in the demand for oil, gas and coal will come to a halt in the next decades (some even project within the next decade) and be reversed due to cheaper renewable energy, dearer fossil fuel and increased incidence of carbon pricing.

5. Drivers of the transition to a low-carbon economy

Before we go on the types of stranded assets that arise in the transition to a low-carbon economy, we discuss the main drivers of such a transition. There are at least four.

Firstly, policy makers will step up climate action to ensure that emissions in their countries are curbed in line with the Paris agreements. Policy makers will do this by pricing carbon either by announcing a path of steadily rising carbon taxes or by organising markets for emissions permits. Pricing carbon is the royal way to cut demand for oil, gas and coal, boost demand for renewable and nuclear energy, stimulate R&D into low-carbon technologies, encourage carbon capture and sequestration, and leave fossil fuel reserves untouched. In addition, effective climate policies might include renewable energy subsidies in case renewable energy production is subject to learning by doing. Governments may also act as launching customer to get new markets for renewable energy of the ground and lower costs, as for instance China did for wind power. Furthermore, policy makers may buy up fossil fuel deposits to prevent them being exploited and burnt, thereby curbing global warming. Secondly, fossil fuel becomes more expensive to extract and less accessible oil and gas fields must be exploited. Thirdly, there has been extraordinary drop in the cost of solar energy, wind energy, batteries and hydrogen fuel. Much of this rise has been driven by learning by doing or what has become known as Wright's law (e.g. Barreto and Kypreos, 2004; Criqui, et al., 2015). For example, for every doubling of installed solar panels, the cost per unit of energy has dropped by about 20%. Finally, if there are strategic complementarities or positive feedback effects in the sense that if one agent switches to green behaviour other agents become greener too. Even if this contagion effect is only very small, there is the possibility of a punctuated equilibrium in which all of society quickly switches to becoming green (cf. Young, 2015). Such social tipping not only applies to consumer, but also to firms and even governments. For example, if Germany and the U.K. switch to a much more ambitious climate policy, it will become less costly for Austria or the Netherlands to switch to a more ambitious climate policy too.

These tendencies together ultimately undermine the business case for fossil fuel production. Once the cost of renewable energies allowing for intermittence has dropped below the cost of fossil fuel including the cost of carbon pricing, the low-carbon or carbon-free economy has become inevitable. Due to ratchet effects and social tipping this process may occur much faster than expected by society and the market. These ratchet effects can worsen the phenomenon of stranded assets.

6. Physical and financial assets that are at risk of being stranded

Here we discuss the different forms of stranded carbon assets. Before we do so, we want to remind the reader that climate policy can also create a Pareto improvement if those gaining are compensating those who lose under it (see section 2). The discussion of stranded carbon assets is sometimes dominated by one group of asset owners (one that leverages significant clout over the public debate as well as policy makers) vocally putting forward their view of climate policy as the destroyer of jobs and wealth, only to follow up with claims for compensation. But the overall positive effects of the transition to a low-carbon economy need to be kept in mind when discussing stranding of carbon-dependent assets and wealth destruction of wealth that relies on fossil fuel. Just like sectors protected from international trade, the fossil fuel industry engages in forms of direct unproductive rent seeking to protects rents, and just like in the case of opening up to trade, this sector and its employees with sector-specific skill sets will want to be compensated from the winners of climate policy. As outlined in section 2, compensation for owners of fossil fuel assets can also turn into obligations of compensation. Smart climate policy is a mix of the measures presented in section 5 and forward guidance to minimise disruption and stranding of assets.

So what exactly is a stranded asset? An intuitive example might help to explain the concept: a ship becomes stranded if it runs on a bank and cannot be used anymore unless it is towed and repaired. The ship's owner, perhaps a Dutch shipping company during its so-called Golden Age, bought the ship based on economic considerations of expected profitability, economic lifetime, and internal rate of return, and carried it as an asset in its books. The stranding event upsets these calculations and forces the company to write off some of the ship's value, since even if its original profitability can be restored, repair requires economic resources which lower the present discounted stream of (net) profits. A general definition of stranded carbon assets is not available, but most definitions centre on write-offs of the market values of carbon-intensive financial assets due to downward revisions in profitability, economic lifetime, capacity utilisation, etc. (Caldecott, 2017). Book values of assets cannot be above their market value and balance sheet adjustments eat into profits. Caldecott et al. (2013) highlight the fact that asset values can also become negative by defining stranded assets as "assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities". This is easy to see if the ship in our example above is an oil tanker which causes a major oil spill in which case stranding occurs if damages exceed the value of the tanker. The loss and damages from climate change could in the future create similar liabilities for high carbon emitters (Covington et al., 2016; Mechler and Schinko, 2016). Finally, we want to emphasise that similar considerations hold *a fortiori* for all assets due to the deleterious effects of climate change. Climate change literally turns assets under water.

What causes assets to strand? Multiple factors can lead to a souring of business plans. The definition of a stranded asset as "an asset which loses significant economic value well ahead of its anticipated useful life, as a result of changes in legislation, regulation, market forces, disruptive innovation, societal norms, or environmental shocks" (Generation Foundation, 2013, p. 1) in this context is encompassing. We add that for assets to lose economic value, they need to exhibit some degree of irreversibility, since without such irreversibility investments can be shifted effortlessly between uses: a coal power plant, that has become economically obsolete due to legislation or too high production costs, can also operate as a hydro plant or a museum. While the former is impossible, the latter has been achieved in the past, but only with large additional investment. The extent to which asset strand and stock market value is wiped out depends on how irreversible these investments are and how costly they are to adjust for other purposes (e.g. van der Ploeg and Rezai, 2019; Karp and Rezai, 2019). Without such inter-sectoral (or inter-temporal) adjustment costs or some form of irreversibility in exploration investments, assets do not strand but are simply put to different profitable use.

Section 3 highlighted the problem of unburnable carbon. Here we discuss in more detail the related concept of stranded assets. To the extent that oil and gas companies have invested heavily in exploitation capital, exploration capital and pipelines and are hit by an unanticipated drop in demand for their products, these capital stocks get stranded and this will have negative consequences for the market valuation of these companies. In addition, downstream business and producers of electricity and final goods that rely heavily on fossil fuel are also strongly exposed to forced write-offs of their carbon assets, if these investments are irreversible or costly to be used for another purpose (Guivarch and Hallegatte, 2011; Carbon Tracker Initiative, 2013; Koch and Bassen, 2013; Bertram et al., 2015; Rozenberg et al., 2019). This aspect of economic obsolescence of physical capital in the oil, gas and coal sectors, power generation, and transportation sectors follows quantitatively and qualitatively different dynamics from that of locking up fossil fuel in the ground. The industry of this type most immediately impacted by the developments in carbon pricing, technological change, and market developments is probably the coal industry.

Pfeiffer et al. (2016) define as the ‘2°C capital stock’ all global infrastructure which, if operated at historical capacity to the end of economic life, implies global mean temperature increases by 2ºC or more (with 50% probability). Using IPCC carbon budgets and the IPCC’s AR5 scenario, and attributing the emissions for coal power plants permissible under these, Pfeiffer et al. (2016) calculate that this stock has effectively already been reached on current trends (while other analyses argue that this is already the case for a 1.5°C).[5] Hence, even if other sectors curb emissions in line with the 2°C (or 1.5°C) target, no new emitting infrastructure can be built unless existing capital stock is used at lower than planned capacity, other electricity infrastructure is retired early or retrofitting with carbon capture technologies becomes economically viable. Still, global generation capacity from coal keeps rising.

Investment decisions are necessarily forward-looking and, ignoring the “dark forces of time and ignorance” (Keynes, 1936), agents investing today rationally expect future developments. In the discussion so far, we relied on climate policy which in a *deus ex machina* fashion entered the scene to upset past investment decisions and carry the day. Ad hoc policy surprises cannot be ruled out, however, as due to all kinds of political imperatives policy makers try to postpone making unpopular decisions. Even

[5] See Knoch and Bassen (2013) for a study of carbon risk exposure of European utilities.

if they do wake up, it is not clear that they will price carbon at its socially optimal level. Policy makers in the real world must allow for endogenous responses by investors to expectations about policy announcements.

The *unanticipated* credible announcement of a carbon tax in the future creates market responses today, devaluing natural and physical capital in the fossil fuel industry (cf. Mukanjari and Sterner, 2018; Bretschger and Soretz, 2019; Kalkuhl et al. 2019; Rozenberg et al., 2019; van der Ploeg and Rezai, 2019). With some of the reserves becoming unburnable, excess supply leads to a drop in the resource's scarcity rent, increasing demand, extraction, emissions, and global warming over the business-as-usual scenario. These adverse effects on short-run carbon emissions underpin the Green Paradox (Sinn, 2008). Similar effects arise, if politicians might use high renewable energy subsidies as a second-best policy to compensate for the political infeasibility of pricing carbon. In that case, fossil fuel producers also accelerate extraction of fossil fuel and thereby accelerate global warming. While owners of fossil fuel race to burn the last run and natural capital is used more quickly, investment into the industry ebbs off. Lower returns send investors pursuing higher yields elsewhere, e.g. in the renewable sector whose business prospects brightened by the same extent that those of the fossil industry darkened. Investors' concerns about stranding of physical assets in the fossil fuel industry due to anticipated climate policy cautions irreversible investments in carbon capital. This stems from irreversibility forcing them to have skin in the climate game and thus leads to a cut in short-run carbon emissions. This *reverse* Green Paradox softens the usual Green Paradox (Baldwin et al., 2019).

From a societal perspective, immediate policy implementation is always preferable, since it shifts the economy from a business as usual scenario to the welfare optimum. These policy surprises are politically often infeasible and feasible second-best policies often come with deadweight losses.[6] For example, if carbon pricing is delayed, the delayed carbon price path has to be higher than an immediately implemented carbon price to meet the same cumulative emissions or temperature target and to make up for the time wasted and the additional emissions due to the Green Paradox. Paradoxically,

[6] van der Ploeg (2016b) shows that aggregate welfare increases of a delayed tax depends on whether oil and gas supply is more responsive to prices than energy demand, which often is the case.

since this second-best climate policy shifts carbon emissions to the near future (rather than spreading them out as an immediate first-best policy would), it discourages exploitation investment and discoveries, and curbs exploitation investment and drilling activities, it bolsters the profitability of existing capital stock and preserves some of the shareholder wealth compared to the loss under the immediate tax, giving owners of fossil wealth ample incentives in delaying and hindering policy implementation (van der Ploeg and Rezai, 2019).

7. Fickle climate policies and stranded carbon assets

Studies like the one on the exhaustion of the 2°C coal capital stock of coal-fired power stations indicate the urgency of the 2°C challenge and should be a clear warning against investing in new long-lived energy infrastructure based on coal or other types of fossil fuel, especially as these investments only earn themselves back over a long economic lifetime. Similarly, the Paris Agreement commits most economies to limiting global warming and to stringent climate policy. Such announcements should translate into immediate re-valuations of carbon intensive and carbon-free capital. Yet, share prices of oil and gas majors hardly reacted to the news of the agreement even though coal companies took a bigger hit.[7]

Whether unanticipated tightening of present or future climate policy leads to an immediate reduction in the market valuation of natural and physical capital crucially depends on the credibility of this policy. If agents attach certain probability to the policy announcement, current or future demand for fossil fuel will fall an both the scarcity rent of fossil fuel and the price of capital installed in the fossil industry drop.[8] With forward-looking rational expectations, these effects materialize instantaneously as soon as new information becomes available. One way to interpret the relative stoic indifference of share prices after the Pairs Agreement is that investors believe politicians talk a lot and do little and that the Paris Agreement is nothing but paper

[7] Although share prices of coal companies dropped quite a bit, the U.S. oil and gas index fell by a mere 0.5%. Renewable energy stocks rose after the Paris agreement.

[8] We use credibility and commitment synonymously, thereby sidestepping the potential time inconsistency of such policies which have been analysed before in a context where renewable energy production is subject to learning by doing (e.g. Rezai and van der Ploeg, 2017b).

promises. Just like full credibility, this assumption would be extreme, since surely some aspects of the Agreement will materialise eventually, albeit the timing of this would be uncertain. A more realistic approach is, therefore, to model climate policy as a tipping event, which occurs with a certain probability (van der Ploeg and Rezai, 2019). The probability of policy makers tipping into action may increase as temperature gets closer to the cap to which countries have committed. This framework reduces the issue of credibility to one of risk rather than one of trust and reputation, but it captures the essential feature that there is uncertainty about announcement concerning the stepping of climate policy. Market participants also need to adhere sufficiently large probability to the announcements happening for them to move the market valuation of carbon-intensive and low-carbon industries.

Figure 1 illustrates the risk of tipping of climate policies. The market assigns a probability $0 < \pi < 1$ that policy makers change tack at some future date t_0 and from then on implement carbon pricing compatible with the internationally agreed upon temperature cap. The market assigns a probability $0 < 1 - \pi < 1$ that policy makers' efforts fail, and their lower instinct prevail and business as usual continues. Here, uncertainty involves whether at some future point of time a ceiling on cumulative emissions compatible with the temperature cap is imposed or not. Alternatively, uncertainty could range on the timing of the introduction of a given carbon price path. Both types of events could occur repeatedly.

Uncertainty about the timing and forcefulness of climate policy leads to an additional potential stranding off assets in the transition to a carbon-free economy. Once the tipping event occurred and uncertainty is resolved, agents know that policy will be sustained and this realisation is equivalent to the case of a policy surprise discussed above (cf. Bretschger and Soretz, 2019; Karydas and Xepapadeas, 2019). However, the period before the tip is qualitatively different from the case of an announced and fully anticipated policy. Instead agents take the expected value over both scenarios, given probability π. Changes in the expected policy still impact prices as before, however, now the probability π also determines the extent to which assets are reassessed. This is easy to see when one considers the extreme values of π. With $\pi = 0$ the economy faces BAU with certainty and with $\pi = 1$ the economy faces climate policy from $t > t_0$ onward with certainty. Moving from zero to one reproduces the Green Paradox and other effects of anticipated climate policy. In reality π will increase gradually at intermediate values, leading to a constant repricing of assets, making it hard to identify asset stranding (Carattini and Sen, 2019). However, given the self-reinforcing nature of ongoing technological change and unanticipated cost reductions in renewable energies, discrete and significant downward revisions of fossil assets can still occur.

Given that setting an end date of the fossil fuel era leads to voracious depletion of reserves, uncertainty can have positive implications for the environment. With a positive probability of a continuation of BAU, fossil fuel firms are pacing their race to burn the last ton. This reduces the Green Paradox effects in the pre-tip phase and, if the economy ends up on the policy branch, requires less forceful pricing of carbon later on (van der Ploeg and Rezai, 2019). In this sense, policy makers might want to rely on strategic ambiguity about their ability to enact climate policy.

8. Breakthrough technologies and stranded carbon assets

Technologies for renewable energy are being developed at an expanding rate and yield substitutes for coal, oil and gas, which are getting cheaper all the time as production increases and cost reductions result from learning by doing. These technical innovations drive down the cost of carbon-free energy sources such as wind, solar, hydro and geothermal energy, and will help to eventually render oil or gas obsolete. In some places of the United States it is already cheaper to build and operate new wind farms than fully amortised coal plants and increasingly the same holds for gas-fired power plants. Other renewable energy sources such as energy from algae might become competitive too in the future, allowing the displacement of fossil fuels in all aspects of life. There is even a small chance of a breakthrough technology such as fusion energy in small-scale reactors becoming economically viable in the next fifty years. All these energy sources have the advantage that at the margin they can be supplied at almost zero cost (not unlike mobile telephony and internet), but the problem is that many of these energy sources are intermittent and thus their success depends on cheap and effective storage devices (batteries) attached to every wind and solar energy generator. If technological breakthroughs occur in energy storage too, then renewable energy will impose an even larger existential threat to oil, gas and coal producers. There is a lot of uncertainty about the timing of technological breakthroughs in renewable energies. Due to the difficulty of patenting new knowledge, the probability of breakthrough typically depends on investments made by rival companies and countries (Jaakkola and van der Ploeg, 2019). At the moment of such breakthrough, one might sudden a sudden decline in market valuation of carbon-intensive industries with some of their assets becoming stranded whilst there will be a sudden improvement in the market valuation of renewable energy industries.

9. Systemic risks, contagion and financial supervision

Stranded carbon assets are only one small asset class among a large diversified world economy. Fossil fuel companies constitute about $5 trillion out of world stock market capitalization in excess of $70 trillion and total financial assets of roughly $300 trillion (Bullard, 2014; Witkowski, 2015). So why should anyone with basic financial literacy (i.e. a well-diversified financial portfolio) worry about stranded carbon assets? Even more so, why wouldn't fossil fuel companies hedge their own risks of a carbon-free world which holds no place for them by investing and diversifying into renewable energy sectors? After all, climate change is the externality whose correction creates the Pareto improvement, not climate policy.

The top 100 coal and top 100 oil and gas companies hold listed reserves of 204 Giga tonnes of carbon and keep expanding their exploration and exploitation infrastructure while investing only 1.3% of their capital expenditure on low carbon technologies. Their portfolios are not diversified, and they are prone to sharp selloffs if investors decide to go clean. Counting in reserves held by sovereign states, up to 80% of declared reserves owned by the world's largest fossil fuel companies and their investors might become stranded. Carbon Tracker (2017) suggests that 20-30% of market capitalisation of the stock exchanges of London, San Paolo, Moscow, Australia and Toronto is connected to fossil fuels.[9] About one third of the total value of the FTSE was accounted for by mining and resource companies. What is worse, financial market participants themselves are not sharing the risks of a bursting of the carbon bubble equally, with some pension funds and investment funds having nearly half of their equity portfolios exposed (Battiston et al., 2017).

Just like the mortgage sector, which was at the root of the financial crisis of 2007/08, the fossil fuel industry is large enough to ignite a financial crisis, if the transition to renewable energy is disorderly and a market panic ensues. Insights about the last financial crisis translate readily to the fossil fuel industry: high leverage and borrowers' balance sheets expose favouring fire sales to deleverage; drying up of lending channels causing a general credit crunch and money hoarding; runs on financial institutions – not only on banks; and strong network effects and a large shadow banking sector (Brunnermeier, 2009). Despite these strong similarities, participation in a bubble is rational for all as long as these self-reinforcing linkages push prices up.[10] Financial regulators are aware of these risks and Carney (2015) has made a strong case for climate stress testing the financial system (see Battiston et al. 2017; ESRB, 2016; Stolbova et al., 2018; Delis et al., 2019) and (activist) shareholders are slowly taking note.

Andersson et al. (2016) point out that one can design dynamic investment strategies that allow long-term investors to hedge long-term climate risk without sacrificing financial returns. Such strategies divest away from carbon-intensive assets and optimise the composition of the low-carbon portfolio to minimise the tracking error with the reference benchmark index. The green trackers that have been constructed in this way have already matched or outperformed their benchmark. The beauty is that on the day that carbon climate policy is stepped up, these trackers outperform the benchmark. Since the markets are not pricing in the risk of a policy shift, these trackers are still relatively under-valued. Litterman (2013) states that "it's very possible that

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[9] Carbon Tracker Initiative (2013), Climate Counts (2013), Lewis (2014) and Bettis et al. (2017) offer similar arguments, and Malova and van der Ploeg (2017) discuss the issue of stranded assets for sovereign states.

[10] Helpful is the "musical chairs analogy" of John Maynard Keynes: "when the music stops, in terms of liquidity, things will be complicated. But so long as the music is playing, you've got to get up and dance. We're still dancing." (quote from Citigroups' CEO Chuck Prince, 10 July 2007).

fear of catastrophic outcomes will lead to rational global pricing of emissions much sooner than the market has built into current prices of stranded assets". The market does not realise that the lacklustre climate policy is irrational as it ignores catastrophic or fat-tailed risk. A correction must come and probably sooner than markets expect. Hence, financial markets, and regulators too, should be worried about stranded assets and have a total return swap strategy to hedge against stranded assets in the portfolio without otherwise disturbing the portfolio.

10. Conclusion

Oil, gas and coal producers face two threats: stepping up of climate policy and a resulting upper limit on carbon emissions and fossil fuel use, and innovation producing cheap renewable substitutes for oil and gas. These threats lead market analysists to conclude that demand will peak in the coming decade and, unless fossil fuel producers radically change their business model, they face a real risk of being put out of business. With substantial intertemporal and inter-sectoral investment costs this means that much of the capital resulting from exploration and exploitation investments risk being stranded and a significant downward valuation of oil and gas producers. Such stranding requires an unanticipated stepping up of climate policy or breakthrough in renewable technologies. Capital assets built up in carbon-intensive industries also risk being stranded. Governments compound the problem by failing to announce credible climate policies compatible with limiting global warming to 1.5 or 2 degrees Celsius. An orderly transition to a green economy requires a credible sustained path of rising carbon prices. The problem of stranded assets is compounded by dithering politicians who postpone ambitious climate policy and thereby inadvertently cause a race to burn the last ton of carbon and thus accelerate rather than curb global warming in the short run.

Carbon Tracker Initiative (2017) calculates that $2.3 trillion of upstream projects in the oil and gas industry, roughly a third of business-as-usual projects to 2025, are inconsistent with global commitments to limit climate change to a maximum 2˚C. It highlights the wide-ranging exposure to carbon risk in this sector. More work is needed on how the Paris agreements affect the stock market value of carbon-based industries. For example, Karydas and Xepapadeas (2019) decompose the Barro (2009) disaster risks into those that are temperature related and those that are not and use a CAPM model to show the effects of such risks on asset pricing and asset holdings. Institutional investors must limit the systematic risk to their portfolio from global warming.[11] Governors of central banks have warned for the carbon bubble and for the need of capital markets regulators are to carry out the necessary oversight and ensure that full corporate disclosure of carbon risks (e.g. Carney, 2015).

[11] Bansal et al. (2016) also discuss the effects of climate risk on asset prices.

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Table 1: Unburnt fossil fuel compatible with 2 degrees Celsius

Percentage Unburnt Reserves	Oil	Gas	Coal
Middle East	38	61	99
OECD Pacific	37	56	93
Canada	74	25	75
China and India	25	63	66
Central and South America	39	53	51
Africa	21	33	85
Europe	20	11	78
United States	6	4	92

Source: McGlade and Ekins (2015)

Figure 1: Climate policy tipping