Assessing transition risk with a stress test methodology

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Abstract

Traditional risk analysis disregards climate change risks. We introduce a microeconomic dimension in the climate change risks debate, with a focus on one of the two climate change risks: transition risk. For measurement purposes, a carbon stress test methodology is put forward. The introduction of the stress testing technique is justified and standard stress tests are customized to make them suitable for transition risk assessment. Carbon stress test elements are gathered and the stress test model, the transmission channels, is discussed.

1. Introduction

A close look to the Basel Committee on Banking supervision's publications suggests that traditional risk analysis fails to give appropriate attention to climate change risks (CISL & UNEP FI, 2014). Physical sciences and recent international-political events, like the COP 21 in Paris and the COP 22 in Marrakesh, suggest that this disregard is not justified and climate change risks should be carefully considered. Today, the introduction of a microeconomic dimension in the climate change risks debate is fundamental, as it permits to meet concerns, of firms and investors, about the effects of a 1.5° trajectory on their businesses and investments; this complement passes through the innovation of climate change risks traditional measurement tools, which focus on a macroeconomic dimension. This paper focuses on one of the two climate change risks – transition risk – and contributes to the debate around its measurement by putting forward a new assessment methodology based on stress testing.

Climate change indicates a change in the state of the climate – the average weather for a particular region and time period, usually taken over decades or longer – which can be identified by changes in the mean and/or the variability of its properties, and that persists for an extended period (IPCC, 2014). Shifts are attributed to two different causes, namely natural climate variability – natural internal processes or external forcings – and human activity that alters the composition of the atmosphere (UNFCCC, 1992, IPCC, 2014). There is a wide scientific consensus on the effects of anthropogenic emissions on the climate – according to Cook et al. (2016), when publishing climate scientists take a position on anthropogenic climate change, consensus on anthropogenic global warming is around 90% to 100%.[1]

The breaking point of human contribution to climate change dates to the industrial revolution as economic development is strictly correlated to energy consumption (Giraud and Karhaman, 2014;EIA, 2017; Stern, 2007). This energy, being of fossil origin, produces

[1] "These results are consistent with the 97% consensus reported by Cook et al. (2013) based on 11944 abstracts of research papers where 66.4% of abstracts expressed no position on AGW, 32.6% endorsed AGW, 0.7% rejected AGW and 0.3% were uncertain about the cause of global warming. Among abstracts expressing a position on AGW, 97.1% endorsed the consensus position that humans are causing global warming" **(Cook et al., 2016)**.

greenhouse gas (GHG) emissions which contribute to global warming. Out of these GHG, carbon dioxide is the most prominent forcing factor: since the industrial revolution the burning of fossil fuels has increased the concentration of atmospheric carbon dioxide, as the burning process combines carbon and oxygen. Atmospheric carbon dioxide levels in the atmosphere have raised from 280 parts per million to 400 parts per million from pre-industrial levels (Wagner and Weitzman, 2016).

Ultimately, risks associated to climate change can be split in two categories: risks associated with physical impacts from climate change and risks associated to non-physical impacts, originating from anthropogenic climate change mitigation. Literature refers to the first category as climate risk (Miller and Swann, 2016; World Resource Institute, 2015; Schoenmaker et Zachmann, 2015), and to the second category as carbon or transition risk (Aglietta et Espagne, 2016; Weyzig et al., 2014; Caldecott et McDaniels, 2014).

Climate risk refers to the occurrence that global warming entails impacts on natural and human systems. Changes in extreme climate phenomena – e.g. temperature extremes, high sea levels extremes, precipitation extremes (IPCC, 2014) –, are likely to cause serious damages to agriculture, coastal zones, and human health (Ackerman et Stanton, 2013), growth (Bansal et al. ,2016; Pycroft et al., 2016; Dell et al., 2014), productivity (Hallegatte et al., 2015; Graff et al., 2014), and value of financial assets (Bowen et Dietz, 2016). The increased costs and frequency of climate-related natural disasters will affect deeply the insurance and reinsurance sector "on both the liability (increasing property and casualty claims) and asset (losses on investments in real estate or equity of firms affected by climate-change-related events) sides" (Farid et al. 2016).

According to the IPCC (2014), in order to likely obtain a warming inferior to 2° over the 21st century relative to pre-industrial levels, CO_2 equivalent concentrations in 2100 need to be around 450 ppm or lower. Emissions scenarios leading to such concentrations are characterized by a change of CO_2 equivalent emissions compared to 2010 of 41 to 72% by 2050 and of 78 to 118% in 2100. The Paris agreement clearly mentions "efforts to limit the temperature increase to 1.5° above pre-industrial levels" (UNFCCC, 2015), which implies that CO2eq emissions need to be further reduced relative to a 2° target. Tackling anthropogenic climate change – and the economic damages entailed by it – implies mitigating GHG emissions[2], making an adjustment towards a lower-carbon economy: this process of adjustment carries a cost that the literature refers to as carbon risk or transition risk. Mitigation efforts are essentially policy-driven – e.g. policies to price greenhouse gases and incentives to technology development – but can also be autonomous, i.e. missing an explicit link to specific national GHG targets (Nobuoka, 2015).

Economic science has generally regarded the trade-off between climate-related economic damages and anthropogenic climate change mitigation in terms of cost-benefit analysis, which is, according to Dietz et al. (2016a), the principal economic tool for decision making.[3] From a CBA prospect, the endeavour against anthropogenic climate change is economically justified if and only if the present value of the damage costs of climate warming, the costs of non-action, are superior to the present value of the cost of action for the reduction of greenhouse gas

[2] Carbon dioxide, the most important "forcing" of climate change, water vapor, methane, nitrous oxide and chlorofluorocarbones

[3] "In a CBA, all current and future costs and benefits, or net benefits, in each period are given a weight and are then summed, with costs entered as negative benefits. Policy options with higher net benefits are generally preferred. Current costs and benefits have a weight of one. The weight placed on future costs and benefits is determined by a number known as the discount rate and, more specifically, in the case of societal rather than private decision making, the social discount rate (SDR). The SDR determines how quickly the weight placed on future costs and benefits diminishes with the time horizon being considered: the higher the SDR, the lower the influence of future costs and benefits on present values" (**Dietz et al., 2016a**).

emissions. The theme of measurement is, therefore, crucial, as public decisions concerning climate change mitigation depend upon the measurement of such costs.

Economic costs of the impacts of climate change, and the costs of action to reduce the emissions of greenhouse gases (GHGs) that contribute to cause it, are traditionally calculated in three ways[4] (Stern, 2007, Dobes et al., 2014). Nevertheless, these methodologies present limitations[5]: structural uncertainty permeates the assessment of costs of action[6] (Dietz, 2011) and the assessment of the costs of non-action[7], which makes evaluations highly problematic and determines the limitations of traditional risk measurements approaches. In order to cope with uncertainty, the literature is moving towards stress testing. In this context, Bowen and Dietz (2016) call for both micro and macro carbon risk stress tests, the Bank of England Prudential regulation authority (2015) suggests an integration of climate change risk factors in standard stress-testing techniques, the Canfin-Grandjean Commission (2015) suggested that the Bank for International Settlements (Basel Committee) define methods to include climate risks in stress tests for banks and insurance companies, Zenghelis et Stern (2016) encourage financial corporations and fossil fuel to undertake stress tests to evaluate their "future viability against different carbon prices and regulations", Schoenmaker and van Tilburg (2016a) call for , as next step, the developing of a "carbon stress tests to get a better picture of the exposure of the financial sector", and the World Bank (Fay et al., 2015) has also taken this direction[8].

On the transition risk side – i.e. the cost of action –, these endorsements have been followed up by research on carbon stress test design: three proposals have been published under working paper form. Literature on the subject is scant. Battiston et al.(2016) study the financial relations between investors, i.e. the systemic or second-round effects, after assigning a negative shock of 100% to the equity holdings – of 50 EU banks – in companies in various aggregations of

[4] « Using disaggregated techniques, in other words considering the physical impacts of climate change on the economy, on human life and on the environment, and examining the resource costs of different technologies and strategies to reduce greenhouse gas emissions; using economic models, including integrated assessment models that estimate the economic impacts of climate change, and macro-economic models that represent the costs and effects of the transition to low-carbon energy systems for the economy as a whole; using comparisons of the current level and future trajectories of the 'social cost of carbon' (the cost of impacts associated with an additional unit of greenhouse gas emissions) with the marginal abatement cost (the costs associated with incremental reductions in units of emissions) » **(Stern, 2007)**

[5] « All three of these approaches would lead to exactly the same estimate of the net benefits of climate-change policies and the same extent of action if models were perfect and policy-makers had full information about the world. In practice, these conditions do not hold, so the three perspectives can be used to cross-check the broad conclusions from adopting any one of them » **(Stern, 2007)**

[6] « The key observation here is that uncertainty about the SCC is currently a great deal larger than uncertainty about the corresponding marginal abatement cost (MAC) of CO2. Using recent reviews of the literature, we concluded that the range of estimates of the present SCC was a factor of ten larger than the corresponding range of estimates of the present MAC (Dietz & Fankhauser, 2010). Since recent research has stretched out the upper tail of SCC estimates, this ratio could now be even greater. Another observation is that all models, whether of the SCC or MAC or both, are imperfect, and few would disagree with the need to look to other forms of evidence in setting the stringency of climate policies» **(Dietz, 2011)**

[7] For example, **Weitzmann (2009)** has shown that structural uncertainty fattens the PDF tails of high impact, low probability catastrophes.

[8] « A fundamental innovation being considered is extending stress testing of financial actors - that is, simulations of what would happen in the event of an equity markets crash, high unemployment, or other drivers of financial crisis- to take the long term into account (beyond the two years that are currently being looked at) and to include unconventional factors, such as climate policy (carbon exposure) and environmental constraints…()…Discussion on this topic are still at an early stage, but stress tests could evaluate the financial impacts of plausible environmental scenarios on assets, portfolios, institutions, and financial markets as a whole » **(Fay et al., 2015)**

climate sensitive sectors. ICBC (2016) evaluates the impact of upcoming environmental protection policies – tightening of emission limits and raise of pollutant discharge fees – for two industries, thermal power and cement, in order to figure out the changes of the firms' financial indicators and assess their resulting new credit ratings and probabilities of default by using the bank's rating models. Cambridge Centre for Sustainable Finance (CISL, 2016) assesses the impacts on oil, gas and utility firms' profitability of scenarios on environmental regulation and carbon pricing (45€/tCO2) in order to improve stock picking..

This paper contributes to carbon stress test literature by justifying the application of stress tests for transition risk measurement and by addressing the preliminary steps to carry them out. Following Borio (2014), a stress test has four essential features: shocks, risk exposures, outcome measure and stress test model. The exogenous shocks – the transition risk factors –, the outcome measures and the risk exposures are, firstly, obtained via a literature review and, successively, examined. An additional feature, physical carbon accounting, necessary for transition risk quantification, is added. Specific interrelations between stress test features are discussed, providing a theoretical framework for the stress test model. The paper is structured in the following way: section 2 presents the stress testing paradigm and justifies its use by Environmental Economics as a supplementary risk measurement tool; section 3 provides three carbon stress test elements: shocks, risk exposures and outcome measures; section 4 submits the fourth feature, carbon accounting; section 5 examines and formalizes the fifth feature, the stress test model; section 6 provides a discussion and concludes.

2. Stress tests: from engineering to environmental economics

Stress testing is a technique used to test the stability of an entity or a system under adverse conditions and originated in Engineering (Borio, 2014).[9] Varying types of stress tests are encountered across different fields of engineering such as mechanical engineering, structural engineering and software engineering. Financial services – and regulators – absorbed the stress testing technique in the last thirty years (Weber, 2014).[10] Financial stress tests are analyses of what would happen to financial institutions' balance sheets and liquidity under various adverse economic scenarios: a risk management tool whose purpose is to assess the potential impact on a company of a specific event and/or movement in a set of variables, which is "used as an adjunct to statistical models such as value at risk (VaR)" and is increasingly viewed "as a complement, rather than a supplement to these statistical measures" (Committee on the Global Financial System, 2005). Now, however, one question arises: is it worth for Environmental Economics to absorb the stress testing technique from Finance for measurements of the costs of action of GHG abatement?

Stress testing is quintessential to financial risk management (Bensoussan et al. 2014). The economic and financial literature describes stress testing through dichotomies: top-down and bottom-up approaches, first and second round effects, sensitivity and scenario analysis, historical and hypothetical scenarios, direct and reverse. In the top-down approaches "the empirical relationship between a banking variable and an exogenous stressor is assumed at the

[9] "Stress testing originated not in finance but in engineering. In its broadest sense, stress testing is a technique to test the stability of an entity or system under adverse conditions. In finance, it was originally used to test the performance of individual portfolios or the stability of individual institutions ("micro stress tests"). More recently, similar techniques have been employed to test the stability of groups of financial institutions that, taken together, can have an impact on the economy as a whole ("macro stress tests") (**Borio, 2014**)

[10] "Over the past three decades, stress testing techniques have become an integral part of the risk management infrastructure of a typical financial firm. In the late 1980s and 1990s, most financial firms developed systems of risk management to respond to increased exposures to market, credit, and operational risks on account of the proliferation of derivatives during the same period" **(Weber, 2014).**

portfolio level of low granularity" (Kapinos et al, 2015), while in the bottom-up approach, "the empirical relationship is estimated at the highest possible level of granularity of a banking variable" (Kapinos et al., 2015).[11]First-round effects come from the immediate impact of the shock on the financial system, while second-round effects include "possible domino effects from the institutions that are directly affected by the shock to other intermediaries and, possibly, to market infrastructures and the entire financial system" (Quagliarello, 2009). Sensitivity testing is a process that aims to determine how changes to a single risk factor will impact the institution or the portfolio while scenario analysis studies the effect of a simultaneous move in a group of risk factors (Ionescu et Yermo, 2014). Historical scenarios rely on a significant market event experienced in the past, whereas a hypothetical scenario is a significant market event that has not yet happened (Committee on the Global Financial System, 2005). Scenarios have been subjects to requirements by the Basel committee on Banking supervision which demand them to be plausible but severe (BCBS, 2009). Direct stress tests set scenarios and derive losses, while "starting from a big loss and working backward to identify how such a loss would occur is commonly referred to among risk management professionals as reverse stress testing" (Breuer et al., 2012).

Following Borio (2014), any stress test has four features:

"The first is the set of risk exposures subjected to stress. The second is the scenario that defines the (exogenous) shocks that stress those exposures. The third is the model that maps those shocks onto an outcome (or impact), tracing their propagation through the system. The fourth is a measure of the outcome."

The third feature, the stress test model, is what differentiates stress testing, as a risk detection tool, from other risk measures like Value at Risk and Expected shortfall. Value at Risk and Expected Shortfall[12] are "summary statistics of the forecast return or solvency distribution in a stochastic model" (Ionescu et Yermo, 2014). According to Grundke (2011):

"Quantitative risk management models, such as RiskMetrics for market risks or CreditMetrics for credit risks, should yield the probability distribution for portfolio losses over a specified risk horizon. Based on this loss distribution, risk measures such as value-at-risk (VaR) or expected shortfall (ES) can be computed. However, the financial and economic crisis of 2007–9 has shown that, for various reasons, the models' risk predictions are not always reliable. Banks (and taxpayers) had to bear huge losses that should not have been possible according to the risk models".

What differentiates stress tests from these "summary statistics" is that they do reveal how the losses might occur, instead of only evaluating the likelihood and size of the losses. This is done by means of the third feature, the model that connects the shocks to the risk exposures and that quantifies the impacts, taking into account the economic consequences of the shocks.

There are three main arguments to absorb stress testing, not as a complementary but as a supplementary technique, into the environmental economics' set of measurement tools for transition risk. Firstly, costs of action (for GHG abatement) traditional evaluation instruments have only a macroeconomic dimension. While this is perfectly justified from a social perspective, concerns from the entrepreneurial world and investors about the effects, on their businesses and their investments, of a 1.5° trajectory are likewise warranted. Carbon stress tests fill the gap in the literature for the assessment of the costs of action for reduction of GHG emissions at microeconomic level. Secondly, as mentioned in section 1, structural uncertainty

[11] The division refers to the US definitions, whereas in Europe top-down refers to stress tests carried out by regulators and bottom-up by banks **(Kapinos et al., 2015)**

[12] **Artzner et al. (1999)** have proved that VaR is not a coherent risk measure as it violates the property of sudadditivity

permeates the assessment of the costs of action with traditional measurement methodologies. Stress tests are a "what-if" analysis that by construction reduces – but doesn't eliminate – uncertainty by making forward-looking assumptions on a limited set of risk factors. Thirdly, a rigorous assessment of the idiosyncratic risk at microeconomic level can lay the foundations for a new assessment of climate-change induced systemic risk. In other words, stress testing, by employing an uncertainty-reducing-assumption on a set of exogenous shocks in order to determine its impact on an entity or on a portfolio, can in turn deliver the basis for a novel assessment of the impact at macroeconomic level.

3. Stress test set-up for transition risk: risk factors, risk exposures, outcome measurement

According to Borio's classification, a stress test is composed of four features. The objective of this section is to gather three out of the four features: risk factors, risk exposures and outcome measurement. Intuitively, these three elements are constitutive parts of the definition of the notion of transition risk; this implies that the methodology employed to obtain them is to conduct a literature review of academics and international organizations who made explicit reference – i.e. defined the concept –, in their works, to transition risk and then look for the three elements within such definitions. This methodology will permit us to obtain a collateral objective, that of clarifying the state of the art notion of transition risk, which is still, today, vague and unsteady.

According to Hurley (2005) a definition is:

> "a group of words that assigns a meaning to some word or group of words. Accordingly, every definition consists of two parts: the *definiendum* and the *definiens*. The *definiendum* is the word or group of words that is supposed to be defined, and the *definiens* is the word or group of words that does the defining"

Defining is a process by which the predicate of a term or a syntactical unit is determined: it associates a term or phrase to be defined, the *definiendum*, with other terms included in the predicate, the *definiens.* Defining something means attributing meaning to a term or syntactical unit through an association with other terms with an established meaning – in our case the syntactical unit "transition risk" is the *definiendum* and, by means of a literature review, we will search for what the authors propose as its predicate, i.e. we will search for the proposed *definiens*. The analysis will permit us to gather the three stress test elements as these are constitutive parts of the *definiens*: sections 3.1, 3.2 and 3.3 are organized according to a stress test element partition.

From a time perspective, the landmark chosen to start the literature review is 2006, the year the Stern Review came out. The review received praises and criticisms along the years but it has been highly visible[13] and had the merit to reinvigorate debate on climate policy (Tol, 2016). The articles, spanning through the 2006-2016 period, were selected through searches for "transition risk", and, as this syntactical unit is not used by all commentators, it was supplemented with keyword searches for "carbon risk", "transition risk" AND "carbon", "carbon asset risk", "carbon bubble" and "stranded assets". Articles containing the syntagmata were identified using the full-text keyword searches available on websites of the top four – in terms of number of published journals – publishers: Elsevier, Springer-Verlag, Taylor and Francis, John Wiley and sons[14]. Only articles that contained definitions were retained, all the others making only peripheral reference to our subject of study were discarded. This led to an

[13] « The Stern Review has certainly been visible. According to Scopus, it has been cited 6780 times (as at September 21, 2016). Of these, 1434 citations are in the economics literature, including prominent critiques»
[14] Statistics provided by International Scientific Institute (ISI)

identification of a total of 45 publications. Within these publications, 20 were articles published in peer-reviewed journals. Additionally, a query of repositories has been carried out; the list of repositories, along with the list of the peer-reviewed journals, can be found in the annex.

3.1 Risk exposures

Authors reviewed acknowledge two types of transition risk exposures: assets and users of assets. A part of the literature prefers to put emphasis on the *users* of capital instead of capital itself; from these perspective certain authors refer generally to these users as "enterprises", "firms", and "companies" (Zhou et al., 2016; Jung et al., 2016; Oestreich et Tsiakas, 2015; Jung et al., 2014; Koch and Bassen, 2013). Other authors put emphasis on the nature of these firms, making reference to their activities: coal value chain companies (Caldecott et al., 2016a), oil producers (Hultman, 2006), fossil fuel companies (Caldecott and McDaniels, 2014; Ritchie et Dowlatabadi, 2015), fossil energy industry (Mathieu, 2015), power producers (Daskalakis et al., 2015), energy sector investors (Barradale, 2013), banks and other lenders (Manninen, 2016). Given this list of exposures, it comes natural to deduce that some industries are more exposed than others to carbon risk: the fossil energy industry, centred on products that have a molecular composition that includes high concentrations of carbon, such as petroleum, coal, and gas, and the electrical power industry, as the source of electrical power are mainly fossil fuels (IEA, 2016), carry a greater carbon risk. This being said, a part of the literature keeps the focus on carbon intensive assets rather than users of assets (Aglietta et Espagne, 2016; Thomä and Chenet, 2016; Espagne, 2016; Batten and al., 2016; Coeslier, 2016; Carney, 2015), and sometimes explicitly refers to the nature of the asset, whether physical (Comerford and Spiganti, 2015) or financial (Caldecott et al., 2016b).

3.2 Risk factors

Transition risk factors are those variables that, on one hand, act upon transition risk exposures of section 3.1, and, on the other hand, are the drivers of GHG emissions mitigation and of the decarbonisation of the economy. The literature's most acknowledged risk factor – every author reviewed makes explicit reference to it – is policy and regulation. According to Stern (2007), carbon pricing, technology policy and policies to remove barriers to behavioural change are the three key elements of a climate change policy[15].

Less mentioned and developed drivers of transition risk, are the market and the technology risk factors. The market risk factor, sometimes called economic risk factor, is intended as autonomous supply side decisions to implement energy saving and emission reducing plans and

[15] « The first essential element of climate change policy is carbon pricing. Greenhouse gases are, in economic terms, an externality: those who produce greenhouse gas do not face the full consequences of the costs of their actions themselves. Putting an appropriate price on carbon, through taxes, trading or regulation, means that people pay the full social cost of their actions. This will lead individuals and businesses to switch away from high-carbon goods and services, and to invest in low-carbon alternatives. But the presence of a range of other market failures and barriers mean that carbon pricing alone is not sufficient. Technology policy, the second element of a climate change strategy, is vital to bring forward the range of low-carbon and high-efficiency technologies that will be needed to make deep emissions cuts. Research and development, demonstration, and market support policies can all help to drive innovation, and motivate a response by the private sector. Policies to remove the barriers to behavioural change are a third critical element. Opportunities for cost-effective mitigation options are not always taken up, because of a lack of information, the complexity of the choices available, or the upfront cost. Policies on regulation, information and financing are therefore important. And a shared understanding of the nature of climate change and its consequences should be fostered through evidence, education, persuasion and discussion» **(Stern, 2007)**

market demands for low carbon products (Zhou et al., 2016) and consumer boycotts (Branco et al., 2012). Technology – developments in the commercial availability and cost of alternative and low-carbon technologies (e.g.: carbon capture and storage, alternative fuels) – is also acknowledged by some parts of the literature as a driver of transition risk (Caldecott et al., 2016a; Zenghelis and Stern, 2016; WRI, 2015). Less recognized transition risk determinants are "the interaction of economic agents' beliefs about the climate policies they will face with the behavior of policy makers" (Bowen et Dietz, 2016), and litigation (Zenghelis et Stern, 2016), which has been recently classified by Carney (2015) as a subsection of climate change related risks – the others being climate, or physical risk, and transition risk itself. The recently published recommendations of the task force[16] on climate related financial disclosure (TCFD, 2016) confirms these findings: within the transition risk category they enumerate policy, technology, market and reputational risks[17].

3.3 Outcome measurement

The literature acknowledges that risk factors can give rise to values reassessments of the risk exposures. Some authors speak of uncertainties (Zhou et al., 2016; Jung et al., 2016) of future cash flows; some others, while pointing out the threats, highlight also the opportunities associated with transition risk (Jung et al., 2014; Subramaniam et al., 2015; Caldecott et al., 2016b). Mostly, literature lingers on the repricing of carbon intensive assets (Aglietta et Espagne, 2016; Batten et al. 2016; Zenghelis and Stern, 2016; Meltzer, 2016), sometimes providing explicit distinction between physical assets and financial assets (Thomä et Chenet, 2016; Manninen, 2016). The "new valuation of a whole set of assets" or "the reassessment of value" is exemplified by key concepts such as "stranded assets" (Caldecott, 2016a; Boissinot et al., 2016; Heede and Oreskes, 2016) and "carbon bubble" (Ritchie et Dowlatabadi, 2015; Comerford et Spiganti, 2015; Schoenmaker et al., 2016b). Stranded assets are assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities (Caldecott, 2016a) while the carbon bubble concept refers to an:

> "overvaluation of fossil fuel reserves and related assets should the world meet its stated objective of limiting climate change to 2° compared to the pre-industrial age. Meeting this target puts a limit on future carbon dioxide (CO2) emissions and hence on the amount of fossil fuels that can be burned, requiring a sharp bending of the current trend" (Schoenmaker et al., 2016b).

Stranded assets and carbon bubble have, therefore, a similar referent, as they both allude to a "value reassessment" or a "repricing" due to the transition risk factors exposed in section 3.2.

4. Additional element for carbon stress test: carbon accounting

In addition to the stress test elements underscored in the previous sections, a transition stress test requires an additional element with respect to a traditional stress test: carbon accounting. Carbon accounting is a technique used to calculate total GHG emissions at entity level and is a key factor in determining firms' cash flow reductions due to transition risk factors; for example,

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[16] The TCFD is formed by a team of 16 experts from the financial sector, 8 experts from non-financial sectors, 8 other experts

[17] The TCFD defines reputational risk as : « Climate change has been identified as a potential source of reputational risk tied to changing customer or community perceptions of an organization's contribution to or detraction from the transition to a lower-carbon economy".

given a marginal abatement cost, a carbon price, this will be paid on every ton of CO2, and, therefore, these emissions need to be quantified. As Ascui and Lovell (2011) put it, carbon accounting has become an essential enabler of society's key responses to global warming "including national emissions limitations commitments, corporate climate change performance targets and carbon markets". Physical carbon emissions accounting is indispensable for the measure of transition risk impacts.

Carbon accounting is a sub-division of an economic branch of studies named environmental accounting, which emerged in the 1960s-1970s following a critical reflection on the links between economics, society and environment. A cornerstone of this line of thinking is the publication of "The limits to growth" by Meadows et al. (1972) which is the first study which focuses on the environmental dangers that economic growth can cause (Rambaud, 2015). Following Richard (2012), national environmental accounting begins with a seminal article by Nordhaus and Tobin (1972), in which the question asked is whether the growth process inevitably wastes our natural resources, concluding that:

> "at present there is no reason to arrest general economic growth to conserve natural resources, although there is good reason to provide proper economic incentives to conserve resources with currently cost their users less than true social cost"

On the corporate accounting side, Müller-Wenk, in 1974, with the essay "*Die ökologische Buchhaltung*" can be considered as the pioneer of micro-economic environmental accounting (Rambaud, 2015), with his proposal consisting of an "eco-points" accounting system appealing to non-monetary units of measurement for the assessment of the degree of rarity and of pollution of the constitutive elements of natural capital (Richard, 2012).

Providing a detailed history of environmental accounting is out of scope for this study and, for interested readers, a specific overview can be found in Owen (2008) and Ding et al. (2014). What matters to our purposes is the establishment, by the literature, of a taxonomy in environmental accounting: following Richard (2012) environmental accounting can be of three kinds: quantitative, monetary and in ecological values.

Quantitative environmental accountings rely on pure quantitative data and give out an indication of the quantitative influences of an entity on the environment (e.g.: ecological balance sheets). Monetary environmental accountings give out a monetary evaluation of capital, conceived under its natural form. Environmental accountings in ecological values – indicators of rarity and pollution degree of natural capital – refute monetary evaluations and consider quantitative accounting insufficient: ecological values (eco-points, Müller-Wenk, 1974; solar energy accounting, Odum et al., 1971; and surface accounting or ecological footprint, Rees and Wackernagel, 1998) would reflect better the ecological rarity of services yielded by nature than marginal prices, as they are not influenced by technological, economic and social factors which have nothing to do with biophysical scarcity.

Carbon accounting is a subset of quantitative environmental accounting, characterized by a special focus on GHG emissions, therefore a limited amount of ecological outputs. Following Ascui (2014), carbon accounting in the social and environmental accounting literature can be tackled under different perspectives: discussions about carbon accounting, carbon management accounting, carbon disclosure and reporting, carbon financial accounting, and carbon accounting education. The set of theories and techniques aimed at measuring carbon intensity are part of Ascui's carbon management accounting cluster.

Carbon footprint can be assessed at product level or at corporate level. At product level alternative standards have been formulated by different organizations: the British standards institution (PAS 2050, 2011), the World Resource Institute and the world Business Council for Sustainable Development (GHG Protocol, 2011), the International organization for standardisation (ISO 14067, 2013). Standards for carbon footprint at corporate level are ISO

14064 (2006) and GHG protocol for organizations (2004, 2011) (Navarro et al., 2017). The GHG protocol covers the accounting and reporting of the six greenhouse gases covered by the Kyoto Protocol — carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6) and was amended in May 2013 to include a seventh greenhouse gas: nitrogen trifluoride (NF_3). This GHG are calculated separately and then converted to CO_2 equivalents on the basis of their global warming potential. The GHG Protocol categorizes these direct and indirect emissions into three scopes: scope 1 (all direct GHG emissions), scope 2 (indirect GHG emissions from consumption of purchased electricity, heat or steam), and scope 3 (other indirect emissions, the full corporate value chain emissions from the products they buy, manufacture and sell).

The three main approaches used to calculate Carbon Footprints are the bottom-up (LCA), top-down (EE-IOA) and hybrid approaches (Ercin et Hoekstra, 2012). The bottom-up approach is based on LCA, a method that estimates the environmental impact of products by 'cradle to grave' analysis. LCA is generally performed in a process-oriented approach, a "bottom-up" approach which needs to build the supply chain of the process and get data from each process unit. While LCA is more suitable at product level, for mesosystems and macrosystems a top-down approach is preferable (Wiedmann et al., 2009). Environmentally Extended Input-Output Analysis (EE-IOA) is the main method for top-down calculations (Minx et al., 2009; Huang et al., 2009; Wiedmann et al., 2009). Such analysis makes use of an economic input-output model, which represents the interdependencies between different sectors and final consumption in the national economy or between the sectors in different national economies. The hybrid approach (using both process-LCA and EIO methodologies) is a "top down" approach in which inventories are quantified using monetary data at a high aggregation level, and hybridized with "bottom-up" process-based data collection, when more detail is needed (Navarro et al., 2017).

5. The carbon stress test model

The mapping of the risk factors onto an outcome, which permits to trace their propagation through the system, is what the literature refers to with the term "model" (Borio, 2014). The stress test model transforms the exogenous shocks into an impact: it is a transmission mechanism which permits to quantify the impact of risk factors on risk exposures. The objective of this section is to provide a theoretical framework for the microeconomic carbon stress test model. We propose to frame the subject in the following way:

Table 1. Stress test model features

Risk exposure	Risk factors	Outcome measurement	Carbon accounting
Corporates	Policy, market, technology	P&L variation (income statement); assets-liabilities variation (balance sheet)	Corporates' own computations (scope 1, 2); EE-IOA (scope 3)

Following the literature exposed in section 3.2, three risk factors have been retained: policy – carbon pricing and command and control regulation – market – change in demand structure – and technology. The technology risk factor is intended as any technological risk resulting from a voluntary management decision; the risk per se is the same as command and control regulation (Hepburn, 2006) with the only difference that the latter is "imposed", i.e. there is no voluntary management decision on the adoption of the green capital.[18] The reputational risk factor has been discarded as it is redundant with the market risk factor: the former is, according to the TCFD (2016), a changing "customer or community perceptions of an organization's contribution to or detraction from the transition to a lower-carbon economy", while the latter is, as Zhou et al. (2016) suggest, "market demands for low carbon products". Quantification of risk factors is performed with scenario analysis, e.g. carbon shadow prices are selected following the Interagency working group on the social cost of carbon of the United States government (table 2). These estimates are obtained with three integrated assessment models used by the US government to estimate the Social cost of CO_2 (DICE, FUND, PAGE). The discount rates utilised are 2.5%, 3% and 5%. As there is "extensive evidence in the scientific and economic literature on the potential for lower probability, but higher impact outcomes from climate change" (IAWG, 2016) a fourth value has been added (based on a three percent discount rate) to represent marginal damages originating from such outcomes. The fourth value is selected from "further out in the tail of the distribution of SC-CO_2 estimates" (95th percentile of the frequency distribution of SC-CO_2).

Table 2. Social cost of CO_2, 2010-2050 in IWG (2016)

Year	5% Average	**3% Average**	2.5% Average	High Impact (95th Pct at 3%)
2010	10	**31**	50	86
2015	11	**36**	56	105
2020	12	**42**	62	123
2025	14	**46**	68	138
2030	16	**50**	73	152
2035	18	**55**	78	168
2040	21	**60**	84	183
2045	23	**64**	89	197
2050	26	**69**	95	212

As we have seen in section 3.3, the literature refers to "stranded assets" as assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities (Caldecott et al., 2016a) and to "carbon bubble" as an "overvaluation of fossil fuel reserves and related assets should the world meet its stated objective of limiting climate change to 2° compared to the pre-industrial age" (Schoenmaker et al., 2016b). The two terms refer to the same phenomenon: a value reassessment or repricing. Nevertheless, the measures of the impact (or outcome), introduced in section 3.3, are not operative and need to be refined. In this context, the value assessment, or repricing, is introduced at income statement level and at balance sheet level. The three risk factors impact two features of the income statement: revenues (market risk factor, technology risk factor) and cost of goods sold (policy risk factor). As a consequence, the

[18] The TCFD defines technological risk as : « Technological improvements or innovations that support the transition to a low-carbon, energy-efficient economic system can have a significant impact on organizations. For example, the development and use of emerging technologies such as renewable energy, battery storage, energy efficiency, and carbon capture and storage will affect the competitiveness of certain organizations, their production and distribution costs, and ultimately the demand for their products and services from end users. To the extent that new technology displaces old systems and disrupts some parts of the existing economic system, winners and losers will emerge from this "creative destruction" process. The timing of technology development and deployment, however, is a key uncertainty in assessing technology risk. »

net earnings of the entity will also be affected. This shift in net earnings (income statement) affects also the balance sheet via the retained earnings.

Following Ball et al. (2015), net income is defined by the following accounting identity:

Net Income ≡ Revenue (1)

- Cost of goods sold
- Selling, general and administrative expenses
- Depreciation and amortization
- Interests
- Taxes
+ Non-operating income
+ Special items
- Minority interest income
- Extraordinary items

As the transition risk factors (policy, market, technology) will impact net income through changes in revenue and cost of goods sold, this impact is given by:

$$\triangle Profit = \triangle R - \triangle COGS \quad (2)$$

Consequently, the variation of net earnings will also show on the balance sheet, under the form of a variation of retained earnings. Retained earnings are defined by the following identity:

$$\text{Retained Earnings} = \text{Initial Retained Earnings} + \text{Net Income} - \text{Dividends} \quad (3)$$

In the model, carbon accounting plays a fundamental role: it provides a physical base to compute policy risk. Sometimes, scope 1 and scope 2 emissions are voluntary released by enterprises. Nevertheless, this is not always the case; in such circumstance, scope 1 and scope 2 are estimated with Goldhammer et al. (2016) methodology based on five predictors: firm size, level of vertical integration, capital intensity, centrality of production and carbon intensity of the national energy mix. Scope 3 emissions (almost never released) need to be estimated with an environmental extended input-output matrix analysis. EE-IOA links direct emissions for all economic sectors (in a single or multi-region economy) in an economy with financial transactions between these sectors (intermediate demand) and allows for an allocation of these emissions to the consumption of product groups (Wiedmann, 2009). In other words, national economic accountings need to be augmented with national and environmental social accounts, and then linked to the entity's financial statements. Carbon accounting performed with EE-IOA gives the opportunity to unravel the value chain of the entity: structural path analysis (SPA, Crama et al., 1984) covers the entire supply chain and "unravels a company's impacts into single contributing supply paths. It gives extensive details of the impact of a sector's or company's activities. It allows one to investigate the location of impacts within the supply chain" (Wiedmann et al., 2009). Double counting issues are avoided thanks to the concept of shared responsibility developed by Lenzen et al. (2007).

6. Discussion

Transition risk, from a microeconomic perspective, is the loss or the probability of a loss which is due to three distinct risks: policy risk, market risk and technology risk. These sub-risks are generated by a will to reduce GHG emissions and by a will to acquire a competitive advantage – in the case of voluntary adoption of green capital – which has, as collateral effect, an effective reduction of emissions. Policy risk finds roots in national authorities, both under its form of a carbon pricing or a command and control regulation, i.e. the imposition of a certain technological standard. Technology risk originates from a voluntary technological shift, which is ultimately due to a managerial decision. Market risk derives from an accrued sensibility of the consumer towards the theme of climate change.

In order to assess transition risk at entity level, these three sub-risks need to be evaluated. In order to do so, a stress test methodology has been put forward. Stress tests has an advantage over other risk measures like VaR and Expected shortfall, which are summary statistics: it provides the manner – a possible manner – in which risk factors impact risk exposures. Carbon stress tests have been justified and customized, using as a base standard stress test literature. Transition risk factors, i.e. the sub-risks, risk exposures, and outcome measures have been presented. The outcome measures allow to trace the impact of the risk factors on the entity's financial statements.

Carbon accounting has been introduced as an add-on to traditional stress tests; its presence is justified by the fact that physical carbon emissions are the fundament on which to assess transition risk. Physical emissions are measured according to international standards and methodologies. Corporate standards include Scope 1, direct emissions, scope 2, indirect emissions from energy consumption, and scope 3, indirect emissions from the value chain, both upstream and downstream. Scope 1 and 2 are sometimes released by companies, if not they can be estimated with Goldhammer et al. (2016) methodology. Scope 3 emissions are estimated with environmentally extended input output analysis. Matrix calculus permits us to estimate indirect upstream emissions (scope 3 emissions), which account, on average, for 70% of total emissions. Process analysis, based on bottom-up data of specific production processes, usually produces more accurate results for direct, on-site impacts but involves significant systematic errors caused by the truncation of the life cycle system by a finite boundary (Wiedmann, 2009). Input output analysis, extended with national environmental and social accounts, can handle infinite supply chain systems and hence does not suffer from truncation errors. In addition to this, availability of data is another argument for choosing IO analysis over process analysis. However, IO analysis is not exempt from criticism: data are at economic sector level, and, therefore, not specific to processes and products. The picture obtained is broad. Another inconvenient is lagged data from input-output tables, which need sophisticated methods to be compiled.

Nevertheless, EE-IOA makes possible to quantify the impact of transition risk factors upon a given entity conceived as part of an economic system. This is a crucial aspect, as carbon price won't simply impact the firm directly, but also indirectly, as its suppliers (upstream companies, energy providers), will also be affected by the introduction of the carbon price.

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Annex

A query of the following repositories has been carried out: IMF (International Monetary Fund), Carbon Trucker, 2° Investing Initiative (2°ii), Bank of Finland, World resource Institute (WRI), International association for Energy Economics (IAEE), Inter-American development bank (IADB), Institute for climate economics (I4CE), Clingendael International Energy Programme (CIEP), Academic research center of Canada (ARCC), United Nations Environment Program (UNEP), Organization for Economic Cooperation and development (OECD), Smith's school of enterprise and environment (SSEE), Bank of England, Centre d'études prospectives et d'informations internationales (CEPII), Finansinspektionen (Sweden's financial supervisory authority), London School of Economics (LSE) and SSRN.

The 20 articles have been published in the following peer-reviewed journals: Journal of Industrial Ecology, Global Environmental Change, Energy Strategy Reviews, Journal of Banking & Finance, Journal of Cleaner Production, Financial Markets trends, Journal of applied corporate finance, Chaos Solitons and fractals, Review of Economics and Finance, Energy Economics, Energy policy, The energy Journal, Journal of Business ethics, Journal of Sustainable Finance & Investment.