Pollutant versus non-pollutant generation technologies: a CML-analogous analysis

Paulino Martinez-Fernandez[1,3]
Fernando deLlano-Paz[1] ·
Anxo Calvo-Silvosa[1] ·
Isabel Soares[2]

Abstract In this work, we apply the Modern Portfolio Theory and the Capital Assets Pricing Model financial tools to a portfolio of CO_2-emitting generation technologies under diverse scenarios. We will calculate the efficient—in the sense of having the minimum risk for a given level of emissions—portfolios frontier. The Capital Market Line (CML) is the place where all the possible combinations of a specific efficient portfolio and a pollution-free portfolio—made up with nuclear and renewable generation technologies—lie. In Finance, that specific efficient portfolio is called the market portfolio but we will see that in our case it lacks an evident meaning. Therefore, we will explain which should be the reference portfolio for power generation planning analysis. Anyway, the fact is that those combinations are less pollutant than the portfolios in the efficient frontier. Thus, a policy-maker can analyse which is their effect on emissions reduction. We will start analysing the efficient pollutant generation portfolios. Then, we will introduce the CML-analogous lines (CML-A) to allow the possibility of reducing emissions by combining an efficient portfolio with a non-pollutant portfolio—this non-pollutant portfolio is free of both emissions and risk. Results support the necessity of considering the carbon capture and storage technol- ogy to achieve a less risky generation mix, with less emissions and allowing a higher diver- sification due to the presence of cleaner fossil fuel technologies. All of that leads to better levels of energy security.

Keywords Emissions · Power generation portfolios · Portfolio theory · Capital Market Line

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[1] Department of Business, Faculty of Economics and Business, University of A Coruna, A Coruña, Spain

[2] Faculty of Economics and CEF.UP, University of Porto, Porto, Portugal

[3] Faculty of Economics and CEF.UP, Universidade da Coruna, Campus de Elvina, 15071 A Coruña, Spain

1 Introduction and literature overview

The energy security of a territory depends on the design of its energy portfolio (Vivoda 2009; EC 2011; Winzer 2012; deLlano-Paz et al. 2016a, 2017). This includes both the generation technologies used, the energy sources and resources and those means used for its transport. A State has three different ways of reducing the risk of power supply disruption. It can diversify the available generation technologies, the energy resources—by type, or by origins if they must be imported—and the means that bring those resources (Awerbuch and Yang 2007; Allan et al. 2011; Bhattacharya and Kojima 2012; Vithayasrichareon and MacGill 2012a; Escribano Francés et al. 2013; Kumar et al. 2015; deLlano-Paz et al. 2017). In fact, the relative weight of fossil fuels in the power supply portfolio is a critical variable when talking about supply disruption risk (Tlili 2015). Bhattacharya and Kojima (2012) point that the increase in the price of fossil fuels and its variability might negatively affect the macroeconomic structure of a country, through inflation and unemployment. On the other side, we have the positive effect on the supply security and on the energy dependency levels of having renewable energy sources (RES) in the generation portfolio (Dincer 2000; Uddin et al. 2010; Pan- war et al. 2011; Escribano Francés et al. 2013; Johansson 2013).

According to these ideas, the design of the energy portfolio of a territory is one of the most important instruments available to a State for defining and implementing its energy plans and hence, for reaching an adequate level of energy security (Awerbuch and Berger 2003; Awerbuch 2006; Awerbuch and Yang 2007; Allan et al. 2011; Nath and Behera 2011; Grijó and Soares 2016; deLlano-Paz et al. 2016a). Additionally, influ- encing the energy consumption through measures to increase energy savings and energy efficiency can help a territory to improve its GDP (EC 2014; Magazzino 2015). The aim should be, therefore, a secure access to the resources, on a stable basis and at competitive costs, which would include both economic, social and environmental dimensions (Dincer 2000; Kruyt et al. 2009; Escribano Francés et al. 2013; Tlili 2015).

Energy planning can be seen as an investment selection problem and presented in terms of portfolio design for a long-term perspective (Markowitz 1952; Lesser et al. 2007; Awerbuch et al. 2008; Krey and Zweifel 2008; Zhu and Fan 2010; Roques et al. 2010; Delarue et al. 2011; Gökgöz and Atmaca 2012). One of the most important and widely used methodologies to determine the optimal electricity generation portfolio is the financial Modern Portfolio Theory (MPT), developed by Markowitz (1952), one of the 1990 Nobel Memorial Prize winner economists. According to the MPT, there is a trade-off between return and risk—measured, for instance, by the variance in the returns of an asset. This trade-off makes possible to draw a line in a coordinate axis that rep- resents the combinations of return and risk that are efficient in the sense that they offer the minimum risk for a given level of return or the maximum return for a given level of risk. This line is the efficient portfolios frontier or simply the efficient frontier. When MPT is applied to electricity generation portfolios, it is usual in the literature to take into account not the return but the cost of the technologies and its risk (Awerbuch and Yang 2007; Awerbuch et al. 2008). Therefore, the efficient frontier will be the set of generation portfolios with minimum cost for a given level of risk or with minimum risk for a given level of cost. Awerbuch et al. (2008) reinforce the utility of the MPT for the policy-maker, as it allows to legislate attending the double objective of maximising both the efficiency of the generation portfolio and the energy security level

(Zhu and Fan 2010).

Using the MPT for optimisation of the power generation portfolio offers a multiple perspective approach as it includes different points of view. First, it deals with the electricity production cost assumed by the society for generating and using energy—electricity—. Second, it tackles the exposure assumed by the society to the eventual risk of power supply disruption. Finally, it tears into the economy dependence on external resources, as well as into the social and environmental cost involved in the energy management and the use of the available technologies. In line with these ideas, Panwar et al. (2011) and Vijayavenkataraman et al. (2012) include the social commitment of responsible economies, the efficient employment of the resources and the reduction of pollutant emissions. Göll and Thio (2008) remark the relationship between strategic sustainable goals and institu- tional-specific policies. Cutlip and Fath (2012) analyse how to search for environmentally responsible measures to achieve emission reduction goals. For all these reasons, working in designing efficient portfolios that allow achieving environmental and social aims—lower assumed costs and risks—drives to better levels of energy security and allows achieving cost-effective regulation (Das and Sengupta 2011).

Authors as Jansen et al. (2006), Awerbuch and Yang (2007), Roques et al. (2008) or Westner and Madlener (2010) started to include CO_2 emission in portfolio optimisation models. These approaches include, besides the cost and risk efficiency dimensions, the environmental dimension, by considering the emission costs derived from power generation (Jansen et al. 2006; Awerbuch and Yang 2007; Roques et al. 2008; Arnesano et al. 2012; Lynch et al. 2013; Gao et al. 2014; deLlano-Paz et al. 2015, 2016b; Cucchiella et al. 2016). We can also find proposals performing a sensibility analysis to study the impact on the results of variations in the emission price (Jansen et al. 2006; Awerbuch and Yang 2007; Roques et al. 2008; Vithayasrichareon and MacGill 2012b). In addition, other authors analyse the impact on the results of adding constraints to the optimisation model (Kumar et al. 2015; deLlano-Paz et al. 2015; Jano-Ito and Crawford-Brown 2017).

Chuang and Ma (2013) state that the establishment of emission reduction objectives considers the diverse components of the energy problem: energy security, economic devel- opment, technologic innovation and environmental protection. To achieve those objectives, an important presence of renewable technologies is required (Awerbuch and Berger 2003; Jansen et al. 2006; Awerbuch and Yang 2007; Zhu and Fan 2010; deLlano-Paz et al. 2015, 2017). The indigenous or domestic character of renewable sources allows to reduce the energy dependence (Dincer 2000; Panwar et al. 2011; Escribano Francés et al. 2013). As a result, the power supply security is improved due to the reduction of an eventual disruption triggered by geopolitical reasons (Chuang and Ma 2013; Escribano Francés et al. 2013).

Following these research lines, we will work with a set of CO_2-emitting technologies—coal, coal with CCS (carbon capture and storage), natural gas, natural gas with CCS, oil and biomass—to build up different pollutant portfolios. For each one of these, we will draw the efficient frontier or the set of portfolios that show the lower emission factor for a given level of risk or, alternatively, the lower risk for a given emission factor. For doing that, we use the average emission factor for each one of the technologies involved and the standard deviation of that emission factor (deLlano-Paz et al. 2015, 2016a, b). As in the MPT, we assume that the standard deviation is a good measure of the risk of the emission. In other words, the emission variability gives us the risk of the emissions. We will use the MPT optimisation model to calculate the efficient frontier.

The MPT was evolved by William Sharpe (1963, 1964)—another of the 1990 Nobel Memorial Prize winner economists, together with Markowitz—and others (Treynor 1961; Lintner 1965) whom gave up the Capital Assets Pricing Model or CAPM. The CAPM states that the expected return of a financial asset is the sum of the risk-free return—that return coming from a treasury bond, for instance—and the product of the beta of the asset and the market risk premium. The lower the beta, the lower the risk of the asset and vice versa. The CAPM also brought along the Capital Market Line or CML. In the set of efficient portfolios—the efficient frontier—one portfolio shows the highest rate between expected risk premium and risk. In other words, among the whole set of efficient portfolios, that portfolio is the best efficient portfolio (Brealey and Myers 2003) in the sense that any combination of this portfolio with risk-free assets offers better returns for any level of risk. That efficient portfolio is the market portfolio. In Finance, it is also known as the tangency portfolio because it can be found by drawing the line with the steeper slope that connects the risk-free return and the efficient frontier. In fact, this line—the CML—is tangent to the frontier in the tangency portfolio. When defining the risk-free asset, we follow the proposals from Awerbuch (2000), Awerbuch and Berger (2003) and Escribano Francés et al. (2013) with respect to the consideration of renewable technologies as risk-free technologies. Awerbuch and Berger (2003) contemplate the generation costs of renewable technologies as fixed costs, constant and known a priori. In effect, renewable technologies do not depend on any fuel, whose prices are eventually subject to a high variability. In fact, Awerbuch (2000) define the renewable technologies as passive technologies, since their activity costs and their non-activity costs are similar. Due to the consideration of the renewable technologies as risk-free assets, their representation in an emission–risk coordinate axis is in the coordinate origin—implying no emission and no risk. We can draw a line connecting this point and any portfolio in the generation portfolios efficient frontier. Portfolios lying on this line result from a specific mixture of non-pollutant—the coordinate origin—and pollutant technologies—the portfolio in the efficient frontier. Portfolios in this line and near the coordinate origin imply a higher proportion of non-pollutant technologies while those away from the coordinate origin imply a higher proportion of pollutant technologies. In any case, it is easy to see that the portfolios in the line offer lower emissions than those in the efficient frontier for every level of risk. When dealing with financial assets, the efficient frontier is represented in a return–risk coordinate axis and, therefore, the efficient frontier is concave. Due to this concavity, it is possible to find the efficient portfolio that corresponds to the tangency point of the line and the efficient frontier. That tangency point is referred to as the market portfolio or tangency portfolio. In our case, and due to the convexity of the emission–risk efficient frontier, the market portfolio does not exist. Therefore, we will try to find another portfolio or set of portfolios that constitute a reference point for the power planning analysis.

The main contribution of this study lies in the application of the CAPM methodological proposal to a CO_2-emitting generation technologies portfolio. Pollutant technologies are characterised from their average emission factor and their risk. Renewable technologies play the role of emission-free and risk-free technologies, in the same way than the risk-free asset in the financial CAPM approach. Following this proposal, we will obtain the emis- sion–risk efficient participation shares of the different technologies in the power generation portfolio.

Another contribution of this work focuses on the analysis of the positive impact—from an energy risk and energy security perspective—of the presence of CSS technologies in the power generation portfolio.

The article is organised as follows: In the second section, we develop the empirical model. The third section describes the scenarios and shows the results for each of them. Finally, the fourth section presents the conclusions and the policy implications of this work.

2 Empirical model: pollutant portfolios efficient frontier

2.1 Model description

Let x_i be the participation share of the technology i in the generation portfolio P. The expected portfolio emission factor, f_P, can be calculated as in the following equation, where f_i is the emission factor for technology i—based on deLlano-Paz et al. (2015, 2016a, b) and Lucheroni and Mari (2017). In turn, is the number of generation technologies involved in the model.

$$E(f_P) = \sum_{i=1}^{n} x_i f_i$$

Regarding the emission risk of the portfolio P, $(J_P$, it can be calculated as

n

$$\sigma_P = \left(\sum_{i=1}^{n} x_i^2 \sigma_i^2 + 2 \sum_{1 \le i < j \le n} x_i x_j \sigma_{ij} \right)^{\frac{1}{2}}$$

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$x_i x_j \sigma_{ij}$

In this equation, $(J_i^2$ represents the variance of the emission of technology i . In turn, $(J_{ij}$ is the covariance between the emission of technologies i and j. Remind that the Pearson coef-
ficient of correlation, , is related to the covariance through the expression $_{ij}$ $=\frac{ij}{}$.

Therefore, the last equation can be rewritten
as

$$\sigma_P = \left(\sum_{i=1}^{n} x_i^2 \sigma_i^2 + 2 \sum_{1 \le i < j \le n} x_i x_j \rho_{ij} \sigma_i \sigma_j \right)^{\frac{1}{2}},$$

where $(J_i$ is the standard deviation of technology i emission.

If we denote by the $n \times 1$ vector containing the weights of the technologies in the portfolio P, by F the $n \times 1$ vector containing the emission factors of the technologies and by S the emission variances–covariances matrix, we can rewrite these expressions in a more compact matrix notation—where the superscript t corresponds to the transposition operation—as

$$E(f_P) = x^t F \text{ with } x, \quad F \in \mathbb{R}^n$$

for the expected emission factor, and

$$\sigma_P = \left(x^t S x\right)^{\frac{1}{2}} \text{ with } x \in \mathbb{R}^n, \quad S \in \mathbb{R}^{n \times n}$$

for the portfolio risk. Matrix *S* is a symmetric matrix that contains the variances of the technologies emission in its diagonal. The rest of the elements of the matrix are the respective covariances between technologies emission.

Our problem is to minimise the portfolio emissions risk, subject to a couple of technical restrictions: every weight must be positive, and the weights must sum up to one:

$$\min \sigma_p = \min(x^t S x)^{\frac{1}{2}}, \text{ subject to:}$$
$$\begin{cases} x_i \geq 0, \forall i \\ \sum_{\forall i} x_i = 1 \end{cases}$$

The solution of this optimisation problem gives us the weights of the technologies in the so-called global minimum variance—GMV—portfolio. From this portfolio, we calculate the efficient frontier by adding the constraint

$$x^t F = k,$$

where *k* takes values from the GMV portfolio emission factor to the emission factor of the least pollutant technology—in our case, this technology is the biomass. Notice that a portfolio made up only of biomass will have the same emission factor than the biomass technology itself as in that portfolio $x_{\text{Biomass}} = 1$ and $x_i = 0$, $\forall i \neq$ Biomass. Notice also that it is not possible to build a portfolio with less emission than the least pollutant technology— although it is possible to build a portfolio with less risk than the least risky technology due to the correlations among technologies. In our model, the least pollutant technology determines the lower emission limit because we are not including additional constraints.

Additional constraints could change this assertion. The change in the emission factor must be always upwards—for instance, if we impose a maximum participation of the least pollutant technology, the portfolio emission factor must be higher than the emission factor of a portfolio composed only of the least pollutant technology.

In Finance, there is a point, inside the efficient frontier that shows the highest return factor per unit of risk. That point is the market portfolio or the tangency portfolio as it is the common point—hence a tangency point—between the efficient frontier and the CML—the place in the coordinate plane where the combinations between the market portfolio and the risk-free portfolio lie. In our case and due to the shape of the efficient frontier—it is convex, and in financial MPT, it is concave as it shows the expected returns of the financial assets portfolios—we cannot find a unique market or tangency portfolio. However, we can find a plane region that we consider analogous to the CML as it contains combinations between an efficient portfolio and the risk-free portfolio. This efficient portfolio must be either the one with the lower emission factor—that is the portfolio that contains only the technology with the lower emissions in each model—or the GMV portfolio, depending on the searched aim—minimise the emission given a level of risk or minimise the risk given a level of emission, respectively. Those combinations have the characteristic of emitting less CO_2 than the efficient portfolios for every level of risk or showing less risk than the efficient portfolios for every emission factor.

2.2 Model data

We start with six CO_2-emitting technologies: coal, coal with CCS, natural gas, natural gas with CCS, oil and biomass. Hence, *n* = 6. In this set of technologies, we include traditional pollutant technologies and even a renewable technology. Each one of the pollutant technologies is characterised by its emission factor and its risk. The variability of the emis- sion factor measured by its standard deviation is the measure of the emission risk. Table 1 shows the average levels of emissions and the standard deviation of these emissions. In the table, the values of the emission factors are calculated with data gathered from Bennink et al. (2010) while for the standard deviations of CO_2 we use the CO_2 emission costs stand- ard deviation obtained on the basis of Awerbuch and Yang (2007) and deLlano et al. (2015, 2016a, b) data.

In Table 1, we can see that the most CO_2-pollutant technologies are the coal, the oil and the natural gas. On the other hand, biomass is the technology with less CO_2 emission. In turn, technologies with the highest risk coincide with those with the highest CO_2 emission: coal, oil and natural gas.

Table 1 Average emission factors and emission standard deviations per technology. *Source*: Authors’ own calculations based on data gathered from Bennink et al. (2010), Awerbuch and Yang (2007), and deLlano et al. (2015, 2016a, b)

Technology	Emission factor (kg/ MWh)	SD
Coal	734.09	4.77
Coal with CCS	101.00	0.66
Natural gas	356.07	2.31
Natural gas with CCS	48.67	0.32
Oil	546.46	3.55
Biomass	1.84	0.01

With the average emission factors and the standard deviations, we generated 100,000 normal values for each technology. We used values generated to calculate the variances–covariances matrix shown in Table 2—in the table, the diagonal values are the variances for each technology, while the rest of the cells show the covariance between the technology in the corresponding row and the technology in the corresponding column. As stated before, the matrix is symmetric. With this, we incorporate the relationship between the emissions of every two technologies to the model.

3 Results

We will initially work with four scenarios in order to find the efficient technologies combinations: scenario 1 works with the six pollutant technologies considered; scenario 2 takes the CCS technologies out of the considered technologies set; scenario 3 works again with the CCS technologies but without the biomass; and finally, scenario 4 works without both the CCS technologies and the biomass.

In Fig. 1, we see the GMV technologies weights for each one of the scenarios. Notice that when we include the biomass in the scenario technologies set, it takes the lion’s share in the GMV portfolio—99.88% in scenario 1 and 100% in scenario 2. This is not a surprise as the biomass is the least CO_2-emitting technology and it has the lower emission risk (see Table 1). Due to this, the biomass is the preferred technology when trying to minimise portfolio emissions. But attending to energy security technical reasons and to the importance of diversification (Awerbuch and Yang 2007; Kruyt et al. 2009; Allan et al. 2011; Bhattacharya and Kojima 2012; Escribano Francés et al. 2013; Kumar et al. 2015; deLlano-Paz et al. 2017), we take this technology out of scenarios 3 and 4. By doing so, we

Table 2 Variances–covariances matrix. Source: Authors’ own calculations

	Coal	Coal with CCS	Natural gas	Natural gas with CCS	Oil	Biomass
Coal	22.8462	− 0.0144	− 0.0210	− 0.0034	− 0.0044	0.0001
Coal with CCS	− 0.0144	0.4369	0.0042	0.0005	0.0072	0.0001
Natural gas	− 0.0210	0.0042	5.2990	− 0.0015	0.0026	− 0.0000
Natural gas with CCS	− 0.0034	0.0005	− 0.0015	0.1020	0.0022	− 0.0000
Oil	− 0.0044	0.0072	0.0026	0.0022	12.5947	0.0001
Biomass	0.0001	0.0001	− 0.0000	− 0.0000	0.0001	0.0001

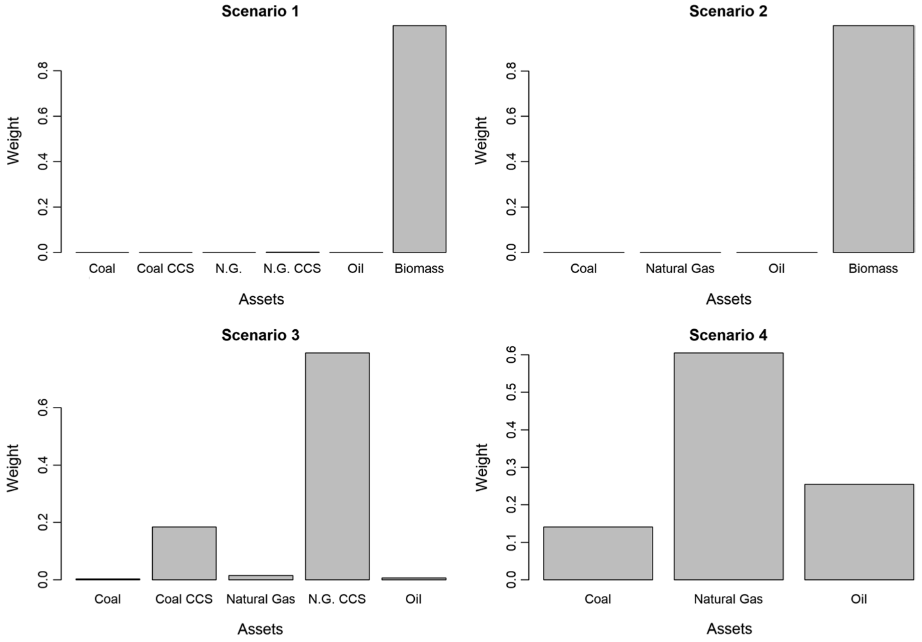

Fig. 1 GMV portfolios composition. *Source*: Authors' own calculations

can let the other technologies to enter into the solution, we can increase the level of diversi- fication and we can reduce the risk of power supply disruption.

In scenario 1, the low levels of correlation between biomass and the other technologies make possible the entrance—only testimonial—of the CSS technologies in the GMV port- folio—0.01% the coal with CCS and 0.11% the natural gas with CSS. Notice that the CSS technologies are the least pollutant after the biomass. We can see in Table 1 that not coinci- dentally, the second least pollutant technology is natural gas with CSS while coal with CSS is the third one. Moreover, the CSS technologies are just after the biomass if we look at the standard deviation. On the other hand, scenarios 1 and 2 results exclude the technologies with the higher risk—measured by their standard deviations—(coal, oil and natural gas) from the GMV portfolio. Notice that these technologies are also the most pollutant ones.

As stated, we calculate the risk associated with different portfolios with emission factor between the GMV portfolio and a 100% biomass—the technology with the lower emission factor—portfolio to build the efficient frontier. In scenarios 1 and 2, the 100% biomass portfolio is identical or practically identical to the GMV portfolio and, due to this reason, the efficient frontier is composed of a very limited set of portfolios and, in the practice, it does not exist at all. The model clearly points to the biomass as the preferred pollutant technology.

Assuming that the results obtained for scenarios 1 and 2 are completely unsatisfactory either from a technical point of view or from an energy security point of view, we will focus on scenarios 3 (with oil, coal, natural gas and CCS technologies but without the biomass) and 4 (with only oil, coal and natural gas). Table 3 contains a summary of the GMV portfolio for these scenarios.

In scenario 3, most of the GMV portfolios consist of natural gas with CCS, and the natural gas with CCS is the one with the lowest emission factor in a portfolio of coal, natural

Table 3 GMV portfolios for scenarios 3 and 4

	Scenario 3	Scenario 4
Technologies	Coal, coal with CCS, natural gas, natural gas with CCS and oil	Coal, natural gas and oil
Expected emission factor	68.67 kg/MWh	457.70 kg/MWh
Risk—standard deviation–	0.28	1.79
Composition	Coal 0.38%	Coal 14.08%
	Coal with CSS 18.38%	Natural gas 60.49%
	Natural gas 1.53%	Oil 25.42%
	Natural gas with CSS 79.09%	
	Oil 0.62%	

gas, coal with CCS, natural gas with CCS and oil. Consequently, the scenario 3 efficient frontier will be a short one—as compared with the scenario 4 efficient frontier—as shown in the lower left part of Fig. 2, where we represent both the scenario 3 and the scenario 4 frontiers. Besides, from the figure, we extract that the risk associated with a portfolio with- out CCS is around five times higher than the one from a portfolio with CSS. In Fig. 2, we also show the upper limit of feasible emission–risk pairs for the technologies considered. In Finance, this limit is known as the feasible frontier—no portfolio can be found upon this limit.

In Fig. 3, we represent the scenario 3 efficient frontier, its GMV portfolio and its CML-A—initially, the shadowed region. The CML-A starts at the coordinate plane ori- gin as the non-pollutant portfolio has zero emissions and zero risk. As seen in the graph, any point inside the CML-A—reachable as a linear combination of an efficient portfolio in each scenario and the non-pollutant portfolio—has a lower level of emissions than any efficient portfolio for every level of risk or a lower risk than any efficient portfolio for every level of emission. In fact, knowing which is the objective—minimise either emissions or risk—will limit the best possibilities to the upper and lower limits of the shadowed zone. In fact, if the objective is to minimise emissions, then we must use the upper limit—the line that connects the coordinate origin and the GMV—because it

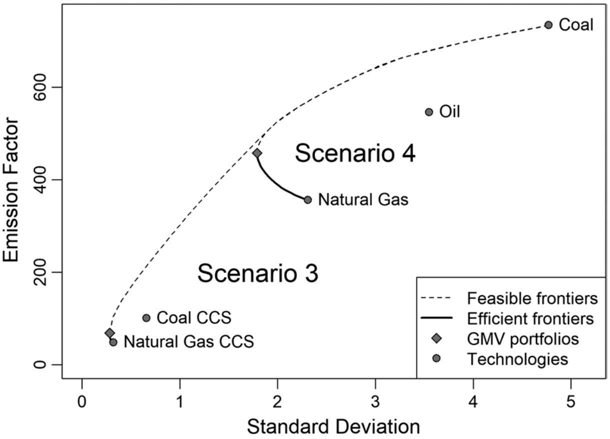

Fig. 2 Scenarios 3 and 4 feasible frontiers, efficient frontiers and GMV portfolios

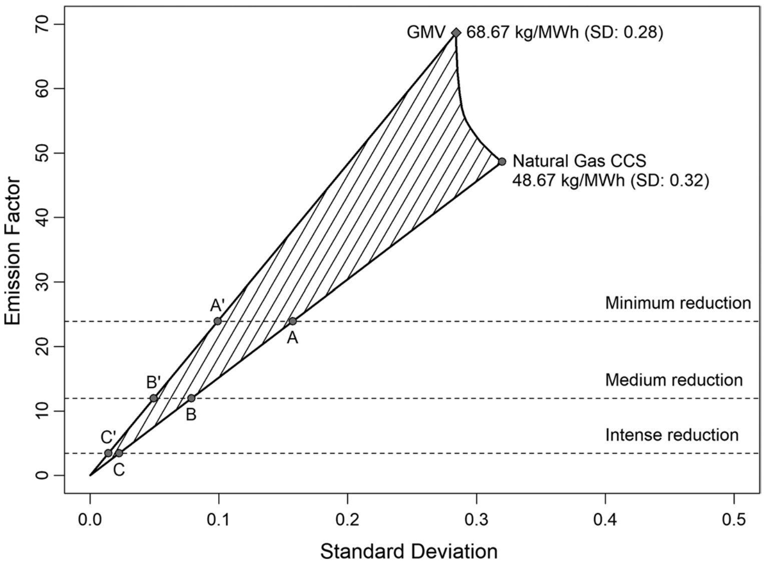

Fig. 3 Scenario 3 efficient frontier, GMV portfolio and CML-A

allows us to minimise the risk for any level of emissions. On the other side, if the objective is to minimise the risk, then we must use the lower limit—the line that connects the coordinate origin and the portfolio that contains only the less pollutant technology of the scenario considered—as it allows us to minimise the emission given a level of risk.

Let us explain with a short example the utility of this analysis for a policy-maker. Taking into account the 2050 horizon CO_2 emission limits from IEA (2011) and the European Commission (2011) proposed by deLlano-Paz et al. (2016a), we can find the proportion of pollutant and non-pollutant—nuclear and renewable—technologies for scenarios 3 and 4 in Table 4. As expected, as we increase the desired reduction, the pollutant-technologies portfolio participation share is reduced from 49 to 7% (scenario 3), and from around 7 to 1% (scenario 4).

We can calculate without difficulty the emission factor and the emission risk associated with these combinations. In Fig. 3—corresponding to scenario 3—the points A′, B′ and C′ show the minimum risk combination for the three reduction levels studied. On the other side, points A, B and C eventually show the minimum emission combination for their respective levels of risk. Table 5 shows the emission and risk of these points.

Table 4 Proportion of pollutant and non-pollutant technologies

	Minimum reduction	Medium reduction	Intense reduction
Emissions limit (kg/MWh)	23.95	11.97	3.42
Pollutant portfolio and non-pollutant portfolio proportions			
Scenario 3	49.21%/50.79%	24.59%/75.41%	7.03%/92.97%
Scenario 4	6.72%/93.28%	3.36%/96.64%	0.96%/99.04%

Table 5 Scenario 3 emission and risk for the different reduction goals considered

Objective	Point	Risk (SD)	Emission (kg/MWh)
Minimise risk	A	0.1575	23.95
	B	0.0787	11.97
	C	0.0225	3.42
Minimise emission	A′	0.0991	23.95
	B′	0.0495	11.97
	C′	0.0142	3.42

Comparing the composition of the scenarios 3 and 4 portfolios, we can observe the pos- itive impact of the CSS generation technologies on the pollutant portfolio. For each one of the proposed reduction objectives—minimum, medium and intense—including CSS tech- nologies will increase the participation share of the pollutant portfolio. Due to this, if fossil fuel generation plants incorporate CCS, the participation share of the CSS technologies will increase in the final portfolio. Besides, and due to the higher diversification, it will enhance the energy security.

4 Conclusions and policy implications

In this work, we developed an application of the MPT and CAPM theories to power generation planning. We introduced a Finance concept—the CML of the CAPM—and adapted it to the peculiar circumstances of the power generation planning and, more specifically, of the CO_2 emission reduction targets. This adaptation, the CML-A, represents the combinations of an extreme efficient portfolio—the GMV portfolio or the portfolio composed of only the least pollutant technology in every scenario considered—with a non-pollutant portfolio composed of nuclear and renewable generation technologies. The composition of the latter portfolio falls far from the aim of this work, but we analysed how the pollutant portfolios can be optimised in terms of emissions and emission risk using the MPT. To demonstrate the applicability of this technique in emission reduction policies, we presented a brief example of application.

When optimising the pollutant portfolios, we found that introducing the biomass in the analysis distorts the results due to the small amount of emissions and emission risk it has. Therefore, we finally take the scenarios that considered this technology out from the analysis

The future presence of pollutant technologies in the generation portfolio of Europe—considering the emission reduction objectives—is strongly conditioned by the participation of the CSS technologies. If the coal and natural gas power generation plants incorporate CCS into their processes, the participation share of the CO_2-emitting technologies will be maintained around 50%—with a minimum reduction goal. Therefore, CSS is a fundamen- tal technology to maintain the generation mix diversification and the energy security in the European Union.

The preferred technology—apart from biomass—is natural gas with CCS, which reaches a huge weight—79%—in the scenario 3 pollutant GMV portfolio. To generate electricity at the lowest risk demands therefore policies enhancing the CCS development. Remind that not considering CCS can multiply by five the generation portfolio risk.

We must continue the research on this line, trying to obtain the analytical properties of the new CML-A. Particularly, we would like to test its validity when the correlation between emissions and emission risks is not as strong as in this work. We also would like to test new pollutant portfolios imposing some type of constraint on the biomass participation to avoid its interference in the results. Regarding the constraints, it is important to notice that—in the presence of them—one of the ends of the efficient frontier could not be the least pollutant technology. Finally, regarding the emissions risk, in this work we used the technologies costs risk as a proxy due to the lack of data. It is our aim to access a data- set of real emissions observations and make our own analysis of standard deviations and correlations.

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