# Climate finance and the restructuring of the oil-gas-coal business model under carbon asset stranding constraints

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April 22, 2019

**Abstract**

Oil-gas-coal companies are particularly concerned by the notion of stranded assets, i.e., the fact that known fossil reserves cannot be burnt should limitations on greenhouse gas emissions become more stringent. Those assets can suffer from unanticipated or premature write-downs, devaluations or conversion to liabilities. This paper simulates the impacts of carbon stranded assets for 17 major oil-gas-coal firms' value until the horizon 2050. The core of the paper is a stochastic model with stopping times that determines by initial conditions (reserves and extraction rates) which companies are left with 'stranded assets.' In the business-as-usual scenario, one-quarter of the Earth's capacity for absorbing emissions will be depleted by 2050. With stringent emissions-curbing policies, an environmental gain of 80% can be achieved. Without a restructuring of their business model, many oil-gas-coal companies stand out from our simulations as being particularly vulnerable to the financial risks of bankruptcies and default events.

**Keywords**: Stranded asset; Stochastic process; Monte-Carlo simulations; Climate finance

**JEL Codes**: F36; G12; Q57

*For useful comments, we wish to thank seminar participants at the ISEFI 2017 Symposium (IPAG BS, Paris, France).

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# 1 Introduction

*If we burn all current reserves of fossil fuels, we will emit enough $CO_2$ to create a prehistoric climate, with Earth's temperature elevated to levels not experienced for millions of years. Such a world would be radically different from today.*

– Nicholas Stern (LSE, 2013)

In 2018, William D. Nordhaus was named co-recipient (alongside Paul M. Romer) of the Nobel prize in economics for integrating climate change into the long-run macroeconomic analysis (Nobel Media, 2018). This recognition of the need to incorporate climate-related topics into economic analysis recalls us that, at current levels, the consumption of fossil energy appears strongly unsustainable. In its 2018 report, the Intergovernmental Panel on Climate Change (IPCC, 2018) stresses – with a high confidence level – that global warming is likely to reach +1.5°C between 2030 and 2052 if it continues to increase at the current rate. As a matter of hope, regional initiatives are at stake, as revealed by the World Bank's (2018) effort to map carbon pricing around the world. As of September 1, 2018: 46 national jurisdictions and 25 subnational jurisdictions are putting a price on carbon; whereas 53 carbon pricing initiatives are implemented or scheduled for implementation.

Unfortunately, the fight against climate change is unlikely to be adequately addressed without a restructuring of the fossil fuel industrial complex. Article 2 of the December 2015 Paris Agreements calls for '*making finance flows consistent with a pathway towards low greenhouse gas emissions and climate resilient development.*' Climate policy, therefore, brings the need that carbon will be priced much more vigorously than nowadays (Bredin et al., 2014; Philip and Shi, 2015; Kalaitzoglou and Ibrahim, 2015). Against this background, many of today's carbon assets would become stranded. For financial investors, these assets are thus at risk. This paper argues that especially oil-gas-coal companies face the risk of stranded assets with ensuing unanticipated and premature write-downs, devaluations and conversions to liabilities.

Global warming proposes to restrict the use of resources for carrying capacities reasons (both biological and ecological), rather than because of fossil fuel depletion. Confronted with the exponential discoveries of new fossil fuel reserves, carbon stranded assets impose a new mode of regulation of resources that are compatible with the objective to reduce carbon dioxide emissions. Caldecott et al. (2014) elaborate that stranded assets are assets that have suffered from unanticipated or premature write-downs, devaluations or conversion to liabilities, and there is a range of environment-related risks that can cause them to occur. Further on this definition, McGlade and Ekins (2015) discuss the geographical distribution of fossil fuels unused using an integrated assessment model. Many investors and pension funds are thinking of taking action to hedge themselves against the risk of stranded assets.

Based on IPCC (2007a,b) documentation, the Carbon Tracker Initiative (2015) has evaluated that, in order to have an 80% chance of keeping global warming below 2°C, only 565 $GtCO_2$ can be emitted between 2010 and 2050. Morrissey (2016) provides an updated calculation that this carbon budget is now equal to 525 $GtCO_2$ between 2013 and 2050. Besides, the International Energy Agency (IEA) stated in its 2012 World Energy Outlook that two-thirds of fossil fuel reserves cannot be burnt if the world is to have a 50% chance of limiting global warming to 2°C. Several international initiatives are underway to fight climate change, such as the COP/MOP meetings, the EU emissions trading scheme, China's provincial and city-level pilot trading schemes, South Africa's carbon tax, Australia's emissions reduction fund, the Mexican carbon platform or sub-national schemes in the USA. If governments live up to their commitments to keep global warming below 2°C, Bloomberg (2013) documents that climate change policy could induce the stranding of company's earnings and share price, particularly those in extractive industries under carbon pollution constraints. MSCI (2015) assesses that companies are exploring the potential impact on their assets of the increase in the Earth's temperature of 2.6-4.8°C based on the current trajectory.

Carbon stranded assets apply mainly to companies that own fossil fuel reserves and companies whose business activities are highly carbon-intensive. That is why this paper focuses mainly on the oil and gas industry, which is deeply concerned about changes in *(i)* the prices of oil and gas, *(ii)* companies' cost of exploring new oil and gas reserves, and *(iii)* the revenues and costs from extracting fossil fuels. If costs are greater than the revenues from fossil fuel extraction, then the company will not extract. These events lead to 'wasted capital' if the price drop of the underlying asset is seen as permanent (LSE (2013)). Changes in $CO_2$ emissions, carbon-intensity levels, and carbon prices could impact financial returns. The market capitalization of oil and gas companies can, therefore, be strongly impacted by the advent of low emissions policies.

The article provides empirical estimates of the loss in market value to be suffered among a sample of 17 fossil companies in the event of *(i)* a proportion of reserves becoming 'unburnable'; *(ii)* a reduction in the price of fossil fuels. The original contribution of this paper is to value carbon stranded assets of oil, gas, and coal companies with a stochastic model. Methodologically, this paper uses the techniques of stochastic modeling with stopping times including Monte Carlo simulations with a horizon up to 2050. The theoretical framework hinges on Hotelling's rule translated by Miller and Upton (1985) into an empirical specification for oil, gas and coal companies. The link with companies' extraction rates and reserves builds on the relationship established by Pickering (2008). The data feeding the simulation range from 2005 to 2015.

Inspired by the IEA's World Energy Outlook (IEA, 2012) statistics, we elaborate several scenarios (regarding the stock of oil and gas reserves that may become unburnable and the profile of the cut in fossil fuels prices). The simulations establish that the extent of the losses in the value of the firms (computed as the share price times the number of shares) varies depending on the stringency of the scenario. The more the default intensity rises (i.e., the probability that a carbon asset stranding scenario impacts the company), the more the oil-gas-coal company loses value.

Regarding the core message of the paper, in the benchmark scenario, the firms gathered in our sample will have emitted nearly 150Gt $CO_2$-equivalent by 2050, i.e., approximately one-quarter of the IEA global target in their 450ppm world. This situation can be avoided by resorting to stringent climate policies, such as the ones simulated in our paper, with a decrease up to 80% of that figure. The carrying capacity of the Earth would, therefore, be preserved. The results feature decreasing values of oil-gas-coal companies in all scenarios, with rapid convergence towards bankruptcy. Therefore, carbon asset stranding seems to threaten the very existence of these firms, unless there are changes in their business model or technology (such as renewables deployment for instance).

The paper is structured as follows. Section 2 details the conceptual framework. Section 3 documents the data and the scenario. Section 4 develops the empirical results. Section 5 develops policy implications for policy-makers and investors. Section 5 concludes.

# 2 Model

Until 2050, we create several scenarios of asset stranding, depending on the severity of the carbon constraint at that date.

Our modeling strategy unfolds in three steps:

1. The value of the oil-gas-coal company is determined by resorting to Hotelling's exhaustible resource theory as formulated by Miller and Upton (1985).

2. Remaining oil reserves are significantly linked with extraction rates as shown by Pickering (2008). This second step is required for the calibration of the simulation model.

3. Stochastic processes with stopping times are fitted to each company in order to simulate the impact of carbon stranded assets for a given scenario. Intuitively, the model allocates the unburnable carbon randomly to companies across the scenarios, based on the probability of occurrence of stopping times and their intensity.

## 2.1 Step #1: Hotelling's exhaustible resource theory for oil, gas & coal companies

Following Hotelling's Principle, Miller and Upton (1985) have created an empirical framework to test that the value of the reserves in any currently operating, optimally managed oil-gas-coal company depends mainly on current period prices and extraction costs. The 'Hotelling Valuation Principle' establishes that the net price explains a large proportion of reserves' market value. To do so, the authors propose to regress the market values of the reserves of a sample of oil-gas-coal companies on their estimated Hotelling values at several points in time during the sample period. Formally, the conceptual framework can be stated by the following equation:

$$\frac{V}{R} = \alpha + \beta(p - c) + \epsilon_t \tag{1}$$

with $V$ the value of the firm (share price $\times$ number of shares), $R$ the total reserves in tonnes $CO_2$-equivalent, $p$ the fuel price, $c$ the marginal extraction cost computed as $\frac{\Delta C}{\Delta q}$ with $C$ the total extraction cost and $q$ the rate of extraction, and $\epsilon$ the error term.

The market values are based on stock market prices for the firms' shares. The Hotelling values are based on estimates of extraction costs and estimated reserves recovered from various data sources, as detailed in Section 3.

## 2.2 Step #2: Linking oil, gas & coal companies' extraction rates and reserves

Digging further into this conceptual framework, we need another equation to link extraction rates and reserves. According to Pickering (2008), the relationship between extraction and remaining reserves is found to reduce to a simple representation: at any point in time, optimal extraction depends on an idiosyncratic constant and the product of a slope parameter and remaining reserves. Therefore, or each company contained in our sample, the linear extraction-reserves relationship writes:

$$q_t = \delta + \theta R_t + \epsilon_t \tag{2}$$

with $q_t$ extraction at time $t$, and $R_t$ reserves at the start of the current period. Simulations feed on these oil extraction-reserves estimates. As detailed in Section 3, the data consists of proven reserves as of the end-of-year, and average daily extraction rates.

## 2.3 Step #3: Stochastic processes with stopping times to simulate carbon stranded assets' trajectories by 2050

Now, we implement the trajectories that would occur in the presence of vigorous climate policies by 2050. Carbon stranded assets are assets that may lose economic value before the end of their expected life. To reproduce this behavior, we resort to stochastic processes with random stopping times.

### 2.3.1 Stochastic model

Consider a probability space $(\Omega, \mathcal{G}, \mathbb{P})$ equipped with a Brownian motion $W = (W_t)_{t\in[0,T]}$ over a finite horizon $T < \infty$. In our study, $T$ equals 2050.

We are given a non-negative and finite random variable $\tau$, representing the default time, on $(\Omega, \mathcal{G}, \mathbb{P})$.

**remark 1** • *The default time $\tau$ models default events which can occur during the time to maturity 2050. This default time can depend on several energy, environmental, technological or financial factors.*

- *The Brownian motion $W = (W_t)_{t\in[0,T]}$ represents the stochastic evolution of the future financial asset such as volatility, or jumps.*

We consider a risky asset subject to environmental default risk, which is the price process $S = \frac{V}{R}$ given by:

$$S_t \;=\; S_t^1 1_{t<\tau} + S_t^2(\tau) 1_{t\geq\tau}, \quad 0 \leq t \leq T, \tag{3}$$

where $S^1$ represents the dynamic of the asset before the possible environmental default event at time $\tau \in [0,T]$. This process evolves according to following stochastic differential equation:

$$dS_t^1 \;=\; S_t^1 \left(\mu^1 dt + \sigma^1 dW_t\right), \quad S_0^1 = S_{0-}, \quad 0 \leq t \leq T, \tag{4}$$

and $\{S_t^2(\tau), \theta \leq t \leq T, \tau \in [0,T]\}$ is a family of processes representing the dynamics of the asset after the environmental default event occurrence at time $\tau \in [0,T]$, and governed for all $\tau < t \leq T$ by:

$$dS_t^2(\tau) = S_t^2(\tau)\left(\mu^2(\tau)dt + \sigma^2(\tau)dW_t\right) \quad \text{and} \quad S_\theta^2(\tau) = S_{\tau-}^2\left(1+\gamma_\tau\right) \tag{5}$$

Here, we denote by $S_{0-}$ the initial value of the environmental asset, and $\gamma$ is a stochastic process valued in $[-1,\infty)$ representing the jump of the asset $S$ at the environmental default time $\tau$.

**remark 2** *The special case of a death of the asset $S$ after the default event $\tau$ is modeled with $\gamma_\tau = -1$ (and $\mu_t^2(\tau) = \sigma_t^2(\tau) \equiv 0$). Indeed, when the possible default time occurs, after the default the asset price $S_t^2$ will be equal at the time $\tau$ to:*

$$S_\theta^2(\tau) \;=\; S_{\tau-}^2\left(1+\gamma_\tau\right) = S_{\theta-}^2\left(1-1\right) = 0$$

*And so for all $\tau < t \leq T$*

$$S_t^2(\tau) \equiv 0$$

The interpretation of the default risk model for the asset price $S$ is the following. The process $S^1$ represents the environmental asset price before the default. There is a jump on the asset price at the default time, represented by the process $\gamma$, which may take positive or negative values (corresponding to proportional loss or gain on the asset price). After the default at time $\tau$, $S^2(\tau)$ represents the asset price process. There is a change of regimes in the coefficients depending on the default time. One typical situation can be as follows: in case of downward (respectively, upward) jump in the asset price at default time $\tau \in [0,T]$, the rate of return $\mu^2(\tau)$ should be smaller (respectively, greater) than the rate of return $\mu^1$ before the default. This gap should increase when the default occurs early, i.e. $\mu^2(\tau)$ is increasing (respectively, decreasing) in $\tau$ with $\mu^2(\tau) <$ (resp. $>$) $\mu^1$.

**remark 3** *In our setting, there are several sources of randomness of the asset price. Indeed, there can be financial market risks modeled with the Brownian motion $W$. There are the possible default events modeled with the stopping time $\tau$. There are the stochastic jumps at the default time $\tau$ modeled by $\gamma_\tau$. Finally, the regime switching shifts of the parameters before and after the possible default events are modeled by the shifting parameters $\mu^1$ to $\mu^2(\tau)$ and $\sigma^1$ to $\sigma^2(\tau)$. Notice that the new parameters values ($\mu^2$ and $\sigma^2$) and the jump factor $\gamma$ depend on the time of default $\tau$. This means that the intensity can depend on the time-to-maturity when the default occurs (i.e., $T-\tau$). This allows us to deal with the case where an earlier default could have a lesser impact on the asset price $S$ than a later one.*

### 2.3.2 Default event

In our framework, we assume that the default event $\tau$ is due to exogenous factors (e.g., any shock related to energy, environmental, financial or technological variables) in the stochastic dynamics of the asset price $S$. The random variable $\tau$ is independent of the Brownian motion $W$. Thus, there exists a deterministic function $\alpha(\tau)$ of $\tau \in \mathbb{R}^+$ such that the survival probability is given by:

$$G(t) = \mathbb{P}[\tau > t|\mathcal{G}_t] = \mathbb{P}[\tau > t] = \int_t^\infty \alpha(\theta)d\theta \tag{6}$$

We assume that the survival probability follows an exponential distribution with constant default intensity $\lambda$. There exists a constant $\lambda > 0$ such that $G(t) = e^{-\lambda t}$. The density function is $\alpha(\theta) = \lambda e^{-\lambda\theta}$. The higher the value of the default intensity $\lambda$, the higher the possibility of a default event in the dynamic of $S$.

# 3 Data and Scenarios

## 3.1 Oil-gas-coal companies' share prices and earnings data

By focusing on the oil-gas-coal industry, we select a subset of 17 companies that are particularly concerned about carbon stranded risks. These companies were selected based on their market capitalization in international financial markets, i.e., we are mainly concerned with oil-gas-coal giants. The training sample of our simulations is restricted to the 2005-2015 period due to data availability.

**** Insert Table 1 about here ****

For each company, we collect from Bloomberg daily share prices (period: July 21, 2005, to October 19, 2015), as well as annual earnings (EBIT).[1]

## 3.2 Oil-gas-coal extraction and reserves data

Oil, gas, and coal total reserves and extraction figures are taken from the U.S. Energy Information Administration (EIA), from their 'International Energy Statistics ' database.[2].

To transform U.S. EIA oil, gas & coal reserves, and extraction figures into $CO_2$-equivalent quantities, we have used engineer's conversion rates reproduced in Table 2.

Besides, for each company selected in our sample, we have extracted extraction costs (in USD) manually from the Consolidated Financial Statements as reported individually in each company's annual reports available from the company website.

**** Insert Table 2 about here ****

## 3.3 Principal Component Analysis

To illustrate our database, we run a Principal Component Analysis (PCA) on the variables $\frac{V}{R}$ for each company given by (1), where $V$ denotes the value of the firm (share price $\times$ number of shares) and $R$ the total reserves in ton / CO2-equivalent. This methodology allows us to represent by clusters the segmentation companies concerning their principal activities: oil, gas, and coal.

The PCA results are given in Figure 1.

**** Insert Figure 1 about here ****

[1]For brevity, descriptive statistics of the raw data are not reported, but they can be accessed upon request.
[2]Accessible at `http://www.eia.gov/beta/international/data/browser/`

We can broadly identify six sub-groups among the 17 companies selected in our sample. On the lower left corner, Huaneng and Datang reflect the firm value characteristics of power production companies (in China). Second, from the left, Exxon and Chevron belong to the same category of oil giants. This group is followed by Shell, BP, and Total towards the middle of the plot, reflecting that global oil companies share the same data characteristics concerning firm value. On the right side of the graph, we notice a fourth group composed of PetroChina and CNOOC, i.e., Chinese oil companies. Next, the fifth group is composed of Peabody (coal), Petrobras (oil), China Resources (power) and China Shenhua (coal) which are highlighted by the PCA to share similar characteristics concerning firm value. The last group on the lower right corner is composed of Engie (gas), RWE, EON, and NTPC (power). Unlike the previous companies belonging to the oil and gas sector, the final group reflects mostly the characteristics of power plants. These latter companies do not own resources – presumably, they are affected by carbon budgets because they cannot use their power plants which burn fossil fuels. Interestingly, this is a very different kind of asset-stranding to leaving reserves in the ground.

The total variance explained by each factor of the PCA are given in Figure 2.

**** Insert Figure 2 about here ****

With the first two principal components, we capture a total of 75% of the total variance, which is regarded as extremely satisfactory by all standards in the factor modeling literature (see Stock and Watson (2002)).

### 3.4 Scenarios

To build our scenarios, we consider as a building block the IEA '450' scenario, whereby GHGs are limited to 450 parts per million, resulting in a 50% chance of limiting global warming to 2°C (IEA, 2012). Our time-frame goes to 2050, i.e., it features both short-term and long-term decision-making without being too distant in the future. Most policy discussions focus on GHG reductions by 2050 (for a review, see Caldecott et al. (2014)). To meet 2°C, there can be minimal additional emissions beyond 2050.

According to the IEA (2012), current oil & gas reserves amount to 762 $GtCO_2$ by 2050, which go far away from the 2°C mark (565 $GtCO_2$ can be emitted between 2010 and 2050, similar calculations have been performed by the Carbon Tracker Initiative (2015) based on IPCC documentation for instance). Additional exploitation of oil & gas reserves could inflate the potential $CO_2$ emissions listed on stock exchanges up to 1,541 $GtCO_2$.

Since there is more fossil fuel listed on the world's capital markets that can be burned, we simulate the following scenario:

**Planet environmental ecosystem preservation**

1. 20% of oil & gas reserves are unburnable;
2. 40% of oil & gas reserves are unburnable;
3. 60% of oil & gas reserves are unburnable;

**Financial crisis and technology improvements**

4. 25% cut in fossil fuels price.
5. 50% cut in fossil fuels price.

Cuts in fossil fuels prices are relevant for asset stranding in the sense that they adversely affect the financial health of the company.

# 4 Empirical Results

## 4.1 *Steps #1 and #2*

Eqs. (1) and (2) feed-in the existing 2005-2015 data to calibrate the 2050 simulations.[3] Results are reproduced Tables 3 and 4.

**** Insert Tables 3 to 4 about here ****

The interested reader can track the significance of the $\hat{\beta}$ for each company (Step #1) or fuel (Step #2) feeding the subsequent stochastic simulations.

## 4.2 Simulations of $\frac{V}{R}$ losses concerning benchmark and scenario

We run $MC = 10,000$ Monte-Carlo simulations of our stochastic model (*Step #3*) with an intensity default event defined in (6). This value has been fitted regarding the empirical standard deviation fluctuation of all historical data values.

[3] These preliminary steps have been executed in Gretl and stored in Excel spreadsheets. They are available for viewing in the data and codes attached to the article.

We begin by regarding the loss of values of each firm per unit of the reserve concerning the forecasting values with different values of the random default. We run forecasting simulations with the impact of default equal to 5%, 10%, 20% and 50% on the dynamic components.

The results for the different scenarios are given in Tables 5, 6, 7, 8 and 9.[4]

**** Insert Tables 5 to 9 about here ****

If we look at the scenario where 20% of oil & gas reserves become unburnable, we observe that each company will lose firms' values per unit of reserve at maturity 2050. *Total SA* will lose 84,21% of its value per unit of reserve and *EON* will lose 99,80% per unit of reserve so goes to bankruptcy.[5]

We observe that, if we increase the impact of the default event, each loss increases and so each company will lose a higher share of its values.

Regarding the scenario where oil-gas-coal reserves are unburnable (Tables 2 to 5), we can notice that with the weakest scenario (20% of reserves are unburnable, and only 5% of intensity of default), there are already 9/17 firms that go into bankruptcy before the maturity of 2050 with a probability higher than 80%. In the worst case, 67.92% of the firms will bankrupt before 2050 and 87.49%. If we take an intensity of environmental default event of 50% moreover, there are in this case 14/17 firms that go into bankruptcy. 11 of the 14 firms have a probability to go into bankruptcy higher than 95%.

Moving to the scenario dedicated to a 50% cut in fossil fuels price, most firms go into bankruptcy before the maturity of 2050. For a price cut of 25% and an intensity of default of 10%, there are still 9/17 firms which go into bankruptcy with a probability higher than 90%. This figure grows to 12/17 with an intensity of 50%, and 13/17 with the same intensity but with a price cut equals to 50%.

We demonstrate that if there is a cut in fossil fuels price, the firms' values per unit of reserve go down extremely quickly. It means that the solvency and the capital of this firms are very correlated to the fuel price. This means that their income comes for the most critical part of the change in the price of the fuel.

This could explain that with a scenario of a cut of 50% and a very low intensity of default, there are still 13/17 firms which go into bankruptcy with a probability higher than 80%, and 7

[4]Recall these numbers are projections of *Step #3* up to the 2050 horizon based on 2005-2015 calibration occurring in *Steps #1 and #2*.

[5]Bankruptcy is defined merely as the value of the firm (share price × number of shares) going to zero.

with a probability higher than 95%. When we look the worst case, we obtain a global probability of bankruptcy before 2050 of 91.92% of the studied firms, and in details 13/17 with a probability higher than 95% and 6 with one higher than 99%.

Economically speaking: firms are relying too much on incomes from fuel sales, and are adversely impacted by a downward trend in the fuel price. We may advance the following policy recommendation: develop alternative income sources that are not correlated with fuel prices; gear towards an energy model based on the consumption of renewables.

Trajectories for each company, depending on the carbon asset stranding scenario, are displayed in Figures 3 to 7.

**** Insert Figures 3 to 7 about here ****

## 4.3 Aggregated companies' market loss by scenario and default intensities

**** Insert Figure 8 about here ****

Figure 8 displays a summary of losses. We remark that:

- The loss increases when the asset stranding scenario is more stringent.
- Firms seem more dependent on fossil fuel price cuts than to their reserves becoming unburnable. Indeed, the scenario of a cut in fossil fuels price is more damaging for the firms' values per unit of reserve. This means that the number of firms which go into bankruptcy is higher in these scenarios than with scenarios where a percentage of oil-gas-coal reserves are unburnable.
- The probability of bankruptcy of firms increases with the intensity of default. The higher the probability of a shock in the value of the firm per unit of reserve, the worse the cash-flow of companies.

## 4.4 Link to the Earth's absorbing capacity: horizon 2050

We compute the contents in $CO_2$-equivalent of each firms' values regarding equation (1). Indeed $\frac{V}{R}$ corresponds to the value of the firm $V$ (share price $\times$ number of shares) divided by $R$ the total reserves in tonnes $CO_2$-equivalent. We go back to the amount of $CO_2$-equivalent in 2050 of the total reserves in ton with the straightforward calculus:

$$CO_2 - Equivalent_{2050} = \left( \frac{V/R}{\text{share price} \times \text{number of shares}} \right)^{-1}$$

Regarding the previous results we display the more optimistic scenario with an intensity default of 5%.[6]

**** Insert Table 10 about here ****

$R_t$ returns the sum of the column for the subset of 17 companies. Without carbon asset stranding, the benchmark scenario (whereby available reserves are burnt on a business-as-usual fashion, without changes in the business model of companies) results suggest the Earth's absorptive capacity is negatively impacted by 147.77Gt$CO_2$ (Table 8, $R_t$ row, first column), i.e., approximately one-quarter of the IEA 565Gt$CO_2$ scenario to meet the 2°C target.

On the other side of the spectrum, the most stringent carbon asset stranding scenario (e.g., 60% of oil-gas-coal reserves are unburnable), the Earth's absorptive capacity is only reduced by 55.56Gt$CO_2$ (Table 8, $R_t$ row, fourth column), i.e. a welcome 60% reduction of the GHG emitted for a path towards a sustainable future.

To complete the picture with respect to our theoretical framework, the last line of Table 10 reflects the actual extraction $q_t$ computed according to the coefficient estimates of Eq.(2) for each type of oil-gas-coal company:

$$\widehat{\text{ld\_q\_OIL\_CO2}} = \underset{(6{,}9326\text{e–}005)}{-5{,}93509\text{e–}005} + \underset{(0{,}0066826)}{0{,}986554}\,\text{ld\_ROIL\_CO2}$$

$$T = 123 \quad \bar{R}^2 = 0{,}9944 \quad F(1,121) = 21795, \quad \hat{\sigma} = 0{,}00076399$$

(standard deviation in parentheses)

[6] Further results are available upon request, but they are even more pessimistic

$$\text{ld\_q\_}\widehat{\text{GAS}}\text{\_CO2} = \underset{(0{,}00033524)}{0,000105676} + \underset{(0{,}0056906)}{0,468949}\,\text{ld\_RGAS\_CO2}$$

$$T = 123 \quad \bar{R}^2 = 0,9823 \quad F(1,121) = 6791,1 \quad \hat{\sigma} = 0,0037159$$

(standard deviation in parentheses)

$$\text{ld\_q\_}\widehat{\text{COAL}}\text{\_CO2} = \underset{(0{,}00029703)}{0,000149110} + \underset{(0{,}0078289)}{0,421504}\,\text{ld\_RCOAL\_CO2}$$

$$T = 123 \quad \bar{R}^2 = 0,9596 \quad F(1,121) = 2898,7 \quad \hat{\sigma} = 0,0032833$$

(standard deviation in parentheses)

Notice the coefficients on oil, gas, and coal depletion rates are positively related to oil, gas and coal reserves, respectively, as documented previously by Pickering (2008). This corroborates the validity of our empirical results.

Breaking down extraction by fossil fuel type reveals the same information as for reserves: departing from the standard scenario (145.77Gt$CO_2$), carbon asset stranding can dramatically dampen the impact of oil-gas-coal companies the Earth's absorptive capacity up to 80% reduction for the most $CO_2$-intensive fuel (coal equals 23.42Gt$CO_2$) in the most stringent stranding scenario.

Recall that our simulation exercises are only focused on a subset of 17 oil-gas-coal companies, henceforth the goal stated in the Paris COP 21 agreements of keeping global temperature rise to below 2 degrees Celsius need strict $CO_2$ emissions reductions. The World Bank (2016), in its latest *State and Trends of Carbon Pricing* report, describes a sense of urgency, with each passing day, the climate challenge grows.

# 5 Policy implications

*Of all the recent ideas climate change campaigners have come up with to convince the world to do more to curb global warming; none has been as potent as the concept of stranded fossil fuel assets.*

– The Financial Times (2015)

$CO_2$ emissions cuts rank very high in policy makers' agenda, as illustrated by the Paris COP-MOP 21 agreements in December 2015, and the subsequent ratification by China in 2016. The EU announced on October 7, 2016 that more than 50 states representing more than half of GHG had ratified the Paris agreements, only ten months after signature, thereby announcing the entry into force of the new international climate treaty[7].

Indeed, when dealing effectively with climate change, authorities attempt to regulate the consumption of carbon assets. The goal is to manage the expectation of investors, and avoid that the market misinterprets the energy transition. Taken together, limitations on future GHG emissions, substitution with other energy sources, and decreases in the overall demand for energy can financially affect the functioning of the energy sector.

Fixed assets that are locked into burning fossil fuels can become stranded in a carbon-constrained world (MSCI (2015)). For instance, consider the case of a coal-fired power plant, that is at risk of being stranded due to its high carbon-intensive content. If carbon emissions are constrained, the power plant is at risk of drastically losing value. The impact of asset stranding varies depending on the carbon exposure of the companies, and across portfolios. For a given company, its carbon exposure varies on two levels: *(i)* current emissions, and *(ii)* fossil fuel reserves representing potential future emissions. Various stakeholders are concerned about climate change and can exert pressure on the company to manage carbon stranded asset risks.

Potentially unburnable carbon is listed on stock exchanges, which is indicative of carbon risk mis-pricing. Companies listed on the London Stock Exchange ought to disclose mandatory carbon reporting. Germany has mostly shifted to renewable energy in 2014, causing hefty

[7]Although, the situation evolved somewhat unexpectedly with the intention of 45th President of the U.S., Donald Trump, to withdraw from the Paris agreements on climate change and to repeal the US Clean Power Act.

write-downs on coal- and gas-fired power plants: EUR 3.3 billion and EUR 4.5 billion for RWE and EON, respectively, whereas the French company GDF-Suez (now re-branded Engie) took a write-down of EUR 14.9 billion on its conventional power plants.

Institutional investors are also concerned about managing carbon risks in their portfolios. Divestment strategies are indeed visible from the investors' perspective. The Norwegian-Swedish pension fund Storebrand ($74bn of asset under management) excluded coal companies from its portfolios in early July 2013. In May 2014, Stanford University announced that its endowment fund would sell off its holdings in coal mining companies. In Sweden alone, the Fourth National Pension Fund, the Church of Sweden, AP3 as well as internationally the French Pension Fund FRR, KPA, APG in the Netherlands, GEPF in South Africa and the United Nations Joint Staff Pension Fund have taken similar steps towards low-carbon asset allocation (Worldbank (2014), Mercer (2014)). UNEP Finance Initiative and UN Secretary-General Ban Ki-Moon support the Portfolio Decarbonization Coalition that aims at reducing the carbon intensity of institutional investors' portfolio up to $100 billion by December 2015. Rebalancing stock holdings based on a higher allocation to carbon-efficient companies relative to their competitors is also gaining momentum among asset managers such as Amundi and MSCI. By construction, such carbon-tilted strategies offer less exposure to carbon risk.

The strong point of this paper is that it attempts to more formally model the risk of stranded assets rather than the previous policy-based studies. Therefore, our simulation results are particularly relevant to asset owners, banks, other financial intermediaries, businesses and governments. Investment strategies that are compatible with these simulations involve divesting from fossil fuels and moving towards a greener energy mix, for instance through investments in green indices (Cummins et al., 2014).

# 6 Conclusion

Carbon stranded assets can be defined as 'blocked assets' that have suffered from unanticipated or premature write-downs, devaluations for oil-gas-coal producing companies. Stranded assets are assets that become obsolete before their complete damping by business cycle or some factors (e.g., regulation, innovation). It results in losses of their market value because of market evolution, or risk to become unusable. For example, it can be the case of coal and hydrocarbon resources.

In the burgeoning field of climate finance, it makes sense to control as well the level of $CO_2$

emissions using asset stranding in order to alleviate the Earth's absorptive capacities. Carbon stranded assets strongly impact oil & gas companies' earnings and share price, thereby altering asset values and introducing significant investment planning discontinuities. In this paper, we show that the concept of carbon stranded assets leads to redefining risk for a sample of oil, gas and coal companies.

Concerning several carbon asset stranding scenarios, this paper develops a partial-equilibrium stochastic model with stopping times to display the firms' value (defined as the share price times the number of shares) of 17 major oil-gas-coal companies. The theoretical framework hinges on empirical specifications of the Hotelling rule from data retrieved from 2005 to 2015, extended by our simulations until the 2050 horizon. First, the valuation of oil, gas and coal companies is following Miller and Upton (1985) based on Hotelling's rule. Second, the oil reserves production relationship is established regarding previous work by Pickering (2008). The third step is to have a stochastic model with random stopping times and stochastic Poisson jumps in the environmental asset prices. The shocks to prices are exogenous.

The empirical calculations for 17 oil, gas and coal companies require extractions costs from the companies' accounts. As a preliminary analysis, principal components explain about 75% of the variation of the dataset. The scenarios considered are that, respectively, 20%, 40% and 80% of oil and gas reserves are unburnable and that, respectively, there is a 25% or 50% cut in fossil fuel prices.

In the absence of ambitious climate policies, the benchmark scenario implies that the Earth's absorptive capacity will be reduced by nearly 150 Gt-$CO_2$-equivalent by 2050, which represents about one-quarter of the IEA's 450ppm target for a subset of only 17 oil-gas-coal companies. With carbon asset stranding, the value of these firms is adversely affected, and in many cases ends up in bankruptcy (without a shift to clean energy, behavioral changes or innovation). 80% of $CO_2$-equivalent emissions can be avoided by restricting the use of coal and hydrocarbon resources.

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Table 1: List of Selected Oil, Gas & Coal Companies

| | Company | Market Cap (USD Billion) | EBIT in USD thousands | | |
|---|---|---|---|---|---|
| | | | **Dec 31, 2014** | **Dec 31, 2013** | **Dec 31, 2012** |
| 1 | *Exxon Mobil Corp* | 339,06 | 51,916,000? | 57,720,000? | 79,053,000 |
| 2 | *Petrochina* | 151,74 | 29,026,000? | 33,226,000? | 29,689,000 |
| 3 | *Chevron Corp* | 168,49 | 31,202,000? | 35,905,000? | 46,332,000 |
| 4 | *Royal Dutch Shell PLC* | 204,17 | 23,026,000? | 27,769,000? | 37,879,000 |
| 5 | *BP PLC* | 106,8 | 9,555,000? | 15,255,000? | 11,901,000 |
| 6 | *Total SA* | 115,96 | 16,579,000? | 25,249,000? | 30,596,000 |
| 7 | *Petrobras Brasileiro SA* | 32,55 | (4,901,000) | 16,083,000 | 16,509,000 |
| 8 | *CNOOC Ltd* | 52,65 | 14,070,000 | 13,926,000 | 14,730,000 |
| 9 | *Engie (GDF-Suez)* | 41,98 | 6,567,000 | 7,515,000 | 9,315,000 |
| 10 | *RWE* | 7,62 | 2,936,000 | 2,923,000 | 4,973,000 |
| 11 | *EON* | 18,44 | 4,562,000 | 4,835,000 | 5,180,000 |
| 12 | *China Shenhua* | 274,48 | 63,665,000 | 70,979,000 | 70,544,000 |
| 13 | *PEABODY* | 456 | (119,700) | (309,100) | 197,000 |
| 14 | *Huaneng Power* | 17,38 | 4,330,060?? | 4,164,284?? | 2,852,813 |
| 15 | *Datang* | 41,53 | 14,537,000?? | 15,887,000?? | 13,036,000 |
| 16 | *NTPC* | 1053,77 | 151,003,000?? | 144,433,000?? | 120,330,000? |
| 17 | *China Resources Power* | 36,64 | (1,038,000) | 2,676,000?? | 2,507,000?? |

Note: EBIT stands for Earnings Before Interest And Taxes.

Table 2: $CO_2$-equivalent conversion rates for oil-gas-coal reserves and extraction figures from U.S. EIA

| | U.S. EIA original unit | Conversion rate in tep | $CO_2$ content of the tep | $CO_2$ content of the original unit |
|---|---|---|---|---|
| Coal Reserves | billions of short tons | 0,619 tep per tonne | 1,123 tonne per tep | 695,13700 millions of tonnes per billions of short tons |
| Coal Extraction | millions of short tons | 0,619 tep per tonne | 1,123 tonne per tep | 0,69514 millions of tonnes per millions of short tons |
| Gas Reserves | 1000 bcf | 0,0242675 tep for 1000 cf | 0,651 tonne per tep | 15,79814 millions of tonnes for 1 000 bcf |
| Gas Extraction | bcf | 0,0242675 tep for 1000 cf | 0,651 tonne per tep | 0,01580 millions of tonnes for 1 bcf |
| Oil Reserves | billions of barrels | 0,14 tep per barrel | 0,83 tonne par tep | 116,20000 millions of tonnes per billions of barrels |
| Oil Extraction Power | millions of barrels | 0,14 tep per barrel | 0,83 tonne per tep | 0,11620 millions of tonnes per millions of barrels |
| Oil Extraction Industrial | millions of barrels | 0,14 tep per barrel | 0,83 tonne per tep | 0,11620 millions of tonnes per millions of barrels |
| Oil Extraction Commercial | millions of barrels | 0,14 tep per barrel | 0,83 tonne par tep | 0,11620 millions of tonnes per millions of barrels |

Note: tep stands for tonne equivalent petrol.

Table 3: Calibration: Step #1

| **Company** | **Beta** | **Sign of the Beta** | **Significance level** |
|---|---|---|---|
| EXXON | 2,88E-09 | + | - |
| PETROCHINA | 2,50E-08 | + | - |
| CHEVRON | 4,16E-09 | + | - |
| SHELL | 6,31E-09 | + | - |
| BP | 7,83E-09 | + | - |
| TOTAL | 4,05E-09 | + | - |
| PETROBRAS | 1,00E+00 | + | 1% |
| CNOOC | 3,14E-08 | + | - |
| ENGIE | 2,21E-08 | + | 1% |
| RWE | 8,10E-09 | + | - |
| EON | 2,06E-08 | + | 10% |
| CHINASHENHUA | 2,14E-09 | + | 10% |
| PEABODY | -8,90E-08 | - | - |
| HUANENG | 2,00E-08 | + | - |
| DATANG | 1,27E-09 | + | - |
| NTPC | 2,19E-08 | + | 1% |
| CHINARES | 4,39E-09 | + | - |

Table 4: Calibration: Step #2

| **Commodity** | **Beta** | **Sign of Beta** | **Significance Level** |
|---|---|---|---|
| COAL | -1,79E-04 | - | 1% |
| GAS | -1,41E-04 | - | 1% |
| OIL | -9,01E-03 | - | 1% |

Table 5: Scenario: 20% of oil & gas reserves are unburnable.

| | Company | **20% of oil & gas reserves are unburnable.** | | | |
|---|---|---|---|---|---|
| | | **5%** | **10%** | **20%** | **50%** |
| 1 | *Exxon Mobil Corp* | 0,2600 | 0,2535 | 0,2406 | 0,2028 |
| 2 | *Petrochina* | 0,7203 | 0,7805 | 0,8618 | 0,9562 |
| 3 | *Chevron Corp* | 0,1428 | 0,2742 | 0,4752 | 0,7832 |
| 4 | *Royal Dutch Shell PLC* | 0,1077 | 0,1089 | 0,1113 | 0,1186 |
| 5 | *BP PLC* | 0,6001 | 0,6530 | 0,7370 | 0,8777 |
| 6 | *Total SA* | 0,8421 | 0,8846 | 0,9356 | 0,9804 |
| 7 | *Petrobras Brasileiro SA* | 0,9926 | 0,9935 | 0,9950 | 0,9976 |
| 8 | *CNOOC Ltd* | 0,8469 | 0,9004 | 0,9537 | 0,9863 |
| 9 | *Engie (GDF-Suez)* | 0,6571 | 0,7203 | 0,8112 | 0,9325 |
| 10 | *RWE* | 0,8824 | 0,9001 | 0,9270 | 0,9678 |
| 11 | *EON* | 0,9980 | 0,9989 | 0,9996 | 0,9999 |
| 12 | *China Shenhua* | 0,8699 | 0,9155 | 0,9620 | 0,9921 |
| 13 | *PEABODY* | 0,9939 | 0,9959 | 0,9977 | 0,9984 |
| 14 | *Huaneng Power* | 0,9517 | 0,9677 | 0,9843 | 0,9957 |
| 15 | *Datang* | 0,9314 | 0,9373 | 0,9475 | 0,9687 |
| 16 | *NTPC* | 0,5301 | 0,5787 | 0,6598 | 0,8139 |
| 17 | *China Resources Power* | 0,7397 | 0,7949 | 0,8705 | 0,9607 |
| | Average | 0,6792 | 0,7148 | 0,7640 | 0,8310 |

Table 6: Scenario: 40% of oil & gas reserves are unburnable.

| | Company | **40% of oil & gas reserves are unburnable.** | | | |
|---|---|---|---|---|---|
| | | **5%** | **10%** | **20%** | **50%** |
| 1 | *Exxon Mobil Corp* | 0,1397 | 0,1427 | 0,1486 | 0,1662 |
| 2 | *Petrochina* | 0,7911 | 0,8226 | 0,8707 | 0,9437 |
| 3 | *Chevron Corp* | 0,4061 | 0,4690 | 0,5739 | 0,7715 |
| 4 | *Royal Dutch Shell PLC* | 0,3996 | 0,4001 | 0,4012 | 0,4044 |
| 5 | *BP PLC* | 0,6851 | 0,7132 | 0,7613 | 0,8578 |
| 6 | *Total SA* | 0,8634 | 0,8897 | 0,9266 | 0,9724 |
| 7 | *Petrobras Brasileiro SA* | 0,9958 | 0,9962 | 0,9968 | 0,9980 |
| 8 | *CNOOC Ltd* | 0,9098 | 0,9317 | 0,9589 | 0,9846 |
| 9 | *Engie (GDF-Suez)* | 0,7703 | 0,8000 | 0,8473 | 0,9264 |
| 10 | *RWE* | 0,8915 | 0,9035 | 0,9235 | 0,9602 |
| 11 | *EON* | 0,9982 | 0,9988 | 0,9993 | 0,9996 |
| 12 | *China Shenhua* | 0,9164 | 0,9370 | 0,9625 | 0,9884 |
| 13 | *PEABODY* | 0,9965 | 0,9976 | 0,9987 | 0,9990 |
| 14 | *Huaneng Power* | 0,9674 | 0,9756 | 0,9854 | 0,9940 |
| 15 | *Datang* | 0,9449 | 0,9474 | 0,9518 | 0,9623 |
| 16 | *NTPC* | 0,6837 | 0,7056 | 0,7446 | 0,8298 |
| 17 | *China Resources Power* | 0,7912 | 0,8213 | 0,8680 | 0,9416 |
| | Average | 0,7736 | 0,7913 | 0,8188 | 0,8647 |

Table 7: Scenario: 60% of oil & gas reserves are unburnable.

| | Company | 60% of oil & gas reserves are unburnable. | | | |
|---|---|---|---|---|---|
| | | **5%** | **10%** | **20%** | **50%** |
| 1 | *Exxon Mobil Corp* | 0,3648 | 0,3660 | 0,3682 | 0,3748 |
| 2 | *Petrochina* | 0,8286 | 0,8424 | 0,8667 | 0,9189 |
| 3 | *Chevron Corp* | 0,5089 | 0,5360 | 0,5855 | 0,7014 |
| 4 | *Royal Dutch Shell PLC* | 0,5571 | 0,5573 | 0,5577 | 0,5589 |
| 5 | *BP PLC* | 0,7559 | 0,7662 | 0,7852 | 0,8317 |
| 6 | *Total SA* | 0,8971 | 0,9072 | 0,9242 | 0,9569 |
| 7 | *Petrobras Brasileiro SA* | 0,9932 | 0,9935 | 0,9940 | 0,9953 |
| 8 | *CNOOC Ltd* | 0,9218 | 0,9316 | 0,9472 | 0,9738 |
| 9 | *Engie (GDF-Suez)* | 0,8285 | 0,8404 | 0,8616 | 0,9088 |
| 10 | *RWE* | 0,9372 | 0,9403 | 0,9459 | 0,9586 |
| 11 | *EON* | 0,9982 | 0,9984 | 0,9987 | 0,9992 |
| 12 | *China Shenhua* | 0,9263 | 0,9362 | 0,9521 | 0,9809 |
| 13 | *PEABODY* | 0,9967 | 0,9972 | 0,9979 | 0,9987 |
| 14 | *Huaneng Power* | 0,9675 | 0,9717 | 0,9782 | 0,9886 |
| 15 | *Datang* | 0,9635 | 0,9646 | 0,9667 | 0,9723 |
| 16 | *NTPC* | 0,7632 | 0,7717 | 0,7878 | 0,8289 |
| 17 | *China Resources Power* | 0,8492 | 0,8611 | 0,8819 | 0,9258 |
| | Average | 0,8269 | 0,8342 | 0,8470 | 0,8749 |

Table 8: Scenario: 25% cut in fossil fuels price.

| | Company | 25% cut in fossil fuels price. | | | |
|---|---|---|---|---|---|
| | | **5%** | **10%** | **20%** | **50%** |
| 1 | *Exxon Mobil Corp* | 0,4776 | 0,4786 | 0,4804 | 0,4859 |
| 2 | *Petrochina* | 0,8523 | 0,8645 | 0,8860 | 0,9325 |
| 3 | *Chevron Corp* | 0,6124 | 0,6344 | 0,6747 | 0,7701 |
| 4 | *Royal Dutch Shell PLC* | 0,6282 | 0,6283 | 0,6287 | 0,6296 |
| 5 | *BP PLC* | 0,8054 | 0,8144 | 0,8312 | 0,8725 |
| 6 | *Total SA* | 0,9165 | 0,9248 | 0,9387 | 0,9654 |
| 7 | *Petrobras Brasileiro SA* | 0,9934 | 0,9936 | 0,9941 | 0,9952 |
| 8 | *CNOOC Ltd* | 0,9383 | 0,9456 | 0,9573 | 0,9766 |
| 9 | *Engie (GDF-Suez)* | 0,8598 | 0,8698 | 0,8875 | 0,9272 |
| 10 | *RWE* | 0,9140 | 0,9170 | 0,9221 | 0,9316 |
| 11 | *EON* | 0,9992 | 0,9993 | 0,9994 | 0,9995 |
| 12 | *China Shenhua* | 0,9456 | 0,9536 | 0,9664 | 0,9887 |
| 13 | *PEABODY* | 0,9965 | 0,9971 | 0,9979 | 0,9987 |
| 14 | *Huaneng Power* | 0,9733 | 0,9767 | 0,9823 | 0,9922 |
| 15 | *Datang* | 0,9678 | 0,9687 | 0,9704 | 0,9750 |
| 16 | *NTPC* | 0,8107 | 0,8174 | 0,8299 | 0,8618 |
| 17 | *China Resources Power* | 0,8716 | 0,8811 | 0,8978 | 0,9341 |
| | Average | 0,8566 | 0,8626 | 0,8732 | 0,8963 |

Table 9: Scenario: 50% cut in fossil fuels price.

| | **Company** | **50% cut in fossil fuels price.** | | | |
|---|---|---|---|---|---|
| | | **5%** | **10%** | **20%** | **50%** |
| 1 | *Exxon Mobil Corp* | 0,4841 | 0,4859 | 0,4895 | 0,5000 |
| 2 | *Petrochina* | 0,8637 | 0,8849 | 0,9175 | 0,9674 |
| 3 | *Chevron Corp* | 0,6341 | 0,6723 | 0,7362 | 0,8569 |
| 4 | *Royal Dutch Shell PLC* | 0,6337 | 0,6341 | 0,6347 | 0,6367 |
| 5 | *BP PLC* | 0,8324 | 0,8474 | 0,8731 | 0,9241 |
| 6 | *Total SA* | 0,9121 | 0,9284 | 0,9513 | 0,9802 |
| 7 | *Petrobras Brasileiro SA* | 0,9957 | 0,9959 | 0,9963 | 0,9973 |
| 8 | *CNOOC Ltd* | 0,9403 | 0,9545 | 0,9726 | 0,9905 |
| 9 | *Engie (GDF-Suez)* | 0,8583 | 0,8772 | 0,9072 | 0,9574 |
| 10 | *RWE* | 0,9520 | 0,9573 | 0,9660 | 0,9821 |
| 11 | *EON* | 0,9992 | 0,9994 | 0,9997 | 0,9999 |
| 12 | *China Shenhua* | 0,9532 | 0,9652 | 0,9802 | 0,9953 |
| 13 | *PEABODY* | 0,9988 | 0,9992 | 0,9996 | 0,9996 |
| 14 | *Huaneng Power* | 0,9743 | 0,9813 | 0,9898 | 0,9979 |
| 15 | *Datang* | 0,9743 | 0,9757 | 0,9784 | 0,9846 |
| 16 | *NTPC* | 0,7925 | 0,8070 | 0,8327 | 0,8894 |
| 17 | *China Resources Power* | 0,8790 | 0,8966 | 0,9239 | 0,9666 |
| | Average | 0,8634 | 0,8743 | 0,8911 | 0,9192 |

Table 10: Earth absorbing capacity for each firms and scenarios at the horizon 2050 (in Giga-Tonne of $CO_2$)

| | Company | Scenarios | | | | | |
|---|---|---|---|---|---|---|---|
| | | Benchmark | Oil-Gas-Coal reserves are unburnable | | | Cut in fossil fuels price | |
| | | | 20% | 40% | 60% | 25% | 50% |
| 1 | Exxon Mobil Corp | 15.74 | 9.28 | 12.49 | 6.12 | 15.63 | 15.50 |
| 2 | Petrochina | 8.41 | 4.95 | 6.66 | 3.27 | 8.30 | 8.23 |
| 3 | Chevron Corp | 10.49 | 6.17 | 8.32 | 4.08 | 10.38 | 10.30 |
| 4 | Royal Dutch Shell PLC | 10.50 | 6.18 | 8.32 | 4.09 | 10.39 | 10.29 |
| 5 | BP PLC | 8.38 | 4.95 | 6.65 | 3.27 | 8.32 | 8.25 |
| 6 | Total SA | 9.47 | 5.56 | 7.49 | 3.68 | 9.37 | 9.28 |
| 7 | Petrobras Brasileiro SA | 3.15 | 1.86 | 2.50 | 1.23 | 3.13 | 3.09 |
| 8 | CNOOC Ltd | 10.51 | 6.18 | 8.31 | 4.08 | 10.41 | 10.29 |
| 9 | Engie (GDF-Suez) | 5.47 | 3.05 | 4.13 | 1.98 | 5.30 | 5.13 |
| 10 | RWE | 5.53 | 3.02 | 4.25 | 1.98 | 5.24 | 5.10 |
| 11 | EON | 2.11 | 1.18 | 1.62 | 0.76 | 2.02 | 1.95 |
| 12 | China Shenhua | 15.21 | 8.62 | 11.80 | 5.46 | 14.86 | 14.36 |
| 13 | PEABODY | 15.13 | 8.51 | 11.89 | 5.49 | 14.80 | 14.09 |
| 14 | Huaneng Power | 2.51 | 1.43 | 1.95 | 0.92 | 2.44 | 2.35 |
| 15 | Datang | 5.00 | 2.82 | 3.88 | 1.79 | 4.81 | 4.63 |
| 16 | NTPC | 15.15 | 8.54 | 11.83 | 5.56 | 14.78 | 14.25 |
| 17 | China Resources Power | 5.00 | 2.79 | 3.80 | 1.81 | 4.82 | 4.62 |
| | $R_t$ | 147.77 | 85.08 | 115.89 | 55.56 | 145.01 | 141.72 |
| | $q_{t,oil}$ | -145.78 | -83.93 | -114.33 | -54.81 | -143.06 | -139.81 |
| | $q_{t,gas}$ | -69.29 | -39.90 | -54.35 | -26.05 | -68.00 | -66.46 |
| | $q_{t,coal}$ | -62.28 | -35.86 | -48.85 | -23.42 | -61.12 | -59.74 |

Figure 1: Principal Component Analysis on $\frac{V}{R}$

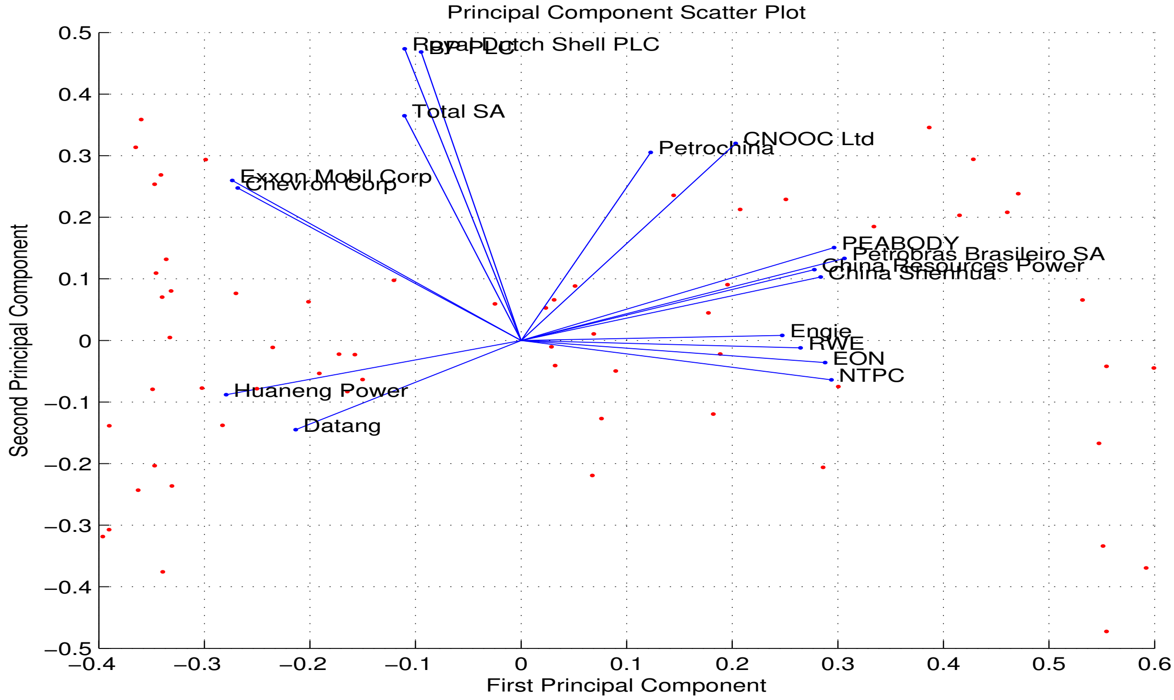

Figure 2: Total variance explained by the components of the PCA.

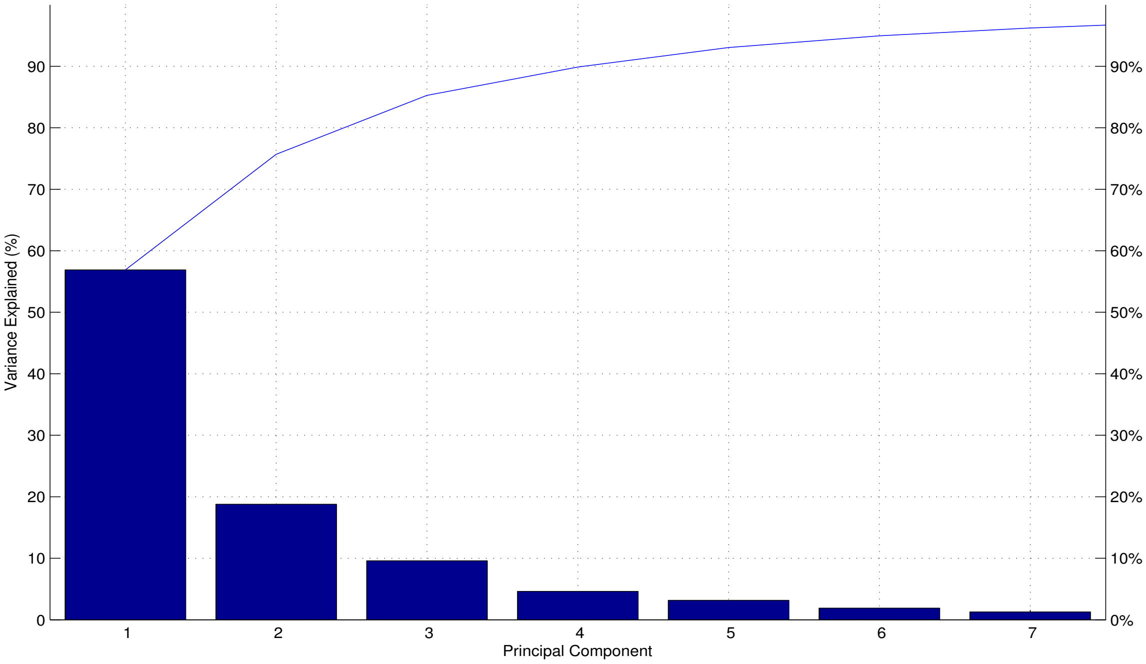

Figure 3: Scenario: 20% of oil & gas reserves are unburnable.

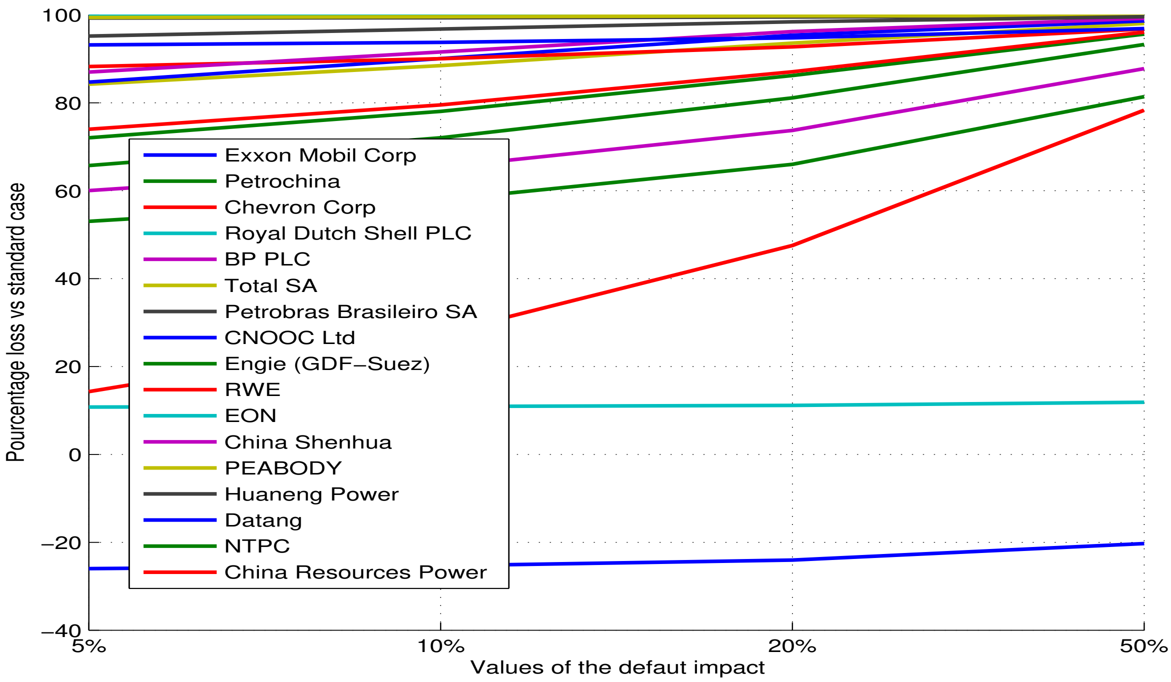

Figure 4: Scenario: 40% of oil & gas reserves are unburnable.

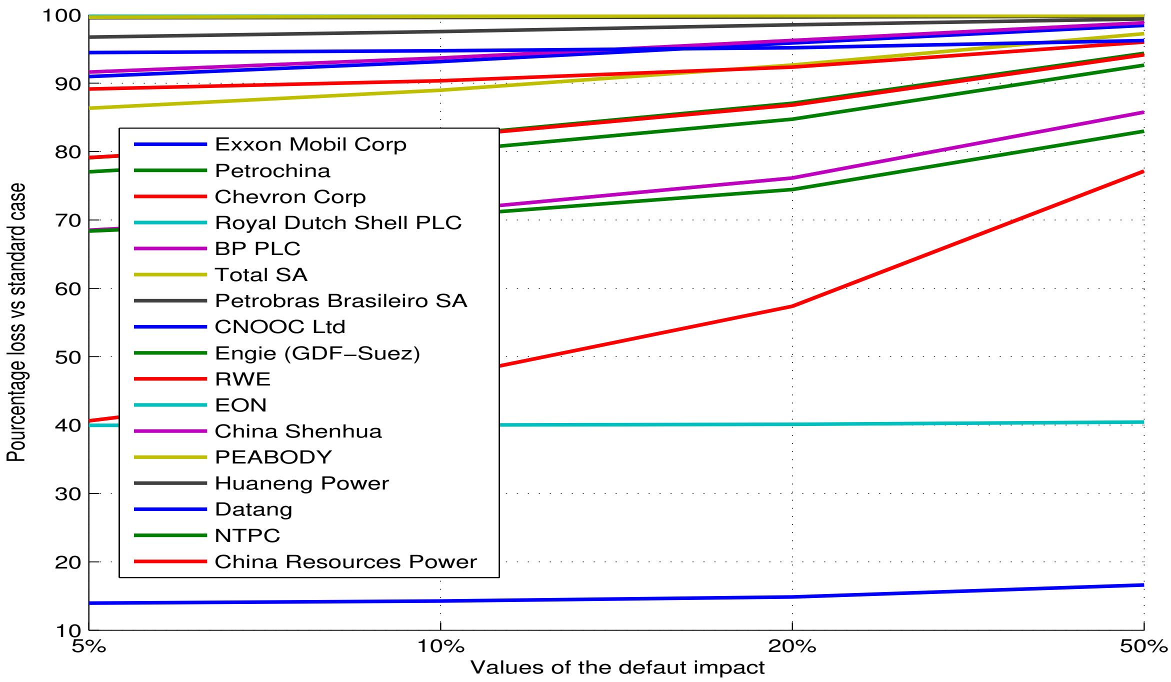

Figure 5: Scenario: 60% of oil & gas reserves are unburnable.

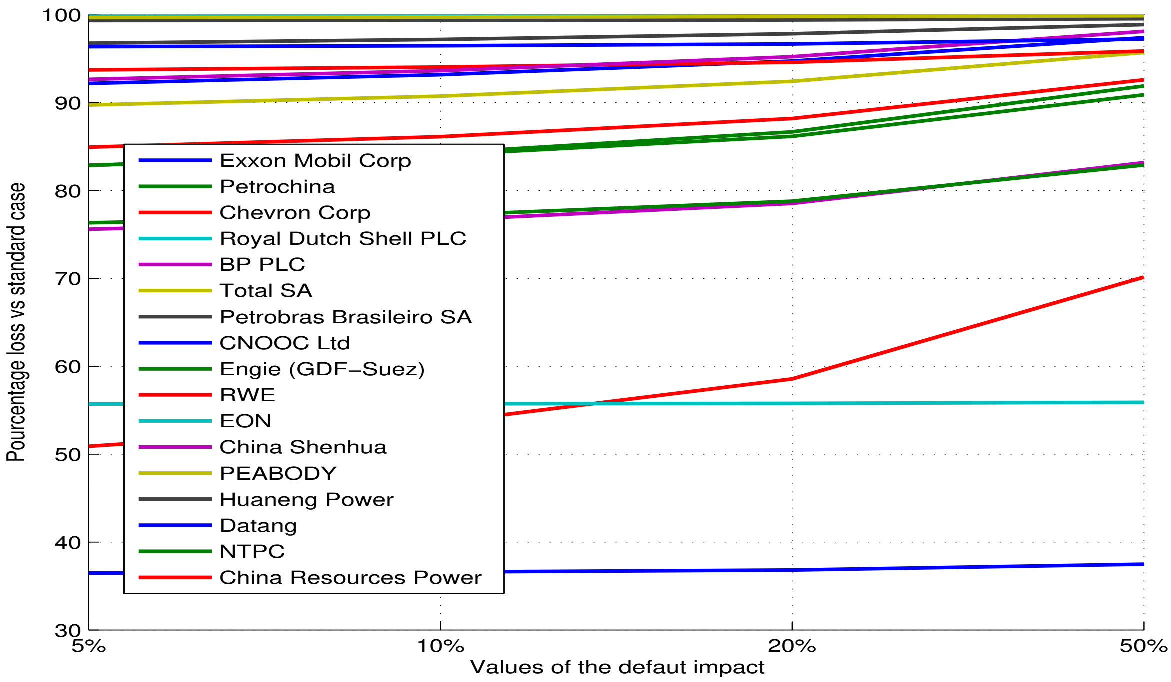

Figure 6: Scenario: 25% cut in fossil fuels price.

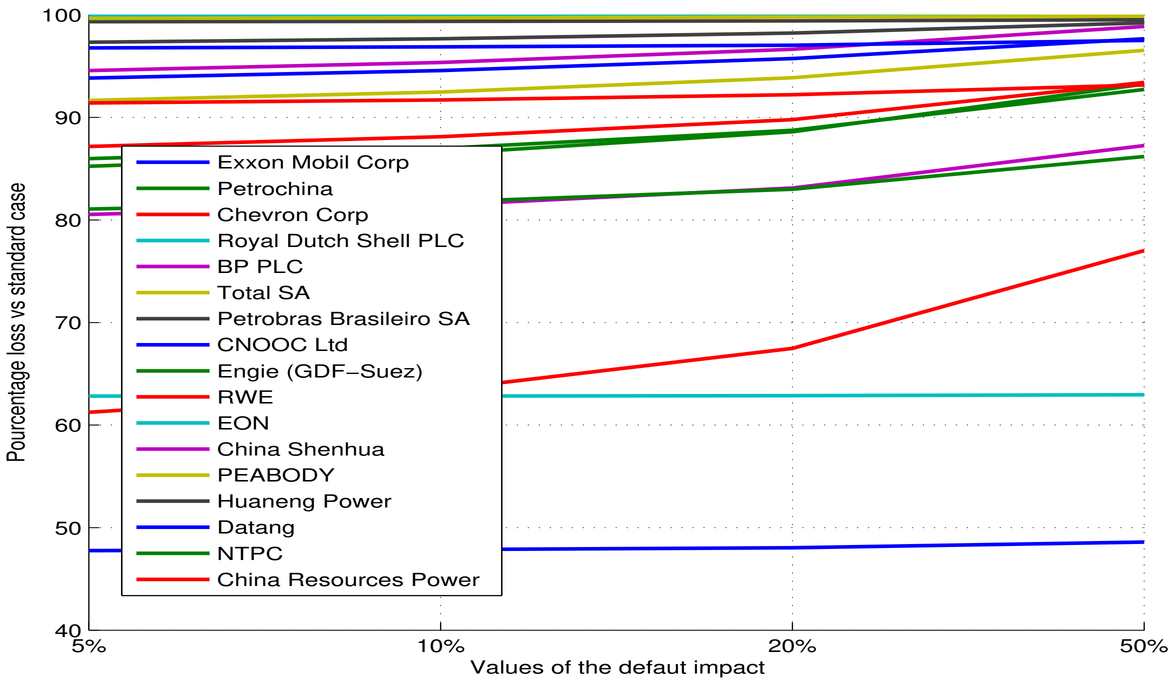

Figure 7: Scenario: 50% cut in fossil fuels price.

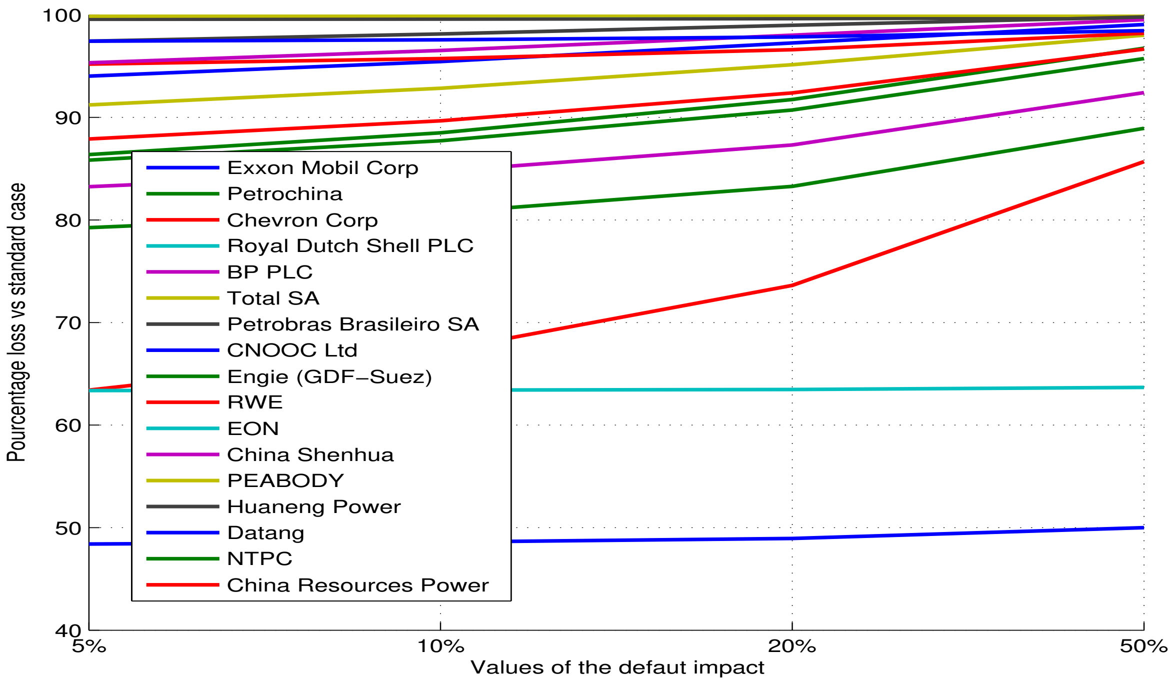

Figure 8: Loss with respect to standard case regarding intensity of default.