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PROGRAMA OFICIAL DE DOUTORAMENTO EN ANÁLISE ECONÓMICA E ESTRATEXIA EMPRESARIAL

An application of the Modern Portfolio Theory to the optimization of the European Union power generation mix from an environmental perspective

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Supervisor
DR. ANXO CALVO SILVOSA
(University of A Coruna)
Co-Supervisor
DR. FERNANDO DE LLANO PAZ
(University of A Coruna)

Author
PAULINO MARTÍNEZ FERNÁNDEZ

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Abstract

The application of the financial Modern Portfolio Theory to energy planning has been proven to be a useful and efficient tool for the design of the medium- and long-term portfolios of generation technologies. Energy planning is one of the most important drivers of energy security, which can be defined as the possibility of accessing electricity without disruptions, at a reasonable cost, and with the lowest possible environmental impact. In this work, we tackle energy security from three different, albeit related, points of view: generation risk reduction through diversification, Renewable Energy Sources generation and Carbon Capture and Storage technologies for coal and natural gas. At the core of the Modern Portfolio Theory lies the concept of diversification as a way to reduce risk. In 2014, the European Union energy strategy considered the importance of diversifying the energy sources and resources to reduce its high level of energy dependence. It also considered the social benefits of an environmentally-friendly energy policy. The European Union's energy policy calls for the gradual substitution of traditional fossil-fuel generation technologies with cleaner technologies, such as those from Renewable Energy Sources, and introducing Carbon Capture and Storage technologies for coal and natural gas to reduce carbon emissions. Furthermore, including Renewable Energy Sources —which have an autochthonous character— in the portfolio also has the advantage of contributing to increase the level of energy security and to reduce the need to import external fossil fuels. In this work, we present a compilation of our published articles aimed at assessing the effects of those policies and improving the set of tools available to decision-makers.

Resumen

La aplicación de la teoría de carteras al campo de la planificación energética se ha convertido en una eficaz ayuda para el diseño de carteras de generación de electricidad a medio y largo plazo. La planificación energética es una pieza clave para la seguridad energética. Podemos definir la seguridad energética como la posibilidad de acceso a la electricidad sin interrupciones, a un coste razonable y con el menor impacto medioambiental posible. En esta compilación de artículos, tratamos la seguridad energética desde tres diferentes, aunque relacionados entre sí, puntos de vista: la reducción del riesgo de generación a través de la diversificación de tecnologías de generación de electricidad, mediante el uso de tecnologías de generación renovables y mediante el uso de tecnologías de captura y almacenamiento de carbono para las plantas de carbón y gas natural. La propia teoría de carteras incorpora la reducción del riesgo a través de la diversificación como una parte fundamental de su desarrollo. Desde 2014, la estrategia energética de la Unión Europea está orientada a la diversificación de fuentes y recursos energéticos para reducir su extremadamente alta dependencia energética. Además, tiene muy presentes los beneficios sociales de una política energética respetuosa con el medio ambiente. La política energética de la Unión Europea impulsa la substitución gradual de las tecnologías tradicionales de generación eléctrica, basadas en combustibles fósiles, por tecnologías renovables. También apuesta por el desarrollo y la introducción de la captura y almacenamiento de carbono para la generación en base a carbón o gas natural como medio para reducir las emisiones. La inclusión de energías renovables en el *mix* de generación tiene además la ventaja de incrementar el nivel de seguridad energético al reducir la necesidad de importar combustibles fósiles, gracias al carácter autóctono de dichas fuentes energéticas. En este trabajo, presentamos una serie de artículos publicados de nuestra propia autoría cuyo objetivo es evaluar los efectos de estas políticas y mejorar las herramientas para la toma de decisiones en ese ámbito.

Resumo

A aplicación da teoría de carteiras ó campo da planificación enerxética converteuse nunha eficaz axuda para o deseño de carteiras de xeración de electricidade a medio e longo prazo. A planificación enerxética é unha peza clave para a seguridade enerxética, que pode ser definida como a posibilidade de acceder á electricidade sen interrupcións, a un custo razoable e co menor impacto medioambiental posible. Nesta compilación contemplamos a seguridade enerxética dende tres puntos de vista diferentes, aínda que relacionados entre si: a redución do risco de xeración mediante a diversificación de tecnoloxías, mediante o uso de tecnoloxías de xeración renovables e mediante o uso de tecnoloxías de captura e almacenamento de carbono para as plantas de carbón e gas natural. A propia teoría de carteiras incorpora a redución do risco mediante a diversificación como unha parte fundamental do seu desenvolvemento. Dende 2014, a estratexia enerxética da Unión Europea está orientada á diversificación de fontes e recursos enerxéticos para reducir a súa extremadamente alta dependencia enerxética. Por outra banda, ten moi en conta os beneficios socias dunha política enerxética respectuosa co medio ambiente. A política enerxética da Unión Europea impulsa a substitución gradual das tecnoloxías tradicionais de xeración eléctrica, baseadas en combustibles fósiles, por tecnoloxías renovables. Ademais, tamén aposta polo desenvolvemento e a efectiva introdución da captura e almacenamento de carbono para a xeración en base a carbón ou gas natural coma medio para reducir as emisións. A inclusión de enerxías renovables no *mix* de xeración ten, ademais, a vantaxe de incrementar o nivel de seguridade enerxético, ó reducir a necesidade de importar combustibles fósiles, por mor do carácter autóctono destas fontes de enerxía. Neste traballo, presentamos unha compilación de artigos publicados e de elaboración propia que teñen o obxectivo de avaliar os efectos desas políticas e de mellorar as ferramentas para a toma de decisións nese ámbito.

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Abbreviations

CAPM	Capital Assets Pricing Model 13, 18–20, 33, 36, 101–103, 112, 115, 116
CCS	Carbon Capture and Storage 9, 18–20, 23, 24, 27, 28, 31–33, 36, 39, 96, 99–101, 103, 111, 112, 114–116
CML	Capital Market Line 13, 18–20, 33, 36, 101, 102, 112, 116
CML-A	CML-analogous area 19, 35, 36, 96, 101, 102, 112, 116
CO_2	Carbon Dioxide 16–20, 22, 29, 31–33, 35, 36, 96, 99–101, 110, 111, 113, 115
ECSC	European Coal and Steel Community 9
EU	European Union 9, 18–20, 25, 29, 32, 38, 39, 96–99, 101, 111
EU-ETS	EU Emissions Trading System 9
GHG	Greenhouse Gases 32, 98, 99
GMC	Global Minimum Cost 19, 21, 22, 25, 26, 28, 29, 32, 36, 37, 97, 98, 101–103, 113–115
GME	Global Minimum Emission 21, 37, 113, 116
GMV	Global Minimum Variance 19–22, 25, 26, 28, 29, 32, 36, 37, 96–98, 100, 102, 103, 113–116
HHI	Herfindahl-Hirschman Index 28, 29, 32, 97, 108
HPR	Holding Period Return 16
IEA	International Energy Agency 16, 99, 111
IPTS	Institute for Prospective Technological Studies 9, 19, 99, 111, 112, 114, 115
kWh	Kilowatt Hour 14, 15
LCOE	Levelized Cost of Energy 15, 16, 108–110
MPT	Modern Portfolio Theory 9–11, 14–16, 18–20, 35, 36, 96, 101–103, 109–112, 115, 116
MWh	Megawatt Hour 14, 15, 22, 23, 29, 31, 32, 35, 101

NEA	Nuclear Energy Agency 16
NO_x	Nitrogen Oxides 32, 113
PM	Particulate Matter 32, 98, 99, 113
PV	Photovoltaic 17, 23, 24, 27, 33, 111
RES	Renewable Energy Sources 9, 17–20, 26, 32, 33, 96–98, 101–103, 110, 111, 114–116
SO_2	Sulphur Dioxide 32, 113
SWI	Shanon-Wiener Index 29, 108
WEO	World Energy Outlook 16

1 Introduction

Energy security is a major objective of power generation regulatory laws. When talking about a specific territory —a country or a region—, energy security can be seen as a set of different medium- and long-term objectives that involve not only economical, but also social and environment perspectives. In the case of the European Union (EU), energy objectives have been clearly present since the creation of the European Coal and Steel Community (ECSC).

In line with the current EU energy security strategy, we define energy security as the access to electricity without disruptions, at a reasonable cost and with the lowest environmental impact (Awerbuch, 2006; Awerbuch, Jansen, & Beurskens, 2005, 2008; Awerbuch & Yang, 2007; DeLlano-Paz, Martínez Fernandez, & Soares, 2016; EC, 2014; Martinez-Fernandez, DeLlano-Paz, Calvo-Silvosa, & Soares, 2018; Winzer, 2012). The EU itself recognizes that its high dependence on imports can become a problem for providing this access to electricity without disruptions in the event of certain geopolitical events. This is the reason why EU directives and recommendations are aimed at promoting Renewable Energy Sources (RES), benefitting from their indigenous character.

In the works presented in this compilation, we tackle the subject of energy security from a medium- and long-term energy supply risk perspective. The energy supply risk can be dealt with by means of different types of diversification: diversification of energy sources, diversification of energy import origins and diversification of power generation technologies — avoiding over dependence on any technology or on a limited set of technologies. The model we propose deals precisely with risk reduction through diversification, by means of application of Modern Portfolio Theory (MPT) to the field of power generation.

We have previously stated that energy security also entails a reasonable power generation cost. The regulatory framework of a territory must be able to anticipate every possible technological change, in order to increase the competitiveness of the generation companies in the EU. Furthermore, it must be able to promote that competitiveness with the lowest environmental impact and the highest sustainability. Emission reduction objectives are fundamental to motivate any environmentally-friendly change. Specifically, the EU Emissions Trading System (EU-ETS) is one of the pillars of the EU energy policy. Once again, RES are playing quite an important role in this area, as they allow for clean power generation. Finally, as we state in one of the works presented, Carbon Capture and Storage (CCS) are going to play an important role over the next 10-15 years, when they eventually reach commercial availability — current projections by the Institute for Prospective Technological Studies (IPTS) (2009) and the EU Global CCS Institute (2018) estimate that these technologies will be commercially available by the decade 2020.

In the models presented in these works, the underlying objective is to minimize the risk or, in other words, to calculate the minimum risk for every possible cost of the generation mix. If we assume there are no constraints on the generation mix, the maximum generation mix cost would be that of a portfolio composed solely of the most expensive generation technology. At the same time, the minimum generation mix cost would be that of a portfolio composed solely of the cheapest generation technology. In terms of risk, things are not so evident, as the different covariances among the generation technology costs can lead to a generation portfolio with less risk than the least risky technology.

Energy planning is one of the most important drivers to improve the energy security of a territory. We define energy planning as the decisions that must be made about power supply infrastructures and power demand over the medium/long term. Nevertheless, the papers included in this work refer solely to power supply infrastructures, leaving out power demand options and decisions. This allows us to eliminate the consumer price of electricity (Awerbuch & Berger, 2003) from the study. In fact, a territory's energy security depends to a great extent on the design of its energy portfolio. MPT can help decision-makers to improve the medium- and long-term installed capacity in therms of the optimal capacity of each technology and the diversification of power generation technologies.

2 State-of-the-art, scientific contribution and research questions

2.1 State-of-the-art

2.1.1 Modern Portfolio Theory

Markowitz proposed this theory to select efficient financial asset portfolios in 1952 (Markowitz, 1952). In financial investments, investors try to maximize their return. But this aim cannot be considered a unique objective, because there is a tradeoff between return and risk: the higher the return, the higher the risk. The only possible way in which investors can reduce his risk exposure is by also renouncing the return and, in the same way, the only way to increase the return is by accepting more risk.

The theory proposed by Markowitz is called the Modern Portfolio Theory. Assuming every risky financial asset can be characterized by its expected return and the risk or variability associated with that return —measured by the standard variation of its historical returns—, it is possible to establish a quadratic optimization model to determine the location of the so-called efficient frontier on a risk-return coordinate plane. The efficient frontier is the concave curve that contains every possible combination of assets that shows the lowest risk for a given level of return — or, alternatively, the highest return for a given level of risk. It constitutes the lower-left border of the feasible set or the place in the risk-return plane where all the possible combinations of assets lie.

It is interesting to note that, while the expected return of a portfolio will always be between the lowest and the highest expected returns for the assets included in the portfolio, the portfolio as a whole can show a risk that is less than the risk of any individual asset in the portfolio. This is due to the covariances among the returns of the financial assets. In effect, where $\mathrm{E}\left(r_i\right)$ is the expected return of every asset in the portfolio and x_i is the participation share of every asset in the portfolio, the expected return of the portfolio is calculated as shown in Equation 1. Equation 2 —where n is the total number of assets in the portfolio, σ_i^2 is the variance of the ith asset return and $\sigma_{i,j}$ is the covariance between the returns of the ith and the jth assets— shows, in turn, how to calculate the portfolio risk.

$$\mathrm{E}\left(r_p\right) = \sum_{\forall i} x_i \mathrm{E}\left(r_i\right) \tag{1}$$

$$\sigma_p = \left(\sum_{\forall i} x_i^2 \sigma_i^2 + 2 \sum_{1 \leq i \leq j \leq n} x_i x_j \sigma_{i,j} \right)^{1/2} \tag{2}$$

Equation 2 can be rewritten as shown in Equation 3, where $\rho_{i,j}$ is the Pearson's correlation coefficient between the returns of the ith and jth assets. Usually, the correlation coefficient offers clearer information about how two random variables behave when considered together, as its interpretation is more intuitive than the interpretation of the covariance. The correlation coefficient varies from -1 —in the case in which two random variables behave exactly the opposite— to 1 — in the case in which two random variables behave in a parallel manner. A correlation coefficient of 0 means that no apparent relationship can be found in the behavior of the two variables. It is precisely this correlation coefficient —or the covariance— that determines whether the joint risk is less than, equal to or greater than the sum of the individual risks.

$$\sigma_p = \left(\sum_{\forall i} x_i^2 \sigma_i^2 + 2 \sum_{1 \leq i \leq j \leq n} x_i x_j \sigma_i \sigma_j \rho_{i,j} \right)^{1/2} \tag{3}$$

Markowitz proposed a quadratic optimization problem like the one shown in Equation 4 where the unknown vector $x \in \mathbb{R}^n$ will contain —once the problem is solved— the weights of the n possible assets in the resulting portfolio, and $S \in \mathbb{R}^{n \times n}$ is the asset return variance-covariance matrix. Throughout this work, we will use the apostrophe ($'$) to indicate the vector or matrix transposition function. We can see that the problem is also constrained to solutions where the sum of the different asset weights is equal to one and where the portfolio return is equal to a given k^*.

$$\begin{aligned} &\text{min. } \left(x'Sx\right)^{1/2} \\ &\text{subject to:} \\ &\begin{cases} \sum_{\forall x_i \in x} x_i = 1 \\ \mathrm{E}\left(r_p\right) = k^* \end{cases} \end{aligned} \tag{4}$$

Solving this problem for a sample of eight common stocks, and adding a $x_i \geq 0, \forall i$ constraint to ensure that every asset participation share is in the interval $[0, 1]$, we get the frontier drawn in Figure 1. In this figure, the efficient portfolio frontier is represented by the curved line that goes from point GMV to point $AMZN$. We have also drawn the lower-left non-efficient part of the feasible portfolio frontier —the dashed blue line that goes from point GMV to point GE, representing portfolios that could be reached but that would be inefficient— just to illustrate the efficiency concept in MPT. For example, we see the portfolio represented by point A: it has a return of 0.20% and a risk of 0.03. The portfolio represented by point B is more efficient as, for the same level of risk —0.03—, it offers a much better return of 1.47%. Therefore, no investor would ever choose portfolio A, given the option to invest in portfolio B and obtain a higher return, while maintaining the same level of risk.

In Finance, it is possible to form a portfolio with some negative weights. The interpretation

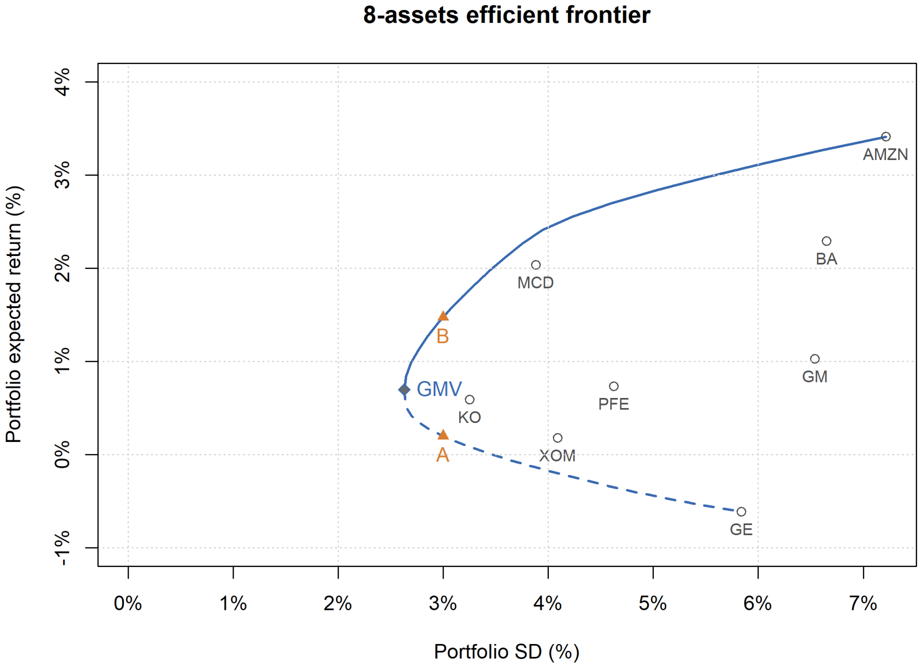

Figure 1: Efficient portfolio frontier

is simple: if, for the ith asset, $x_i \in x$ is negative, it means that the investor is taking a short position with regard to that asset — for instance, by purchasing futures for that asset. In the previous example, we constrained the solution to contain only long positions by adding the constraint $x_i \geq 0, \forall i$, as stated. In Figure 2, we included the feasible frontier when allowing short positions —by removing the $x_i \geq 0, \forall i$ constraint— in the assets as a broken dotted green line, which presents the minimum risk in point GMV_{shorts}. As expected, the feasible portfolio set is larger than the feasible portfolios set when short positions are not allowed.

When a risk-free asset —in the Literature, a Treasury bond is usually understood to be a risk-free asset, even when its risk, as measured by its historical variance, may be not exactly zero— is taken into account (Markowitz, 1952), an investor can dedicate part of his budget to investing in one of the previously determined risky asset efficient portfolios, and another part to investing in the risk-free asset — which offers a return of r_f. By doing so, he would be able to reduce its risk and, most of the time, even increase the return. In effect, a risk-free asset would be located somewhere along the positive ordinate axis of the coordinate plane. The efficient frontier is a concave curve somewhere in the first quadrant of that plane. A combination of the risk-free asset and a portfolio on the efficient frontier can be represented by a straight line joining the risk-free asset and the specific portfolio on the efficient frontier. The straight line can be explained because the risk-free asset has no risk, and therefore its covariance —or correlation— with the risky assets is zero. Thus, any combination of the risk-free asset and the risky assets or portfolios is a linear combination. Depending on the portfolio chosen, that line would cut through the efficient frontier at the point for the risk-return pair corresponding to that portfolio. We can increase the slope of the line until this becomes a tangent to the efficient frontier.

Given the fact that any investor would choose an efficient portfolio or a combination of an

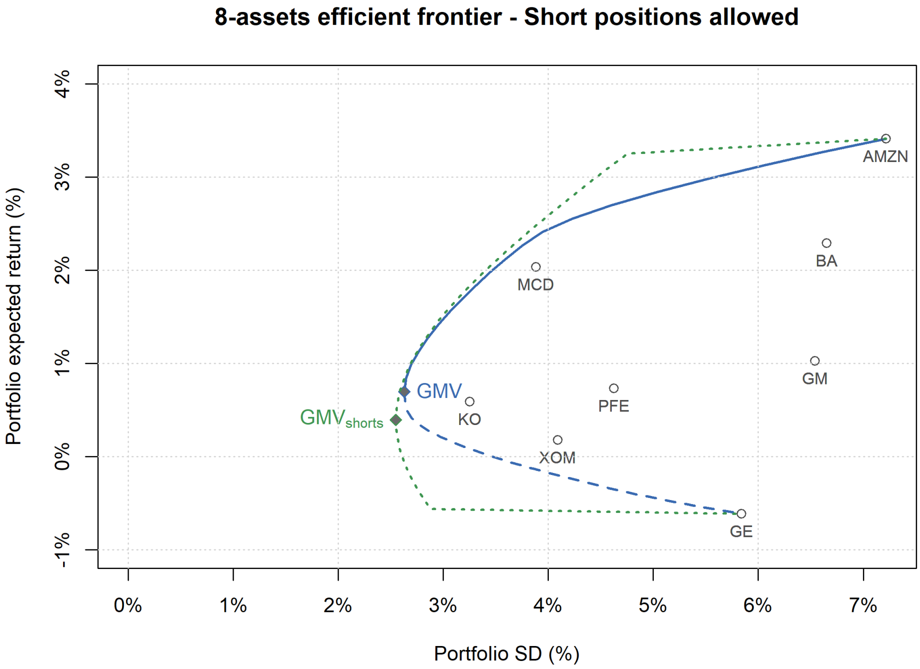

Figure 2: Efficient portfolio frontier with short positions allowed

efficient portfolio and the risk-free asset, the market equilibrium will allow us to determine which of the efficient portfolios is the best portfolio in the sense that any combination of this portfolio with the risk-free asset shows better returns for any level of risk (Brealey & Myers, 2003). This ratio between the return and the risk is known as Sharpe's Ratio, and its expression for the ith asset is shown in Equation 5. In the numerator of that expression we can see that, in fact, it is the excess return on the risk-free asset return, r_f, that is taken into account.

$$S_i = \frac{\mathrm{E}\left(r_i - r_f\right)}{\sigma_i} \tag{5}$$

The portfolio that maximizes Sharpe's Ratio is known as the Tangency Portfolio because it is the tangency point between the efficient frontier and the line containing the possible combinations of the risk-free asset and that specific efficient portfolio. It makes sense to think that, in the equilibrium, every investor would try to reach that maximum value of Sharpe's Ratio and this is the reason why the Tangency Portfolio is also called the Market Portfolio. The line that starts in the risk-free asset and runs tangent to the efficient frontier is known as the Capital Market Line (CML); it was defined as part of the Capital Assets Pricing Model (CAPM) developed by Sharpe (1963, 1964), Treynor (1961) and Lintner (1965) among others. In Figure 3 we can see both the Market or Tangency Portfolio —represented by the point M— and the CML corresponding to our example. Note that for those points of the CML to the right and above the market portfolio M, the investor is borrowing money to get a higher return at the obvious cost of a higher risk. Every combination of the risk-free asset and the market portfolio in the CML shows the same Sharpe's Ratio or, in other words, it shows the higher excess return per unit of risk.

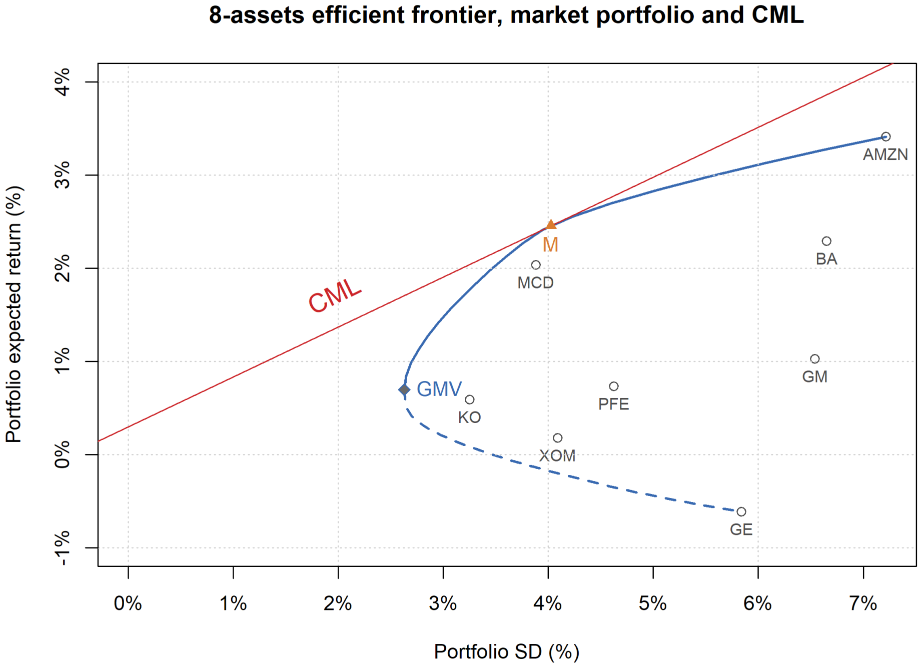

Figure 3: Efficient portfolio frontier, market portfolio (M) and capital market line (CML)

2.1.2 Applications of MPT to energy

In the context of real assets, MPT has been proven to be a useful and effective tool for identifying efficient power generation portfolios, as shown by many works in the Literature (Allan, Eromenko, McGregor, & Swales, 2011a; Arnesano, Carlucci, & Laforgia, 2012; Awerbuch, 2006; Awerbuch & Berger, 2003; Awerbuch et al., 2005; Awerbuch & Yang, 2007; Bhattacharya & Kojima, 2012; Delarue, De Jonghe, Belmans, & D'haeseleer, 2011; Escribano Francés, Marín-Quemada, & San Martín González, 2013; Gökgöz & Atmaca, 2012; Huang, Wu, & Hsu, 2016; Lesser et al., 2007; Vithayasrichareon & MacGill, 2012; Westner & Madlener, 2010; Zhu & Fan, 2010). In effect, the power generation mix can be seen as a portfolio of technologies and every technology can be characterized by its cost and risk or variability of the cost. As we already stated, energy planning —at least, the part involving the supply infrastructures— is to some extent an installed capacity optimization problem. In the paragraphs below we will explain the main adaptations to be made to MPT for its application to power generation.

From returns to costs and the objective function. The first thing we note when applying MPT to real assets —more specifically, to power generation assets— instead of financial assets, is that the variables to deal with are now the cost and its risk. Different approaches have been taken to deal with this. Awerbuch (2000) and Awerbuch and Berger (2003), for instance, chose to use the inverse of the cost as an indicator of the return. Hence, the return is defined as the amount of output produced —Megawatt Hour (MWh) or Kilowatt Hour (kWh)— for every monetary unit spent. From our point of view, and on the basis of some relevant works like that by F. Roques, Hiroux, and Saguan (2010), this can cause an issue when dealing with zero values, and it is not necessary, as the optimization problem can perfectly deal with a joint risk-cost minimization. In the third paper presented, we tackle a joint risk-emissions minimization that would not have been possible using the inverse of the emission as some technologies have zero emissions.

Another point to consider is the dimensionality of the variables. While both the return and its risk were adimensional in the original problem set out by Markowitz, when applying MPT to power generation the cost and its risk —the standard deviation— are measured in monetary units per MWh, or in MWh per monetary unit if we use the inverse of the cost. From our point of view, this is not an issue, and does not affect the model purposes, even when the original Finance model dealt with adimensional returns.

In any case, in the Literature we find several approaches to define the objective function and consequently the optimization problem. As stated earlier, Awerbuch and Berger (2003), together with Kienzle, Koeppel, Stricker, and Andersson (2007), Rodoulis (2010), Arnesano et al. (2012), De Jonghe, Delarue, Belmans, and D'haeseleer (2011) and F. Roques et al. (2010), chose to follow MPT and maximize the return or some indicator of the return, such as the inverse of the cost. Zhu and Fan (2010), Bhattacharya and Kojima (2012) and Delarue et al. (2011), in turn, opted to minimize the power generation risk. Some other authors (Allan, Eromenko, McGregor, & Swales, 2011b; Awerbuch & Yang, 2007; Beurskens, Jansen, Van Tilburg, Beurskens, & Van Tilburg, 2006; White, Lesser, Lowengrub, & Yang, 2007) consider a cost minimization problem or a risk-weighted cost minimization problem (Huang & Wu, 2008). F. A. Roques, Newbery, and Nuttall (2008) and Gökgöz and Atmaca (2012) propose a utility maximization problem, while Muñoz, Sánchez de la Nieta, Contreras, and Bernal-Agustín (2009) maximize an adaptation of Sharpe's Ratio in their work.

Cost calculation. When originally described, MPT used the historical returns average and standard deviation of the financial assets considered as the inputs of the model. Ideally, if we had access to the historical generation costs, we could easily assume normality in its behavior and calculate its average and its standard deviation. But access to this information is not usual, so it is common in Literature to use some kind of Levelized Cost of Energy (LCOE). The LCOE can be defined as the constant average price at which the present value of the whole lifetime categorized costs and expenditures of a specific technology generation plant equals the present value of its revenues (IEA & NEA, 2015; Khatib, 2016). Hence, the LCOE is a break-even price, as its makes the costs and revenues of a generation plant financially identical. In this case, where P is the LCOE itself in monetary units, G the amount of energy produced in a year in kWh, MWh..., C_t the capital costs, $O\&M_t$ the operation and maintenance costs, F_t the fuel costs, E_t the emissions costs, D_t the decommissioning costs —all these in monetary units— and n is the total number of years considered —the sum of the lead time and the plant lifetime—, we have the equality expressed in Equation 6 where the subindex t references the year t and both the LCOE itself and the yearly produced energy are assumed constant — and therefore could be taken out of the summatory.

$$\sum_{t=0}^{n} PGf_t = \sum_{t=0}^{n} (C_t + O\&M_t + F_t + E_t + D_t)\, f_t \tag{6}$$

We can solve Equation 6 for P to obtain the common expression for the LCOE shown in

Equation 7.

$$P = \frac{\sum_{t=0}^{n} \left(C_t + O\&M_t + F_t + E_t + D_t\right) f_t}{\sum_{t=0}^{n} G f_t} \tag{7}$$

In both Equations 6 and 7, f_t represents the capitalization or discount factor to take the amounts to the reference moment in time. If we denote that moment as t^*, and we know the annual rate r to be applied, then $f_t = (1+r)^{-(t-t*)}$. We can assume that the reference moment, t^*, is the initial moment at which we decide to build the plant and, therefore, we start to incur in expenses. In other words, $t^* = 0$, and the factor —now a pure discount factor— f_t^* would be calculated as expressed in Equation 8.

$$f_t^* = (1+r)^{-t}, t \geq 0 \tag{8}$$

So far, we might have a value for the generation cost by technology disaggregated by cost category. In fact, international institutions like the International Energy Agency (IEA), the Nuclear Energy Agency (NEA) and the World Energy Outlook (WEO) periodically publish their detailed LCOE forecasting by country and technology. But what about the risk of these cost categories?

Risk calculation. Awerbuch (2000) and, more specifically, Awerbuch and Berger (2003) and Awerbuch and Yang (2007) assess the risk of some of the cost categories separately. For the fuel cost, they use the volatility —measured by the standard deviation— of the Holding Period Return (HPR) of the historical fuel prices. This is criticized by Kienzle et al. (2007) and Beurskens et al. (2006), due to the loss of dimensionality in the risk. They argued that this way, the risk might lose its monetary notion, and thus they chose to multiply the so-calculated risk by the cost itself, giving it back its dimensionality. For operation and maintenance risk, Awerbuch and Berger (2003) decided to separate fixed and variable operation and maintenance costs and use a financial proxy for each of these subcategories — the historical standard deviation for several corporate bonds for the fixed operation and maintenance cost, and the variability of the S&P 500 for the variable operation and maintenance cost. The rest of the costs have no risk in these authors' works.

In Awerbuch and Yang (2007), capital costs risk and Carbon Dioxide (CO_2) emission costs risk were added to the study using data from the World Bank — to estimate the risk of the capital costs. The relationship between the CO_2 price and the gas and coal prices was used to estimate the CO_2 costs risk. This requires to estimate the correlation between the fuel costs and the CO_2 costs. The authors estimated the correlation using a Montecarlo simulation process.

With regard to the correlation among the cost categories of a specific technology, the so-called incorrelation hypothesis is commonly assumed in the Literature (Allan et al., 2011b; Arnesano et al., 2012; Beurskens et al., 2006; Delarue et al., 2011) to assume . According to this hypothesis, the different cost categories of every technology are uncorrelated, except for the fuel and the emission costs. The justification (Beurskens et al., 2006) lies in the medium/long-term analysis sought by the application of the MPT to energy planning. Under these assumptions, the total risk of the generation cost of a specific technology T can be calculated as expressed in Equation 9 or in Equation 10, if we prefer to see it in terms of the Pearson's correlation coefficient. In these equations, σ_{X_T} represents the standard deviation of the cost category X for technology T —and, consequently, $\sigma^2_{X_T}$ represents its variance—, $\sigma_{(X_1,X_2)_T}$ represents the covariance between the cost categories X_1 and X_2 for technology T and $\rho_{(X_1,X_2)_T}$ represents the Pearson's correlation coefficient between the cost categories X_1 and X_2 for technology T.

$$\sigma_T = \sqrt{\sigma^2_{C_T} + \sigma^2_{O\&M_T} + \sigma^2_{F_T} + \sigma^2_{E_T} + \sigma^2_{D_T} + 2\sigma_{(F,E)_T}} \tag{9}$$

$$\sigma_T = \sqrt{\sigma^2_{C_T} + \sigma^2_{O\&M_T} + \sigma^2_{F_T} + \sigma^2_{E_T} + \sigma^2_{D_T} + 2\rho_{(F,E)_T}\sigma_{F_T}\sigma_{E_T}} \tag{10}$$

In the works presented in this compilation, we follow the approach taken by Awerbuch and Berger (2003), Awerbuch and Yang (2007), de-Llano Paz (2015), de-Llano Paz, Antelo, Calvo Silvosa, and Soares (2014), among others. This approach assumes that the generation technology costs are uncorrelated, except for operation and maintenance costs. Other authors (Beurskens et al., 2006) extend the hypothesis of uncorrelation to even the operation and maintenance costs. Finally, another set of authors such as Allan et al. (2011b), Arnesano et al. (2012) decided to apply a weighting factor to the cost categories when calculating the technology risk. This weighting factor would be incorporated in Equations 9 and 10 as a weigth that multiplies every term in the square root. According to these authors, the weight would be calculated as the proportion of every cost category in the total cost.

When discussing risk, we consider it important to note that in the third paper included in this compilation, we use the risk of the CO_2 emission cost as a proxy for the CO_2 emission risk and we simulate a 10,000-row dataset to calculate the CO_2 emission variance-covariance matrix among the pollutant technologies, following the example of the works referenced in the precedent paragraphs.

The RES risk. We deem the role of the RES power generation in the upcoming years to be excepcionally important. The reasons for this have already been indicated. Briefly, RES power generation will reduce European energy dependence due to its indigenous character and will improve environmental friendliness through the reduction of emissions from electricity generation. In this section, we will refer to some of the different approaches to the treatment of the RES power generation risk in the Literature.

In Awerbuch and Berger (2003) RES generation technologies are assumed to have no risk. The reason is that they have only investment and operation and maintenance costs — other than biomass, the rest of the RES technologies have neither fuel costs nor emission costs. In their work, Awerbuch and Berger explain that the annual variation of these cost categories is small enough that it can be assumed they present no variability or risk.

Another approach is that by Arnesano et al. (2012). According to these authors, both Wind and Photovoltaic (PV) technologies have risk due to their intermittence. They are not 100% available and, therefore, their capacity factor can be considered a source of risk, similar to the fuel cost variation for these technologies.

There is no getting away from the fact that RES generation contributes to reducing the disruption risk of the power supply, through the reduction in energy dependence. Even so, Hernández-Escobedo, Manzano-Agugliaro, and Zapata-Sierra (2010) recognize how difficult are they to predict both in the short- and long-term.

2.1.3 Criticism

The application of MPT for determining optimal power generation portfolios has not been without criticism. Awerbuch and Berger (2003) enumerate and briefly explain the weakest points of this application. Mainly, MPT assumptions for Finance cannot be easily achieved in Energy. More specifically, financial assets are almost infinitely divisible and fungible, while the generation power infrastructures are not. Besides, financial assets returns are mainly normally —or log-normally— distributed, but we cannot claim the same for power generation infrastructures costs due to the lack of information.

However, the object of study in both cases is not the same. MPT, when applied to Finance, is focused on an investor's portfolio and over the short-term. The power generation portfolio for a territory or country over the medium/long-term is clearly not a perfectly divisible asset, but it can be considered as one for the purposes of the model. The same applies to the fungibility of the power generation assets.

From our point of view, the main criticism may stem from the model dataset. In particular, the variance-covariance matrix is difficult to determine, due to the private nature of the cost categories analyzed. This compels the Literature to make some assumptions about cost risks and the correlation among the cost categories and among the technology costs. As stated before, we consider these assumptions to be quite in line with reality, and thus we made use of them.

2.2 Scientific contributions and research questions

In the works presented, we consider the cost of the power generation and its risk, measured as a kind of variability of that cost. Specifically, we use cost variance —or cost standard deviation— to measure that variability. Then, we apply MPT to see how the efficient power generation portfolios frontier would behave over the medium- and long-term in the face of the scenarios contemplated in the European energy strategy. In fact, this means an evolution from the Doctoral Thesis of de-Llano Paz (2015), delving into some of the research lines that were brought up there.

In line with the previously discussed EU energy objectives, the works included in this research compilation delve in depth into research lines related to the environment. We tried to strengthen the analysis by adding new constraints to the model, and by following the path established in Finance by the current evolution from MPT towards CAPM, particularly with regard to CML.

In the first paper included in this work, four different policy scenarios are analyzed for the 2030 horizon: base policies, low emission policies, high RES participation policies and European Union policies, which considers both the low emission and the high RES policies. Furthermore, at a time when the elimination of nuclear generation is a hot issue, we analyze the effects of an eventual nuclear phase-out in the EU.

The second paper included in this work deals with CCS technology. This technology is capable of capturing most of the CO_2 emissions produced by coal and natural gas power generation. Nowadays, it is a developing technology and cannot be deployed at scale, but it is expected to be commercially available by 2030. We use current information about the cost and risk of both CCS coal and CCS natural gas generation to assess the impact on the current European generation portfolio. To anticipate a big change in the economic conditions of CCS technologies we broaden the analysis by changing the cost by ±1 and ±2 standard deviations and the risk by ±50%, and then assessing the effects on the generation portfolios.

The third paper included in this work aims to make use of the CML concept from Financial CAPM in power generation. In CAPM, CML is fundamental to determining the market portfolio —or tangency portfolio—, the portfolio that shows the best risk-return —Financial MPT deals with returns— interchange ratio, called Sharpe's ratio in Finance, and the combinations of this portfolio and the risk-free asset. In fact, the CML is the graphical representation of these combinations. When applied to power generation, MPT replaces the risk-free asset with a risk-free generation technology or set of technologies and shifts the objective from a risk-return perspective to a risk-cost perspective. The latter change causes the efficient frontier to be convex instead of concave, and this convexity impedes us from finding a single market portfolio, and consequently, the CML for power generation. Instead, we decided to adopt a risk-emission perspective, which allows us to have a risk-free set of technologies: the non-pollutant generation technologies. We also opted to use the entire efficient frontier to determine an area of generation portfolios that show lower CO_2 emissions than the efficient pollutant portfolios. We called this area the CML-analogous area (CML-A).

We also consider the effort made in programming a reusable library to calculate the Global Minimum Variance (GMV) and the Global Minimum Cost (GMC) portfolios, together with the efficient and feasible frontiers, a scientific contribution. This effort saved us a lot of time in developing further models and scenarios. The functions contained in this library are explained in Section 3.5.

The research questions we attempt to answer with the presented articles are detailed below:

- How do the EU power generation policies affect cost-risk efficiency, emmissions and the diversification of the power generation mix?
    - How does an intense RES participation in the mix affect these variables?
    - How would these factors affect a stronger commitment to emmision reduction?
    - Is nuclear phase-out an option for the EU? What would the effects be on the cost and the emissions of the generation mix?
- Some institutions, like the Institute for Prospective Technological Studies (IPTS), assume a maximum participation of 18% for CCS technologies over the generation based on fossil fuels. How will this assumption affect the European generation portfolio?
    - Is this assumption compatible with European energy targets for 2030?
    - Which would be the effects of underestimating or overestimating the cost and risk of CCS technologies?
    - Will CCS technologies have a role to play in terms of environmental policies?
- MPT has proven to be a useful methodology for application to power generation. But would it be also possible to apply CAPM theory to power generation?

- How do we select the CAPM risk-free reference in power generation?
- Would the application of CML in power generation be useful to a policy-maker?
- From the CAPM perspective, are CCS technologies still being considered for power generation?

3 Methodology

In this section we explain the models proposed in the articles presented in this work. As stated, the primary methodology applied is MPT using the average generation cost —or CO_2 emissions— and risk, taken as the possible variability of that cost and measured by the standard deviation.

3.1 The base model

Our model follows Markowitz's initial problem of risk minimization. But instead of choosing a cost inverse function to maintain the dual maximization problem, as Awerbuch and Berger (2003) did, we chose to minimize the power generation cost. This fact has important implications that will be evident in the third paper presented. We leverage the power of the model constraints to build different scenarios and draw conclusions through their comparison. For instance, we incorporate into the model in the first paper the minimum RES generation or the CO_2 emission limit defined by the EU for 2030.

In the three papers presented, the model includes a set of n generation technologies, characterized by their expected costs, cost risks and, in the third paper, also their CO_2 emission factor (Martinez-Fernandez et al., 2018). We also take into account the covariances among the technology costs, or emission factors, where appropriate. As a result , the inputs to the model are a $n \times 1$ vector of expected costs and a $n \times n$ variance-covariance matrix. This matrix is symmetric and the n elements of its diagonal are the respective tecnhonology variances, while the element located in row i and column j represents the covariance for technologies i and j costs or emission factors. The result of the model will be a $n \times 1$ vector with the participation share of every technology in the power generation portfolio. Calling this vector x, and the variance-covariance matrix S, our problem will be to minimize $(x' \times S \times x)^{1/2}$.

We do not contemplate in our work the possibility of having negative participation shares —not an easy interpretation when applying MPT to energy— and obviously the sum of all the technology participation shares must add up to one. Therefore, our base model has only two constraints:

- Positivity constraint: every technology share participation must be zero or positive. This can be expressed as $x_i \geq 0, \forall i$.
- Completeness constraint: the sum of every technology share participation must add up to one. This can be expressed as $\sum_{\forall i} x_i = 1$.

In fact, with these two constraints, we are able to determine the Global Minimum Variance (GMV) portfolio: the portfolio that shows the least risk among the feasible portfolios. The

GMV portfolio is one of the extreme points of the efficient frontier. Since we are dealing with cost minimization, the GMV portfolio will be the upper-left extreme of the efficient frontier.

Calculating the efficient frontier requires solving not one, but rather a collection of different optimization problems. In brief, we first calculate the portfolio with the minimum possible risk with the model presented so far. Then, we calculate the portfolio with the minimum possible cost —or emission— among all the feasible portfolios: the GMC portfolio or, alternatively, the Global Minimum Emission (GME) portfolio. Finally, we calculate a set of intermediate efficient portfolios from among these extreme portfolios. The details of these steps are explained below.

1. We calculate the GMV portfolio; i.e., the portfolio with the minimum possible risk according to the dataset used. We do not impose any additional constraints when calculating the GMV portfolio. The problem is presented in equation 11.

$$\begin{aligned}&\text{min. } \left(x'Sx\right)^{1/2} \\ &\text{subject to:} \\ &\begin{cases} x_i \geq 0, \forall x_i \in x \\ \sum_{\forall x_i \in x} x_i = 1 \end{cases}\end{aligned} \tag{11}$$

2. We calculate the GMC or the GME portfolio; in other words, the portfolio with the mininum possible cost or emission factor. Again, we do not impose any additional constraints to calculate these portfolios. Calling the expected costs —or emissions— vector $c\,(c \in \mathbb{R}^n)$, we solve the linear programming problem shown in Equation 12 to carry out this step.

$$\begin{aligned}&\text{min. } x'c \\ &\text{subject to:} \\ &\begin{cases} x_i \geq 0, \forall x_i \in x \\ \sum_{\forall x_i \in x} x_i = 1 \end{cases}\end{aligned} \tag{12}$$

3. We calculate an m-element sequence from the minimum cost —thus, the cost of the GMC portfolio— to the maximum cost —the cost of the GMV portfolio— and compute the efficient portfolio for every intermediate cost — the portfolio that minimizes the risk for that given cost. Thus, we have to solve $(m-2)$ problems like the one shown in Equation 13, where k^* represents every one of the $(m-2)$ portfolio costs computed. For most of the cases, we use 20 as a plausible value for m. When dealing with emissions, we calculate an m-element sequence from the minimum emission factor —the one for the GME portfolio— to the maximum emission factor —that of the GMV portfolio— and solve the corresponding optimization problems, where k^* in this case represents the intermediate portfolio emission factors calculated.

$$\text{min. } \left(x'Sx\right)^{1/2} \tag{13}$$
subject to:
$$\begin{cases} x_i \geq 0, \forall x_i \in x \\ \sum_{\forall x_i \in x} x_i = 1 \\ x'c = k^* \end{cases}$$

3.1.1 Costs and risks calculation

Our dataset follows the referenced methodologies for calculating the costs and risks of each technology. We gather information for calculating every cost category from different sources, following the method used by de-Llano Paz (2015), and we sum them up to calculate the total cost for a specific generation technology. For production costs —capital, operation and maintenance and fuel costs—, we used information from Eurelectric and E.V. (2012), IEA (2010), IRENA (2012) and de Jager et al. (2011). For other costs —dismantling, transport of CO_2, intermittence—, we used data from Awerbuch and Yang (2007), Beurskens et al. (2006), IEA (2010), IPCC (2005) and Awerbuch et al. (2008).

Regarding the risks, and in the same manner as we did for the costs, we used information from different internationally relevant sources such as Awerbuch et al. (2008), Awerbuch and Yang (2007), Bennink, Rooijers, Croezen, de Jong, and Markowska (2010), Beurskens et al. (2006), EC (2005), IEA (2010), IPCC (2005) and Allan et al. (2011b) among others.

Finally, with regard to the correlation coefficients, for both the fuel and emission cost correlation for each technology and the cost correlation in any pair of technologies, we decided to use the information in the works by Allan et al. (2011b), Awerbuch and Yang (2007) and Arnesano et al. (2012) due to the lack of public data about these costs.

3.1.2 Base model results

Using the costs and risks and the variance-covariance matrix shown in Tables 2 and 3, taken from the sources referenced in the previous section, we build an efficient frontier for the power generation like the one presented in Figure 4.

In Figure 4 we highlighted the global minimum variance portfolio with the composition reflected in Figure 5. This composition entails a cost of 49.08 €/MWh for the portfolio and a risk of 1.77 €/MWh. As we can see in the GMV composition, nuclear and hydro (mini) are the preferred technologies when, based on the data used, we want to minimize the power generation risk. Hydro (mini) is preferred, even though its risk is a bit higher than that of natural gas generation. This is an effect of the covariances among the technologies.

We can also see that the other extreme point of the efficient frontier —the GMC portfolio— corresponds to a portfolio composed only of nuclear generation, which is the technology with the lowest generation cost. In fact, we received some criticism due to the low generation cost assigned to nuclear generation; as stated, we are using internationally recognized sources for its calculation. Figure 6 shows how the technologies participation shares change along the efficient

Table 2: Costs and risks by technology

Technology	Cost (€/MWh)	Risk (€/MWh)
Nuclear	30.04	2.84
Coal	52.23	5.61
CCS Coal	78.44	6.80
Natural Gas	38.79	3.51
CCS Natural Gas	63.60	6.67
Oil	93.17	12.48
Wind	60.69	6.46
Hydro	38.62	10.29
Hydro (mini)	42.95	3.59
Offshore wind	73.81	7.21
Biomass	96.62	12.76
PV	212.03	10.50

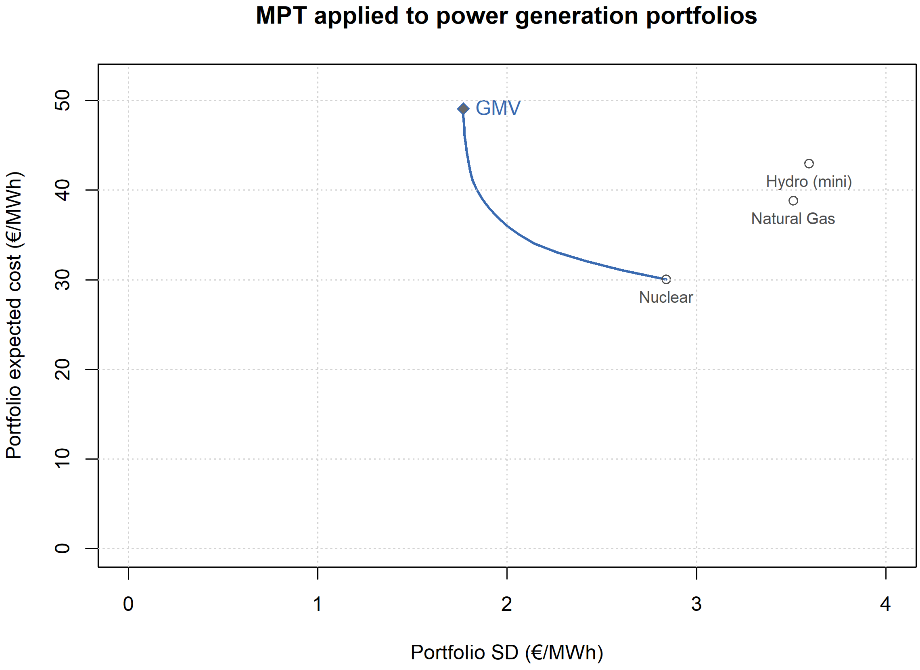

Figure 4: Efficient power generation portfolio frontier

Table 3: Technology cost variance-covariance matrix

	Nuclear	Coal	CCS Coal	Natural Gas	CCS Natural Gas	Oil	Wind	Hydro	Hydro (mini)	Offshore wind	Biomass	PV
Nuclear	8.07	3.84	5.07	3.54	4.26	15.32	-0.07	-0.42	-0.46	-0.10	-6.40	0.20
Coal	3.84	31.51	7.04	4.02	4.81	20.82	-0.21	0.03	0.03	-0.31	-14.09	-0.21
Coal-CCS	5.07	7.04	46.27	5.43	6.60	27.16	-0.45	0.06	0.07	-0.68	-18.52	-0.46
Natural Gas	3.54	4.02	5.43	12.33	6.55	15.44	0.00	-0.08	-0.08	0.00	-3.16	0.05
Natural Gas - CCS	4.26	4.81	6.60	6.55	44.45	18.33	0.00	-0.16	-0.17	0.00	-3.38	0.11
Oil	15.32	20.82	27.16	15.44	18.33	155.83	-4.02	-1.95	-2.11	-6.07	-86.44	-0.16
Wind	-0.07	-0.21	-0.45	0.00	0.00	-4.02	41.69	0.94	1.01	4.68	-0.31	0.09
Hydro	-0.42	0.03	0.06	-0.08	-0.16	-1.95	0.94	105.79	3.64	1.41	-0.33	0.56
Hydro - Mini	-0.46	0.03	0.07	-0.08	-0.17	-2.11	1.01	3.64	12.92	1.53	-0.36	0.60
Wind - Offshore	-0.10	-0.31	-0.68	0.00	0.00	-6.07	4.68	1.41	1.53	52.04	-0.48	0.13
Biomass	-6.40	-14.09	-18.52	-3.16	-3.38	-86.44	-0.31	-0.33	-0.36	-0.48	162.84	0.25
PV	0.20	-0.21	-0.46	0.05	0.11	-0.16	0.09	0.56	0.60	0.13	0.25	110.27

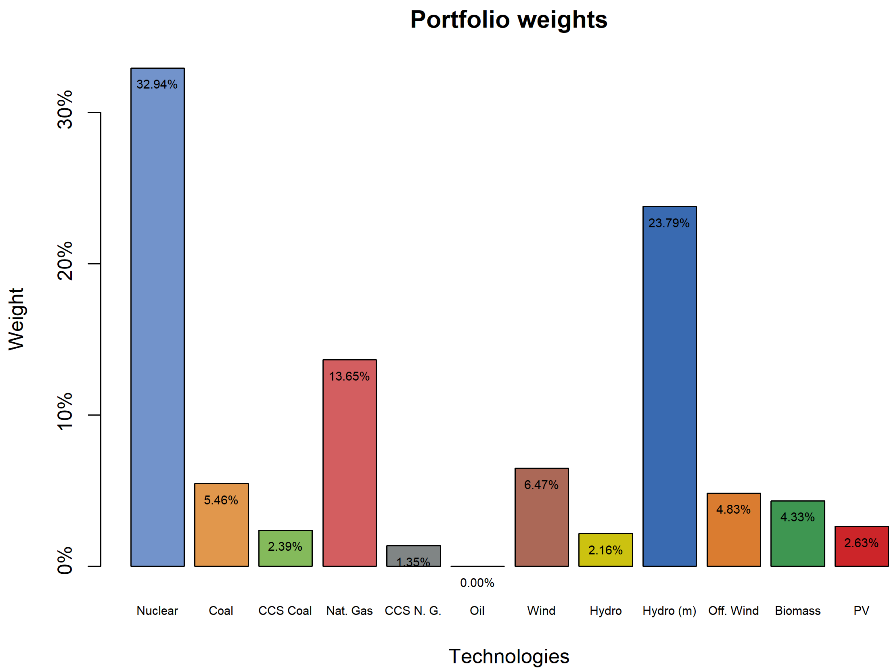

Figure 5: GMV portfolio composition

frontier from the GMV portfolio —on the left side of the figure— to the GMC portfolio — on the right side of the figure.

3.2 Constrained models and scenarios

Once the base model is computed, we adapt the constraints to incorporate the specific analysis we want to study and build the new efficient frontiers, according to every scenario proposed.

The base model serves as a reference for us to compare to the subsequent models computed. We use it as a theoretical limit, a "what if" scenario. If the energy generation had no regulation, the efficient frontier would be the one determined by the base model. But we cannot ignore the fact that power generation has technological limitations; for instance, apart from other important considerations like energy policy objectives and recommendations, it would go against the interests of energy security to implement a generation portfolio like the GMC portfolio of the base model, which assigns 100% of the power generation to the nuclear technology. Furthermore, and especially in the EU, energy policies also search for a reasonable generation cost and for an environmentally-friendly power generation. These facts can be easily added to the base model in order to built what we called constrained models. These models are built on the base model by adding different constraints: generation limits by technology or group of technologies, the minimum generation share for a technology or a group of technologies, maximum portfolio emission factor, maximum portfolio concentration percentage… The flexibility of the model is precisely its capacity to adapt to these constrained scenarios.

In the following sections, we will explain the constraints included for what we called technological models —models incorporating maximum generation limits by technology or group of technologies—, environmental models —models incorporating minimum participation shares for

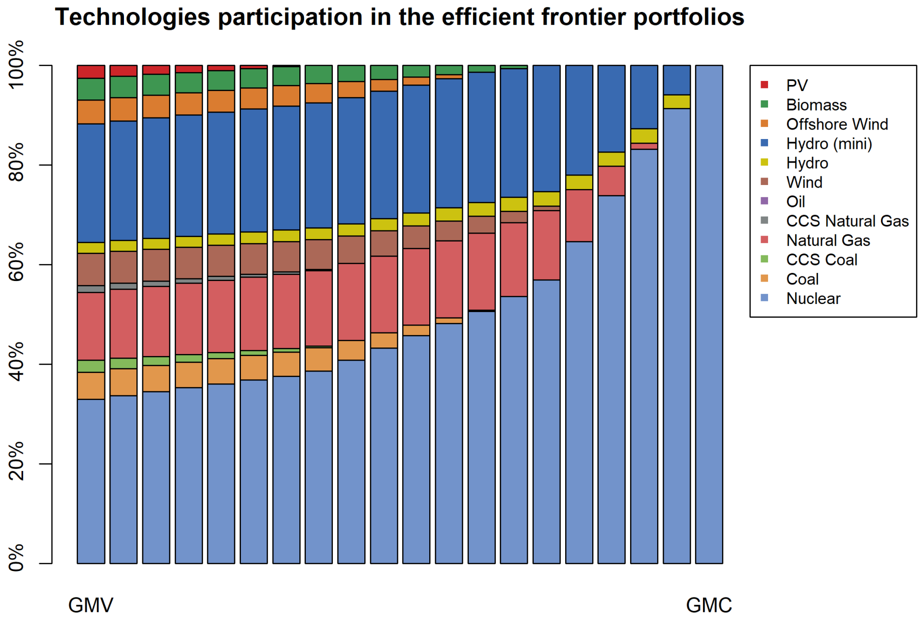

Figure 6: Efficient power generation portfolio composition

RES generation technologies—, and emission models — models whose aim is to minimize the emission factor of the generation portfolios.

3.2.1 Technological models

As explained, the aim of technological models is to bring the model closer to the real world by including constraints on the participation of the different generation technologies considered. These constraints come from energy policies and recommendations and entail improved energy security by enforcing greater diversification of these technologies. In some cases, these policies and recommendations also entail a positive environmental effect: limiting the generation of pollutant technologies causes a higher participation of clean generation technologies and also reduces the emission factor of the generation portfolios.

Now let us include in the base model calculated above the technological limits reflected in Table 4 (DeLlano-Paz, Calvo-Silvosa, Iglesias Antelo, & Soares, 2015; IEA, 2011, 2012; Russ et al., 2009). With these constraints, the efficient frontier of the previous model will obviously be affected. In the GMV portfolio, for instance, nuclear generation participated with a 32.94% share, and in the GMC portfolio its participation was 100%. But now its participation share in the GMV is 29.80% — in fact, its technological limit, meaning that the constraint is active on that technology. Figure 7 compares the efficient portfolio from the previous model with the constrained model efficient frontier. As we can see, the frontier has shifted upwards —meaning a higher cost— and somewhat to the right — reflecting a greater risk.

The GMV of the constrained model is shown in Figure 8. In this figure, we can see that nuclear, hydro (mini) and offshore wind generation technologies participate at their limits. Natural gas and CCS natural gas generation technologies participate near their joint limit — their

Table 4: Generation limits by technology

Technology	Limit
Nuclear	29,80%
Coal and CCS Coal	23,40%
CCS Technologies	18,00% of Coal, Natural Gas and Oil
Natural Gas and CCS Natural Gas	27,60%
Oil	0,80%
Wind	20,30%
Hydro	10,80%
Hydro (mini)	1,50%
Offshore Wind	2,00%
Biomass	8,50%
PV	5,50%

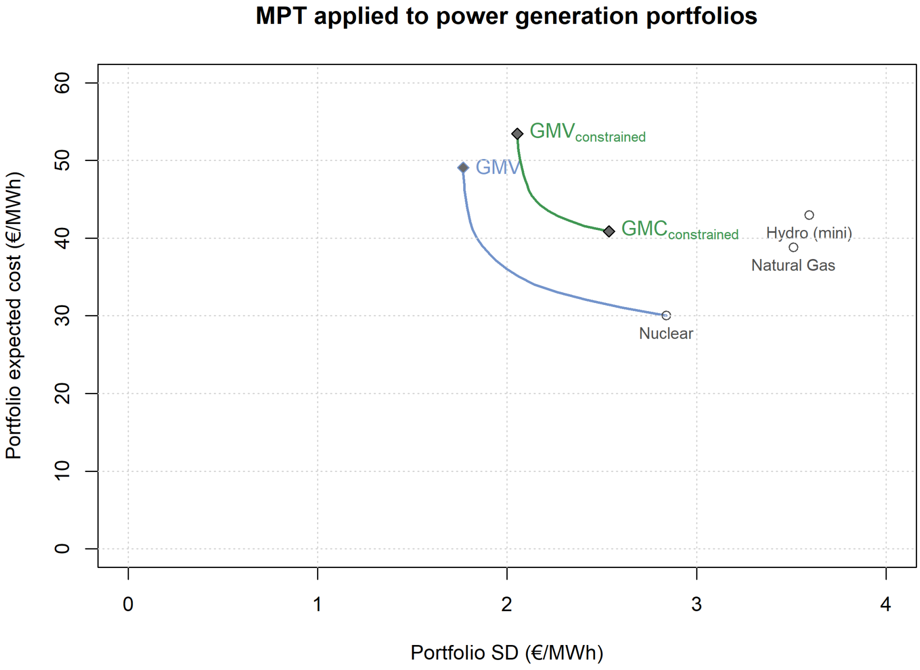

Figure 7: Base model as compared to constrained model

joint share is 27.41% while their joint limit is 27.60%. These results indicate that, under the imposed restrictions, nuclear, hydro (mini), offshore wind and natural gas —both with and without CCS— are the preferred technologies when looking to minimize the generation portfolio risk. On the other hand, Oil does not participate in the power generation GMV portfolio. In fact, oil does not participate at all in any of the efficient portfolios of the constrained model.

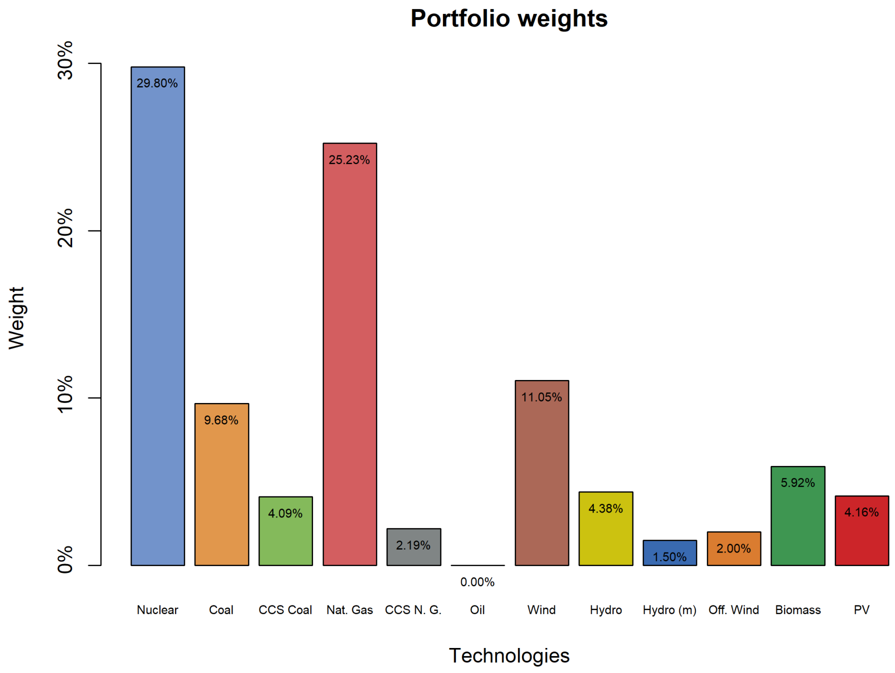

Figure 8: GMV technology participation shares in the constrained model

Figure 9 shows how the participation shares of the generation technologies vary when moving along the efficient frontier from the GMV portfolio to the GMC portfolio. In the figure, we can see that nuclear generation participates at its maximum in any efficient portfolio, reasserting its role as base load technology. Coal is gradually increasing its participation —at the expense of CCS coal— until reaching its maximum in the GMC portfolio. Something similar happens with natural gas generation: it reaches its maximum in the GMC portfolio at the expense of the CCS natural gas. Hydro (mini) generation maintain its participation share at its maximum between the GMV portfolio and the GMC portfolio. Hydro is another technology that increases its participation share in the generation portfolio until reaching its maximum allowed.

The exact composition of the GMC portfolio can be seen in Figure 10. Nuclear, coal, natural gas, hydro and hydro (mini) generation technologies, as stated, participate at their respective maximum allowed participations in this portfolio. Wind also participates, but under its maximum. The rest of the generation technologies do not participate at all in the GMC portfolio. As we see, the GMC portfolio is less diversified than the GMV portfolio, and this is an important variable to have in mind to improve energy security. In the papers, we usually measure the portfolio diversification using the Herfindahl-Hirschman Index (HHI), the expression of which is shown in Equation 14 — where x_i is the weight in a portfolio of the ith technology considered. Sometimes —in particular in the first paper presented in this compilation—, we also

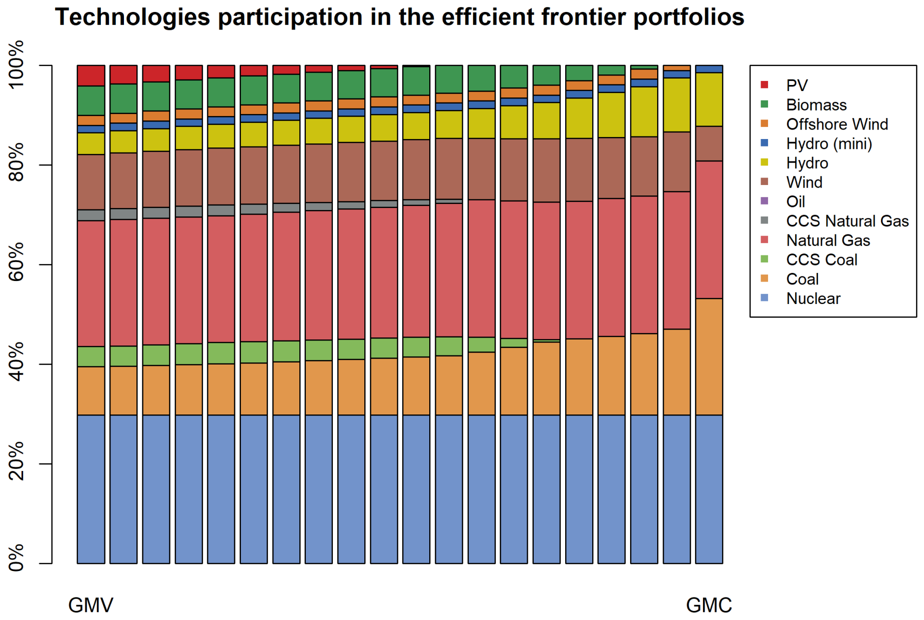

Figure 9: Efficient power generation portfolio composition in the constrained model

use the Shanon-Wiener Index (SWI), the expression of which is shown in Equation 15. In our example, the GMV portfolio shows a HHI of 18.40%, while the GMC portfolio shows a HHI of 23.64%. In Figure 11, we show the HHI for the intermediate porfolios.

$$\mathrm{HHI} = \sum_{\forall i} x_i^2 \tag{14}$$

$$\mathrm{SWI} = -\sum_{\forall i} x_i \ln x_i \tag{15}$$

Knowing the different technoloy weights in any portfolio, it is easy to calculate the portfolio emission factor for any gas considered. For instance, if we consider the CO_2 emission factors shown in Table 5, we will see how the emission factor varies from 166.16 CO_2 kg/MWh in the GMV portfolio to 270.05 CO_2 kg/MWh in the GMC portfolio. In Figure 12, we show the emission factors for the intermediate portfolios.

Table 5: Pollutant technology CO_2 emission factors

Technology	CO_2 emission factor (CO_2 kg/MWh)
Coal	734.09
CCS Coal	101.00
Natural Gas	356.07
CCS Natural Gas	48.67
Oil	546.46
Biomass	1.84

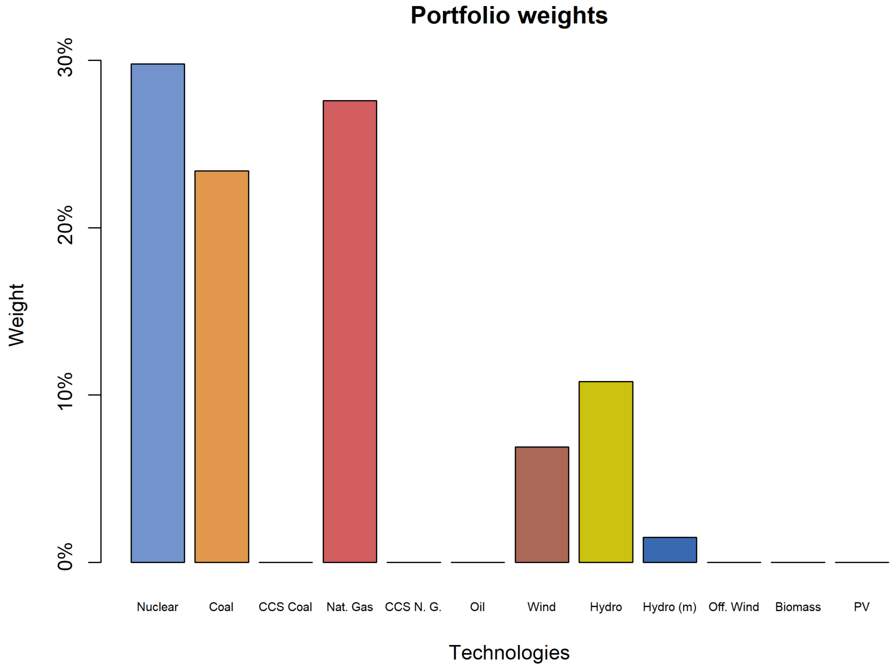

Figure 10: GMC technology participation shares in the constrained model

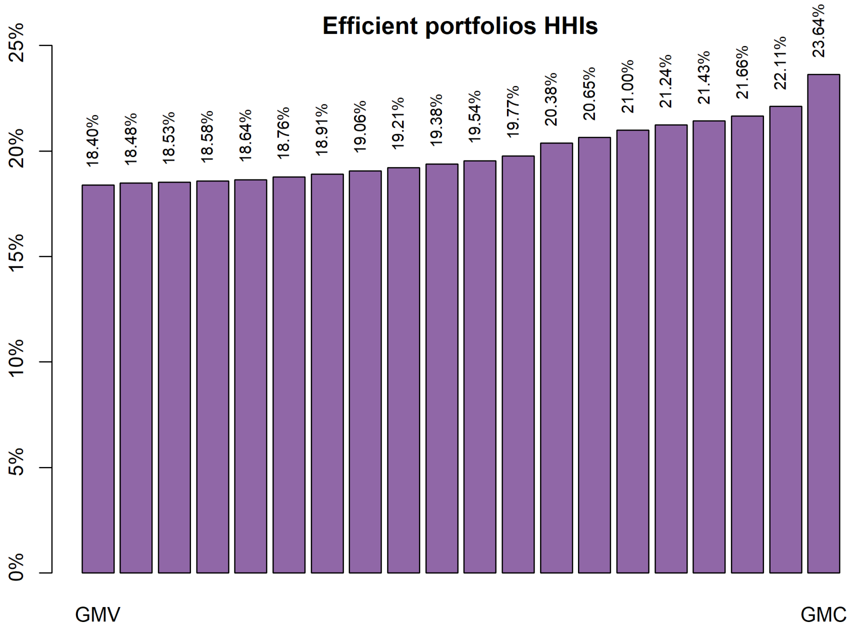

Figure 11: Efficient portfolio Herfindhal-Hirschman indexes

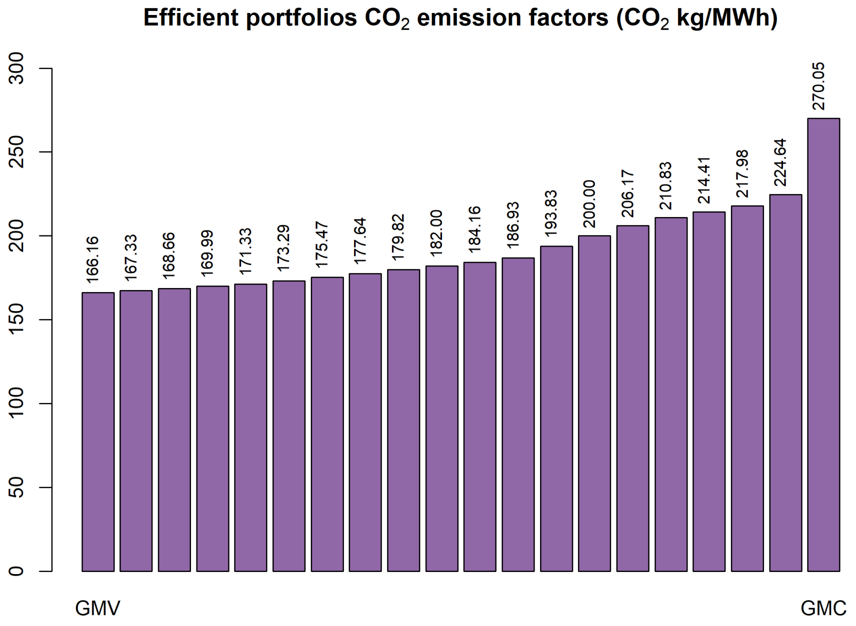

Figure 12: Efficient portfolio CO_2 emission factors

3.2.2 Environmental and emission models

The explained methodology is applied in the works included in this compilation. The three papers presented start from the base model —sometimes called the Markowitz's model— and build more complex models by adding technological constraints, for the most part based on the EU energy commitments for 2030-2050. In the two first papers, we also further develop the constrained models to assess the impact of more ambitious policies regarding the environmental respect.

The first paper includes three additional models: the low emission model, the high RES model and the European Energy Union model. The low emission model incorporates the constraints of the technological model and constraints related to the EU objectives for CO_2 emission reduction. The high RES model add a constraint to the technological model, requiring the EU generation to have at least 43% of the power generation produced by RES. The European Union Energy model uses both types of constraints: the emission reduction and the RES minimum generation constraints.

The second paper studies the eventual impact of the commercial availability of CCS technologies and adds an environmental perspective to the study by imposing a limit on some of the Greenhouse Gases (GHG) emissions. In particular, the GHG considered are Carbon Dioxide (CO_2), Sulphur Dioxide (SO_2) and Nitrogen Oxides (NO_x). In addition, a constraint on Particulate Matter (PM) emission is included in the model. The constraints were set on the basis of the current emission factors of the 2010 generation portfolio presented in Table 6 resulting in three different scenarios: minimum reduction, medium reduction and intense reduction. The exact limits shown in the paper were taken from various European regulations and relevant Literature on the matter.

Table 6: Current 2010 GHG and PM emission factor

	Emission Factor
CO_2	287.70 Kg/MWh
SO_2	29.15 g/MWh
NO_x	126.79 g/MWh
PM	10.97 g/MWh

3.2.3 Scenarios

Once the models are established, we analyze the behavior of the efficient frontier by setting up scenarios. We assess the variations in the efficient frontier, in particular in the extreme portfolios —the GMV and the GMC portfolios—, in light of changes in the input data or constraints. Then we compare the resulting efficient frontiers to the frontiers of the constrained models to draw conclusions.

In the first paper of this compilation, we also include an eventual 50% reduction of nuclear power generation and a complete nuclear shutdown to see the effects of these measures in a time in which countries like Germany are getting rid of this generation technology. These two scenarios are established by adding the convenient constraints on the participation shares of the nuclear technology — in the 50% reduction scenario, we divide the limit shown in Table 4 by 2, resulting in a limit of 14.90% for nuclear generation; and in the nuclear phase-out scenario, the nuclear technology is directly not taken into account. Moreover, in this paper, we considered the possibility of including a restriction on the concentration —via the HHI— of the resulting portfolios, but the results were either similar to those obtained without said restriction or the inclusion of the HHI constraint caused the inexistence of a solution to the model.

In the second paper, the technological and environmental models are calculated for the current expected cost and risk of the CCS technologies, and then several scenarios are presented by changing the expected cost by ±1 and ±2 standard deviations and modifying the risk by ±50%.

3.3 The Capital Assets Pricing Model (CAPM) applied to power generation

The third paper included here imports the CML concept from Finance and applies it to power generation. If we want to apply the CML concept of CAPM to energy and power generation planning, we will encounter a couple of problems. First, to construct the CML we need a free-risk generation technology, and we do not have one. Some authors (Awerbuch & Berger, 2003) argue than the RES power generation plants could be considered as risk-free technologies, since they do not have any variable costs. But, from our point of view, even if we consider the operation and maintenance cost as fixed, some degree of variability still remains that would impede us from branding it as risk-free. Second, in Finance, the efficient frontier is concave (see Figures 1 and 2), so there is a line with a positive slope that is tangent to it (see Figure 3). In the case of calculating optimal generation costs, the efficient frontier is convex and no straight line with a positive slope can be tangent to it.

But if we change the problem from a cost-risk perspective to a more environmental-friendly emission-risk perspective, things change because non-pollutant technologies have no emission risk. This is the idea we defend in the third paper of this compilation. In that paper, we use the information in Table 5 (DeLlano-Paz et al., 2015) to consider the joint minimization of the generation portfolio CO_2 emissions and the risk —in the sense of variability— of those emissions. This is done by separating the generation technologies into two different sets: pollutant and non-pollutant technologies. The emission minimization model is applied only to the pollutant technologies. Previously, we calculated the set of efficient non-pollutant generation portfolios in the same way as explained above. This whole set corresponds to a single point —the coordinates plane origin— if we represent it on a risk-emission plane.

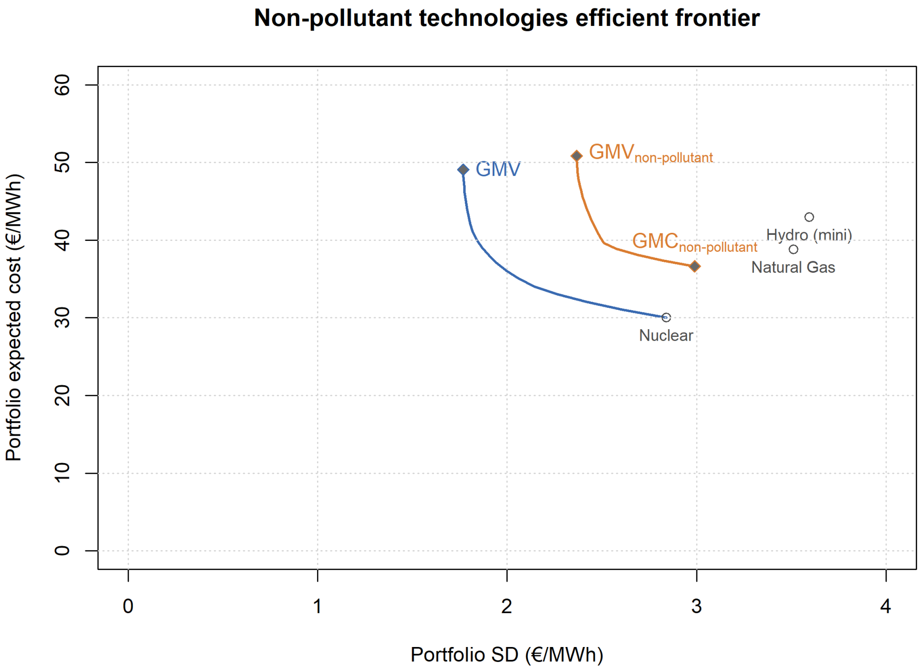

Figure 13: Efficient non-pollutant frontier in a risk-cost plane

Figure 13 shows both the unconstrained model efficient frontier and the efficient frontier for the non-pollutant technologies —nuclear, wind, hydro, hydro (mini), offshore wind and PV generation technolohies— with the information on costs and cost risks shown in Table 2 and adapted constraints for the technological limits. In turn, Figure 14 shows the efficient frontier of the pollutant technologies —coal, natural gas, and oil— on an risk-emission coordinates plane. Biomass and CCS technologies were taken out of the pollutant technology set because they distorted the analysis, due to their low emission factor and emission risk. In fact, if we introduce biomass, it participates at almost 100% in every efficient portfolio. And the effect is similar —although less dramatic— if we introduce CCS technologies. In the third paper, we explain these issues in detail. In Figure 14, we also plotted the non-pollutant efficient portfolios as a point on the coordinates plane origin, as they show neither emissions nor emissions risk. It is important to notice that we are using the CO_2 emission cost risk as a proxy to the emission risk, since we do not have this information available.

In financial CAPM, and because of the concavity of the efficient frontier, we were able to

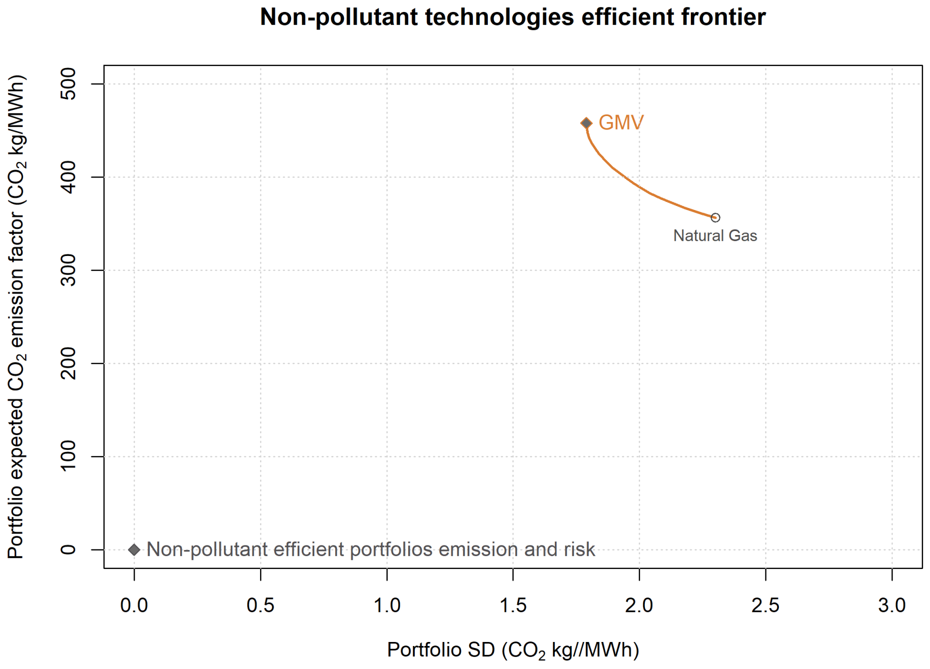

Figure 14: Efficient pollutant frontier in a risk-emission plane

draw a straight line from the risk-free asset in the ordinate axis to the market portfolio. On our risk-emissions plane, the efficient frontier is convex, and we cannot find any tangent point to a line starting in the location of the non-pollutant efficient portfolios. The solution we propose is reflected in Figure 15. Instead of looking for a single point on the efficient frontier, we allow any combination between an efficient pollutant portfolio and an efficient non-pollutant portfolio. The result is the shadowed area in Figure 15 called CML-A, short for CML-analogous area. A policy-maker could use the CML-A to determine specific combinations. For instance, point *A* in Figure 15 corresponds to a risk limit of 1 CO_2 kg/MWh, while point *B* corresponds to a emission limit of 300 CO_2 kg/MWh. Table 7 reflects the characteristics of both points.

Table 7: Portfolio combinations in the CML-A

	Emission (CO_2 kg/MWh)	Emission risk (CO_2 kg/MWh)
Point A	154.14	1.00
Point B	300.00	1.17

3.4 Limitations

3.4.1 Datasets

As commented when presenting the criticism to MPT as applied to energy planning, this field of research has an issue when trying to obtain historical costs for the cost categories of a generation plant, in order to determine its expected generation cost, its risk and the different correlations. In the papers we use our own calculations, based on the seminal papers by Awerbuch (2000) and Awerbuch and Berger (2003), and also the calculations provided by Awerbuch and Yang

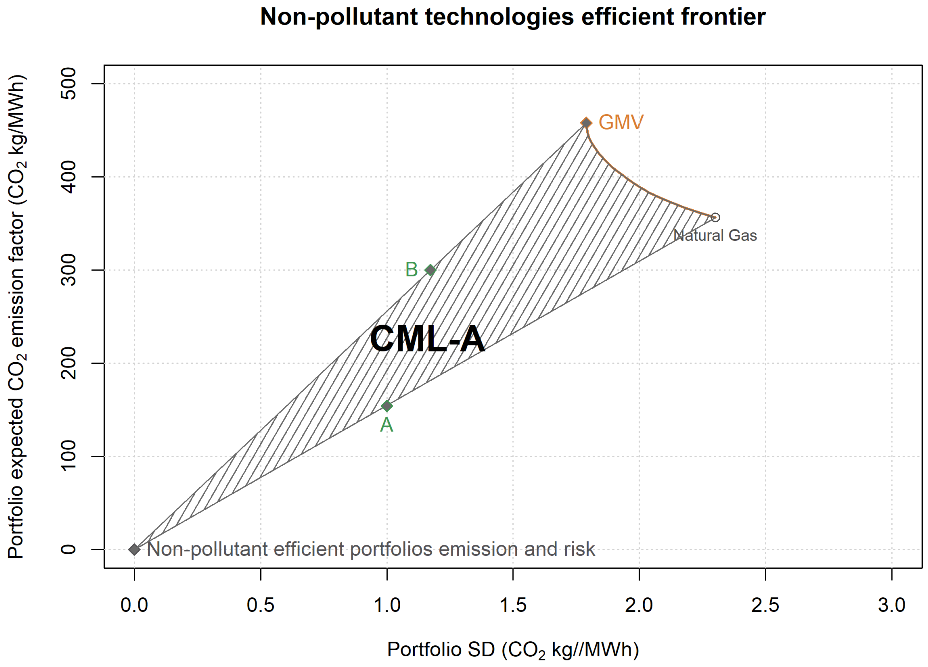

Figure 15: The CML-analogous area in the risk-emission plane

(2007), de-Llano Paz et al. (2014) and de-Llano Paz (2015), as previously stated.

Nevertheless, we think that the difficulty in accessing the information, or even the lack of it, should not be seen as a problem. MPT has proven to be a useful and efficient methodology when applied to power generation, independently of the data used. Of course, the results depend on the inputs to the model —the dataset— and should be addressed as such. The higher the quality of the inputs, the more confident and precise will be the outputs.

For instance, we commented earlier that in the third paper we have used the standard deviation of the CO_2 cost of every pollutant technology as a proxy to the CO_2 emission standard deviation for that technology. Of course, it would have been better to use the real variability of the CO_2 emission, but we were not able to locate this information. The solution adopted —quite similar to the one explained in Awerbuch and Berger (2003)— is, from our point of view, consistent with the research circumstances we faced, and adequate for the problem studied.

3.4.2 Long-term planning with current technologies and past costs

In the papers presented we use calculations based primarily on Awerbuch and Yang (2007), IEA (2011), IEA and NEA (2010) and de-Llano Paz (2015). This means that we are using costs from 2010-2015. In addition, we are using a set of current generation technologies, plus the CCS technologies for coal and natural gas generation. We are also using that information to analyze medium/long-term policies. It is clear that in 10-15 years, the cost of generating electricity will have changed, and so will have the technologies. This is, from our point of view, the main drawback of the model. Despite this, it is true that we are working with all the information available today, and the model results can be updated as new information becomes available.

3.4.3 The convexity of the efficient frontier

As stated, in the third paper presented, we followed the first steps in the natural evolution from MPT to CAPM in Finance. We tackled the problem of the convexity of the efficient frontier when calculated for determining efficient generation portfolios. This issue makes finding a positive-slope tangent impossible. Instead, we delimited a plane area containing every combination of efficient pollutant and non-pollutant portfolios with similar characteristics than the financial CML. But we are inclined to state that continuing the CAPM development in the field of power generation policies will be difficult, at the very least. Even when, from a theoretical point of view, both a line —the financial CML— and an area —the CML-A presented in our third paper— contain an infinite number of portfolios, the fact remains that a straight line is built with two parameters: intercept and slope —in this case, the intercept is already known: the risk-free return— while an area needs three parameters to be defined. In the third paper, we defined the CML-A area with three points: the coordinate origin, the GMV portfolio and the GMC portfolio, which we believe to be appropriate. But further research should be conducted in order to determine which, among all the portfolios inside the CML-A area, should be preferred, if any.

3.5 Models programming

All the steps to build the model have been programmed in a library in R language (R Core Team, 2017). The library code is published for consultation at https://bitbucket.org/paulinomf/an-application-of-the-mpt-to-the-optimization-of-the-eu-power/src/master/. The code, following the guidelines outlined in the work by Zivot (2008), is formed by several functions to calculate the GMV portfolio the GMC —or the GME— portfolio; a specific efficient portfolio given its cost or emission factor; the efficient frontier or the whole feasible frontier; the tangency portfolio and the model itself. The library has also several functions to output the results.

The most important function in the library is `solve.model`. Its objective is to calculate the entire model. It receives as parameters the vector of average values —costs or emissions—, the matrix of variance-covariance, the optional additional inequality ($\geq$) constraints and their limits —any inequality constraint apart from the positivity constraint—, the optional additional equality constraints and their limits —any equality constraint apart from the completeness constraint—, and the optional non-linear constraints — for instance, if we need to constraint the results to a non-linear function like the Herfindahl-Hirschman concentration index. With these inputs, the `solve.model` function executes the aforementioned steps (see Section 3.1) to compute the whole model results.

The code uses a couple of packages from the R packages repository: the `quadprog` package (Berwin A. Turlach & Weingessel, 2013) and the `NlcOptim` package (Chen & Yin, 2017). Both are based on Goldfarb and Idnani (1983). These authors propose a method for solving a strictly convex quadratic program like the one shown in Equation 16.

$$\min f(x) = a'x + \frac{1}{2}x'Gx \tag{16}$$

$$\text{subject to:}$$

$$C'x - b \geq 0$$

According to this model, the constraints conform a matrix in which every row is a constraint itself and each column corresponds to the specific variable in vector x. The elements in this matrix are the coefficients to multiply by. By default, we already programmed the `solve.model` function with the completeness constraint and with the positivity constraint. Thus, our function starts with the matrix C' and the vector b shown in Equation 17. The fact of the completeness constraint is an equality constraint is contemplated in the functions for the referenced R packages — `quadprog` and `NlcOptim`.

$$C' = \begin{pmatrix} 1 & 1 & \dots & 1 \\ 1 & 0 & \dots & 0 \\ 0 & 1 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 1 \end{pmatrix} \quad b = \begin{pmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{pmatrix} \tag{17}$$

Even though we do not use it in this work, our library also contains a function for calculating Euclidean distances from a specific portfolio to the efficient frontier. This requires the use of the `sp` (Pebesma & Bivand, 2005) and the `rgeos` (Bivand, Pebesma, & Gomez-Rubio, 2013) R packages. In some of our current research works we are using this Euclidean distance as a measure of the inefficiency of a given portfolio.

4 Publications

4.1 Publications overview

In this section we include the articles which this compilation refers to. Before reproducing them, we include some information about the impact factor and quality of the journals in which they were published and the congresses in which they were presented.

The first paper, "Addressing 2030 EU policy framework for energy and climate: Cost, risk and energy security issues" was presented at the "2nd International Conference on Energy and Environment: bringing together Engineering and Economics", organized by the School of Engineering (University of Minho) and the School of Economics and Management (University of Porto), that took place in Guimarães (Portugal) on June, 2015.

The contributions of each author are as follows:

Author	Concept	Analysis	Writing	Total
deLlano-Paz, Fernando	45%	55%	50%	**50%**
Martinez-Fernandez, Paulino	45%	45%	50%	**47%**
Soares, Isabel	10%	0%	0%	**3%**

Currently, it is published in the journal “Energy”, number 115, part 2, November 2016, pages 1347-1360 (DOI: 10.1016/j.energy.2016.01.068). The quality indicators of the journal are presented hereunder.

- **Journal**: Energy.
- **Journal Index**: JCR.
- **Impact Factor (2015)**: 4.968.
- **Categories:**

Category	Quartile (2016)	Ranking (2016)
Energy and fuels	1st (17/23)	17/92
Thermodynamics	1st (3/14)	3/58

- **Cites:**
    - WoS: 17 (the article is inside the 10% of the most cited works in the field of Engineering (2016)).
    - Scopus: 18 (the article is in the 94th percentile of citations, i.e. inside the 6% of the most cited works in Scopus in the field of Environmental Science. The citation impact is high with a Field-Weighted Citation Impact of 3.0).
    - Google Scholar: 25.
    - CitEc: 11.
    - Microsoft Academic Search: 15.
    - Journal webpage: 18.
    - CrossRef: 17.
    - Dimensions: 19.
    - Research Gate: 16.

The second paper, “The effects of different CCS technological scenarios on EU low-carbon generation mix” was presented at the “2nd International Conference on Energy and Environment: bringing together Engineering and Economics”, organized by the School of Engineering (University of Minho) and the School of Economics and Management (University of Porto), that took place in Guimarães (Portugal) on June, 2015.

The contributions of each author are as follows:

Author	Concept	Analysis	Writing	Total
deLlano-Paz, Fernando	40%	50%	50%	**47%**
Martinez-Fernandez, Paulino	50%	50%	50%	**50%**
Soares, Isabel	10%	0%	0%	**3%**

Currently, it is published in the journal “Environment, Development and Sustainability”, number 18, issue 5, October 2016, pages 1577-1600 (DOI: 10.1007/s10668-016-9809-4). The quality indicators of the journal are presented hereunder.

- **Journal**: Environment, Development and Sustainability.
- **Journal Index (2016)**: SJR.
- **Impact Factor (2016)**: 0.385 (H-Index: 43).
- **Categories:**

Category	Quartile (2016)	Ranking (2016)
Economics and econometry	3rd (122/136)	257/545
Geography, planning and development	2nd (52/155)	206/623
Management, monitoring, policy and law	3rd (61/63)	112/254

- **Cites:**
    - WoS: 2.
    - Scopus: 2.
    - Google Scholar: 2.
    - Microsoft Academic Search: 2.
    - Springer Citations: 2.
    - Dimensions: 2.
    - Research Gate: 2.

The third paper, “Pollutant versus non-pollutant generation technologies: a CML-analogous analysis” was presented at the “3rd International Conference on Energy and Environment: bringing together Engineering and Economics”, organized by the School of Economics and Management (University of Porto) and the School of Engineering (University of Minho), that took place in Porto (Portugal) on June, 2017.

The contributions of each author are as follows:

Author	Concept	Analysis	Writing	Total
Martinez-Fernandez, Paulino	70%	70%	80%	**73%**
deLlano-Paz, Fernando	10%	15%	10%	**12%**
Calvo-Silvosa, Anxo	10%	15%	10%	**12%**
Soares, Isabel	10%	0%	0%	**3%**

Currently, it is published in the journal “Environment, Development and Sustainability”, number 20, suplement 1, December 2018, pages 199-212 (DOI: 10.1007/s10668-018-0195-y). The quality indicators of the journal are presented hereunder.

- JCR Quality Indicators:
    - **Journal**: Environment, Development and Sustainability.
    - **Journal Index**: JCR.
    - **Impact Factor (2017)**: 1.379.

Category	**Quartile (2017)**	**Ranking (2017)**
Environmental science	3rd	166/242
Green and sustainable science and technology	4th	25/33

  - **Categories:**
  - **Cites:**
    - WoS: 1.
    - Scopus: 1.
    - Google Scholar: 1.
    - Microsoft Academic Search: 1.
    - Dimensions: 1.
    - Research Gate: 1.

- SCOPUS Quality Indicators:
  - **Journal**: Environment, Development and Sustainability.
  - **Journal Index (2017)**: SJR.
  - **Impact Factor (2017)**: 0.392 (H-Index: 43).
  - **Categories:**

Category	**Quartile (2016)**	**Ranking (2016)**
Economics and econometry	3rd	310/613
Geography, planning and development	2nd	256/699
Management, monitoring, policy and law	3rd	142/306

4.2 Paper 1: Addressing 2030 EU policy framework for energy and climate: Cost, risk and energy security issues

Energy 115 (2016) 1347–1360

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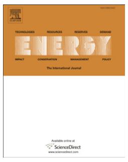

Addressing 2030 EU policy framework for energy and climate: Cost, risk and energy security issues

Fernando deLlano-Paz [a, *], Paulino Martínez Fernandez [a, 1], Isabel Soares [b, 2]

[a] *Faculty of Economics and Business, Department of Financial Economics and Accounting, University of A Coruña, Elviña Campus, 15071, A Coruña, Spain*
[b] *Faculty of Economics and CEF.UP., University of Porto, Rua Dr. Roberto Frias, 4200-464, Portugal*

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ABSTRACT

The different energy sources, their costs and impacts on the environment determine the electricity production process. Energy planning must solve the existence of uncertainty through the diversification of power generation technologies portfolio. The European Union energy and environmental policy has been mainly based on promoting the security of supply, efficiency, energy savings and the promotion of Renewable Energy Sources. The recent European Commission communication "*Towards an European Energy Union: A secure, sustainable, competitive and affordable energy for every European*" establishes the path for the European future. This study deals with the analysis of the latest EU "Energy Union" goals through the application of Markowitz portfolio theory considering technological real assets. The EU targets are assessed under a double perspective: economic and environmental. The model concludes that implementing a high share of Renewable Energy target in the design of European Policies is not relevant: the maximization of Renewable Energy share could be achieved considering a sole Low Emissions of carbon dioxide policy. Additionally it is confirmed the need of Nuclear energy in 2030: a zero nuclear energy share in 2030 European Mix is not possible, unless the technological limits participation for Renewable Energy Sources were increased.

1. Introduction

The energy policies of a territory are aimed at achieving secure, permanent access to resources at an established level of quality and a reasonable cost for consumers, with the lowest possible environmental impact. They are also focused on increasing the level of energy efficiency and savings, which will contribute to reducing energy intensity. This ultimately improves competitiveness and the sustainable development of the State in question, as reflected by less pollution [1].

The design of the portfolio of technologies used to produce electricity takes on special importance in the context of energy and environmental planning. It is a matter of defining "how" electricity should be produced over the medium-long term in a territory. In play are not only acceptable production costs to the consumer, but also the level of dependence on outside resources, the corresponding energy security of the territory, and the social and environmental impact that the use of the available technologies might entail.

However, the application of the energy policies is subject to a high degree of uncertainty. The origin of this lies in the insecurity associated with the anticipated technological development, the evolution of the economic situation, possible changes in the regulatory framework, the evolution of the factors that impact the final price of the policies to be implemented, and the efficacy of compliance with the environmental objectives that have been set. All of these circumstances clearly complicate decision making.

The quest to determine the environmental dimension of the portfolio can be framed within a social trend that seeks not only the efficient use of resources, but also waste reduction, the conservation of local resources and the reduction of pollutant gas emissions [2]. The most developed economies with the highest levels of income are the ones that show the greatest demand for environmental protection [2,3]. As a matter of fact, a European technologies

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* Corresponding author. Tel.: +34 981 167000x2599.
E-mail addresses: fdellano@udc.es (F. deLlano-Paz), paulino.martinez@udc.es (P. Martínez Fernandez), isoares@fep.up.pt (I. Soares).
[1] Tel.: +34 981 167 000x2553.
[2] Tel.: +351 225 571 100x4269.

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portfolio that is both environmentally and socially friendly would also provide greater energy security.

In the European Union, its energy dependence amounted to 53% in 2012 [4]. It meant an impact over its economy of a 3.1% of its GDP (gross domestic product) [5,6]. In this context, the European Union has based its energy policy on the improvement of its competitiveness, security of supply and sustainability [7–9]. In 2009, the European Union approved Directive 2009/28/EC [10] establishing the environmental and energy targets for 2020, referred to as the “20-20-20 strategy”. It calls for a 20% reduction in pollutant gas emissions as compared to 1990, 20% of all energy consumption from renewable sources and a 20% improvement in energy efficiency, understood as the ratio between gross energy consumption and the gross domestic product. The strategy was clear, to continue to reduce energy dependence and pollutant gas emissions, while increasing energy efficiency.

Recently, in October 2014, the European Union [11] presented its energy targets for 2030, the “Energy Union”: attaining at least a 40% reduction in greenhouse gas emissions as compared to 1990 levels (rising to a 61% reduction for power sector[3]), and increasing the share of energy efficiency and renewable energies to 27% of gross energy consumption (a 43% of renewable power portfolio share[4] [5]).

The energy horizon for the European Union has been clearly defined. There is also a clear commitment to increase the level of energy security by reducing the risk of disruptions and increase the level of respect for the environment by means of emissions reductions up to 2030 and 2050. The main question in relation to this strategy is whether the European Union is on the right track towards an efficient design in terms of the cost and risk of its future technology portfolio.

We seek the answer of this question through the application of Modern Portfolio Theory –hereinafter, MPT- to energy planning, which has been widely accepted as a valid, proven methodology. We decide to design an efficiency assessment model that would permit minimizing the risk of generating electricity while still meeting the three proposed EU 2030 goals: minimum portfolio share of renewable energies, efficiency improvement, CO_2 emissions reduction and the diversity level of each portfolio.

In order to facilitate the analysis we propose four policies scenarios for 2030: the *Base* scenario, the *Low Emissions* scenario which incorporates the European CO_2 emission reduction goal, the *High Renewable Energy Sources* (hereinafter, RES) scenario which considers the minimum share of RES target, and the European *Energy Union* scenario, which includes both restrictions: emission reduction and minimum RES share goals in the 2030 European power mix. Additionally the study about two cases of nuclear energy share reduction is proposed: the impact over policies and efficient portfolios considering 50% or 100% reduction on nuclear energy share in 2030. It is based on the analysis of the effects of a possible generalization of German shutting down nuclear energy decision in 2022 in European Union policy [12].

The contribution made by this paper is to evaluate the efficiency of the proposed framework of European Union energy and environmental policy to 2030 in terms of power technologies portfolio –Markowitzás approach-. The paper presents an enriched quadratic optimization mathematical model perspective and its solutions contain the different issues of the European energy and environmental policy: cost, risk, technological change, efficiency, the environmental impact and security of supply. The analysis allows calculating the costs of this policy comparing to different scenarios of policies and targets. The approach seeks the *social and environmental aim* [13,14] of European electricity generation with a triple perspective: an acceptable level of risk for society, a low social cost and respect for environmental conditions. To this end, in the second section we begin by outlining and reviewing the methodological approach of MPT applied to power real assets and portfolios and we present our model. Right afterwards, in the third section we report the results of EU 2030 energy and environmental policy scenarios. Next, in the fourth section we discuss about the effects in terms of cost, risk and emissions policy impacts of a possible nuclear energy shutting down scenario. Finally, we conclude in the fifth section with a discussion about the policy implications of our analysis.

2. The Markowitz portfolio model: an useful tool for energy planning

Considering that Financial Portfolio Theory can be implemented in a context of real assets, some recent studies have stated that it has become a valid and useful methodological tool to identify efficient power technologies portfolios [15,18–25,27–30,41,44–48]. A less-than-strict assumption of the portfolio theory hypotheses is required with regard to market efficiency.

The Portfolio Theory proposes that the expected performance of the Portfolio can be calculated as the weighted sum of the costs of each technology which participates in the mix, and the expected risk is associated with the variability of the considered cost - measured by each standard deviation and the different correlations between costs and technologies-. The different technologies are defined employing the same approach: expected cost and risk. The aim of this proposal is the achievement of the minimum costs or risks depending on the objective function approach. The model will define the efficient portfolios frontier with different cost-risk combinations through different technologies shares (which compose the portfolio). The portfolio optimization model seeks the minimum risk or the minimum cost, including the Markowitz's model constraints and four specific ones. These constraints would permit considering the three proposed EU 2030 goals and the level of energy supply of each portfolio: minimum portfolio share of renewable energies, efficiency improvement, CO_2 emissions reduction and the diversity level of each portfolio.

Portfolio theory can result in a valid and contrasted methodology for evaluating real assets and electricity production portfolios. The application is based on an approach change: substituting return by asset and portfolio cost. Proposing the analysis from the simultaneous conceptual consideration of the cost and the risk confers the approach a greater capacity and conceptual wealth than that of the simple least-cost individual generating technology perspective [15].

The Markowitz model [16] follows a quadratic optimization mathematic formula. The analysis of the technology portfolio by model is based on the study of both variables defined for each technology. In this manner, the expected cost of the portfolio $[E(C_p)]$ (Eq. (1)) consists of the weighted sum of the share of each technology $[x_t]$ and is defined by its expected cost value:

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[3] This 2030 GHG reduction objective for Power Sector is calculated as the average of the EU reduction interval lower and upper bounds [32]. Thus, as these bounds are 54% and 68%, we used 61% as the reduction objective.

[4] According to EC (2014) [5], the 27% overall Renewable Energy Sources share in 2030 of gross energy consumption would translate into a 43% Renewable Energy Sources-Electricity share.

$$E(C_p) = x'c,\ x\in\mathbb{R}^T,\ c\in\mathbb{R}^T, \tag{1}$$

being C_p the total cost of the portfolio p -based on production costs[5] and externality costs[6]-; $x_t\in x, 0<t\leq T, T=12$, the participation of the technology t in the portfolio p (x_t) and $c_t\in c, 0<t, \leq T, T=12$, the total generation cost for technology t in €/MWh.

This study follows the mathematical expression for the total technology costs presented in De-Llano et al. (2014), based on including the externality costs as important costs in the total production cost of electricity generation. A number of 12 generation technologies is considered, the most important in the EU [12,17]: coal, coal with carbon dioxide capture and storage (hereafter, CCS), natural gas combined cycle, natural gas combined cycle with CCS, oil, nuclear energy, large hydro, small hydro, on-shore wind, off-shore wind, solar photovoltaic and biomass energy.

The expected risk for a portfolio (σ_p) is defined according to the standard deviation of each technology and the possible interrelationships that might exist among the different types of costs[7] for each pair of technologies, weighted according to the individual share of each technology in the portfolio. The risk by technology (Eq. (2)) is obtained from data on the variability of the different cost components:

$$\sigma_p = \left(x'Vx\right)^{\frac{1}{2}},\quad V\in\mathbb{R}^{T\times T},\ v_{ij}\in V = \begin{cases}\sigma_{t_i}^2 \text{ if } i=j\\ \sigma_{t_it_j} = \rho_{t_it_j}\sigma_{t_i}\sigma_{t_j} \text{ if } i\neq j\end{cases} \tag{2}$$

In this expression, the shares ($x_t\in x, 0<t\leq T, T=12$) are the solutions proposed by the model for portfolio optimization.

The problem of the inexistence of historical data for the variation of costs components is solved through the generation of data by simulation techniques —MonteCarlo- or through the assumption of risk data from other studies [18–21].

The objective function is the minimisation of the generation portfolio risk forcing the cost to be equal to a determinate value [22–25]. Its expression would be in Eq. (3):

$$Min\{\sigma_p\} = Min\ (x'Vx)^{\frac{1}{2}} \tag{3}$$

The Markowitz's approach is completed by the inclusion of three specific restrictions as the addition of shares being equal to the unit (Eq. (4)), the non-negativity of the variables (Eq. (5)) and a restriction on the cost variable (Eq. (6)):

$$\sum_t x_t = 1 \tag{4}$$

$$x_t \geq 0 \tag{5}$$

$$E(C_p) \leq Portfolio\ Cost\ Value \tag{6}$$

This work follows the approach outlined by De-Llano et al. [26]. Data of expected costs and estimated risks for the different technologies can be consulted in ANNEX A (Table 4; Table 5). It includes additional restrictions on the share of generation technologies: $\{\ x_t\leq Maximum\ percentage\ of\ the\ technology\ share\ \text{“}t\text{”}\}$, following the literature [13,20,22,25,27–31] (ANNEX A; Table 6), and on the technologies portfolio carbon dioxide emission $\{Portfolio\ Emissions\ Factor_{CO_2} \leq CO_2\ EU\ emissions\ limit\}$. For the CO_2 emission constraint the model includes the proposal of DeLlano-Paz et al. [9]. The portfolio emission factor (in kg CO_2/MWh) is calculated in these terms (Eq. (7)):

$$\begin{aligned} CO_2\ Portfolio\ Emission\ Factor = {} & 734,09\ X_{Coal} + 101\ X_{coal\ with\ CCS}\\ & + 356,07\ X_{Natural\ Gas}\\ & + 48,67\ X_{Natural\ Gas\ with\ CCS}\\ & + 546,46\ X_{Oil} + 1,84\ X_{Biomass} \end{aligned} \tag{7}$$

Additionally for the $CO_2\,EU\,emissions\,limit$ calculation was considered the IEA (International Energy Agency) 2010 [17] portfolio $CO_2\,Emission\,Factor$ value and the emissions reduction target contained in the Communication from the European Commission “A Roadmap for moving to a competitive low carbon economy in 2050” [32] which consists on a 61% of carbon dioxide emissions from 1990 levels (53,63% from 2010 levels).

The output of the model is a vector $x\in\mathbb{R}^{12}$ of share percentages. Each element in the vector, x_t, with $1\leq t\leq T$ and $T=12$, represents the technology t share in the portfolio. We calculate the risk and the expected cost of the portfolio using equations (1) and (2). The resulting pair of risk and cost can be plotted in a Cartesian coordinate system (Fig. 1). A curve, called solution portfolios curve, can be drawn by joining these points —risk-cost pairs—. This curve has a relevant subset of points: the so called efficient frontier. This curve is limited by the absolute minimum risk portfolio —on the left of the Figure— and the absolute minimum cost portfolio —on the right of the Figure—. The efficient frontier is composed by those portfolios having the best risk-cost combination to be assumed by the society in order to generate power. These portfolios cannot see reduced their cost without increasing their risk and vice versa.

Four models are presented as four different scenarios. The *Base* scenario only includes technological constraints, in relation to stablish a limit for the maximum share of each technology in 2030, attending its development and implementation —see ANNEX A-. Therefore it not includes any constraint about minimum RES share or pollutant emissions reduction goal. The *Low Emissions* scenario incorporates in addition CO_2 emission reduction goal. The third scenario, the *High RES* adds to the restrictions of the *Base* the minimum share of RES ones: 43% of total electricity produced by RES. The last scenario, the European *Energy Union* is the fullest model due to the inclusion of both restrictions: emission reduction and minimum RES share goals in the 2030 European power mix.

The objective of this methodological approach is the generation of efficient portfolios. Efficient portfolios according to the model form what is called the efficient frontier. These are those that

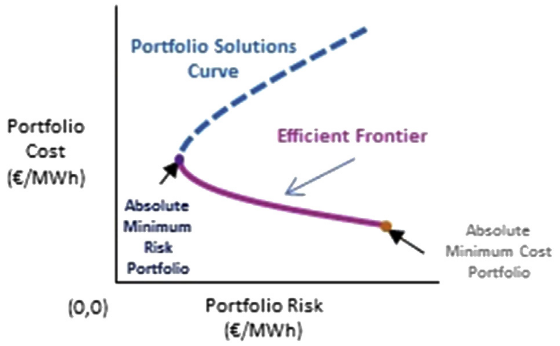

Fig. 1. Portfolio cost-risk representation.
Source: Own author's calculation.

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[5] Investment, fuel, O&M, and complementary cost (intermittency, decommissioning and waste treatment costs).

[6] Pollutant gas emissions, radioactivity, land use for biomass and accident in technological plant.

[7] Included are correlations between the costs and O&M, and between fuel costs and CO_2 emissions costs.

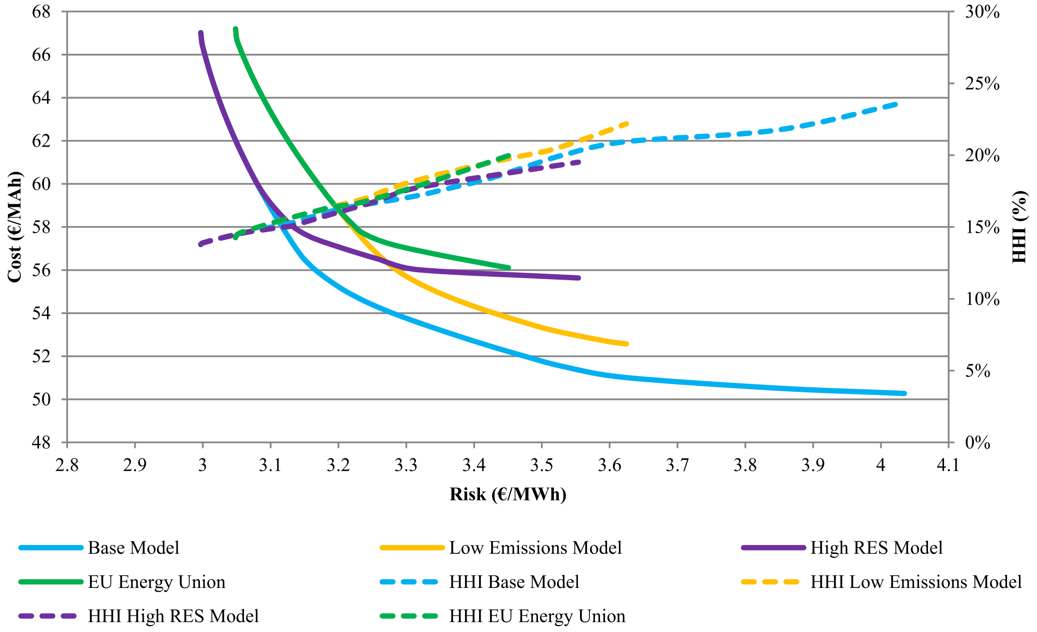

Fig. 2. Efficient portfolios and HHI Index results by scenario.
Source: Own author's calculation.

permit minimizing the portfolio risk for a given cost. The frontier is bounded on the left by the portfolio with the minimum absolute risk and on the right by that with the minimum absolute cost. We study these two portfolios because of they are the most relevant ones in the efficient frontier.

In addition is considered the inclusion of another restriction about the level of diversification of the portfolio. The Shanon-Wiener (SWI from now on) –Eq. (8)- and the Herfindahl-Hirschman[8] (HHI, hereinafter) –Eq. (9)- indexes are employed. There are several studies in the literature that are based on these measurements to define the degree of diversification, disparity, concentration or the relative size of the power generation portfolio [33–40].

$$\mathit{Shanon - Wiener\ Index\ (SWI)}: \quad -\sum_i p_i \ln p_i \tag{8}$$

$$\mathit{Herfindahl - Hirschman\ Index\ (HHI)}: \sum_i p_i^2 \tag{9}$$

There are different opinions about which one of these indexes should be preferred. Hickey et al. [39] prefer HHI versus SWI because it provides a broader analysis by defining different weights regarding diversity and balance. In other words, if the analysis focuses only on the global concept of diversification, and does not consider weights for variety and balance, the authors propose the SWI as the best index due to the compliance of most of the several criteria needed to be consistent. However Grubb et al. [35] agree with Stirling [34] and choose the index SWI against the HHI. The reason is mathematical: the order proposals (rankings) are not sensitive to changes in the logarithms basis. Grubb et al. [35] prefer to show the results of both indexes relying on the quality of their information which is consistent and reliable in both cases. In this regard, Kruyt et al. [38] highlight the power of both indexes in relation to two important properties of diversification: variety and balance. Stirling [34] mentions simplicity in calculation based on historical data and the potential for future calculations (necessarily supported by projections) as key to the generalization of the implementation of these indices.

3. Results

The different efficient frontiers can be represented in a cost and risk Cartesian diagram (Fig. 2). Free-emissions technologies (nuclear and RES –biomass excluded-) share exceeds the 50% into power generation efficient portfolios. The impacts over costs and risks of the efficient portfolios, which include EU targets, are reasonably balanced compared to no-targets portfolios. In the next points the different results are analysed in terms of portfolio cost and risk, CO_2 emissions, diversification and technological change. Considering an emission reduction policy implies higher portfolio cost and risk, as the rightward. However achieving the high RES share goal, individually, it can be possible with the same cost-risk that the minimum risk portfolio.

3.1. *Cost and risk policy impacts*

The costs of electricity production remain at high levels under an implementation of emission reduction targets -*Low Emissions* scenario-. We can see in Fig. 2 how the efficient frontier of *Low Emission* moves from the base scenario right and upwards: It means an increase in cost by 5%. It moves from 50.27€/MWh in *Base* scenario to 52.57€/MWh in *Low Emissions* scenario (Table 1). Its risk undergoes an important reduction of 10%, from 4.03€/MWh –*Base*- to 3.62€/MWh. -*Low Emissions*-. The Absolute Minimum

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[8] It allows the competition analysis by assessing the degree of market concentration, taking into account the relative size of the company and its individual distribution. It agrees with Simpson limit in ecology Bazilian and Roques [36].

Table 1
Portfolio costs and risks. Absolute minimum risk and absolute minimum risk portfolios.

Risk & cost portfolios/Scenarios	Absolute minimum risk porfolios				Absolute minimum cost portfolios			
	Risk (€/MWh)	Cost (€/MWh)	Risk evolution	Cost evolution	Risk (€/MWh)	Cost (€/MWh)	Risk evolution	Cost evolution
Base	3.00	67.02			4.03	50.27		
Low Emissions	3.05	67.20	1.71%	0.27%	3.62	52.57	−10.16%	4.58%
High RES	3.00	67.02	0.00%	0.00%	3.55	55.63	−11.91%	10.66%
Energy Union	3.05	67.20	1.71%	0.27%	3.45	56.11	−14.47%	11.61%

Source: Own author's calculation.

Risk portfolio does not present significant variations in cost and risk (Table 1).

In the *High RES* scenario in which the EU would only implement a minimum share of RES (43%), the power production cost would never be less than 55.63 €/MWh. It supposes an increase of 10.66% over *Base* scenario (Table 1). The reason is the high cost of biomass technology, which nevertheless would participate in the Absolute Minimum Cost portfolio. The *High RES* efficient frontier moves again up and rightwards, which implies high portfolio cost values (Fig. 2). Additionally the maximum risk becomes shorter, with a value below 3.6 €/MWh (Table 1). Therefore the Absolute Minimum Risk portfolio overlaps with the *Base* potfolio. This is considered an important fact because it means that the EU would reach both the goal of minimum share of RES and a joint share of RES technologies over 46% –above the 43% target– if they look for the minimal risk to produce electricity (Table 3).

We included in Annex B an analysis –through tornado diagrams– of how each technology affects the portfolio cost –and also the portfolio emission factor– when they *ceteris paribus* participate at their minimum and at their maximum.

We can draw some relevant conclusions comparing the impact on the portfolio average cost and risk of the separate implementation of both policies. In terms of cost, it would be more costly –over a 4.69%- maintaining a *High RES* share portfolio than another with *Low Emissions* –with an increase of 2%- (Table 2). However, we get the opposite situation when we look at the risk. *High RES* portfolios –due to the inclusion of a greater RES share– achieve lower portfolio risk values (−3%) on average (Table 2).

Reaching the *Energy Union* scenario would cause the greatest cost increase (5%) of the different options, and a risk reduction of 1% on average from the *Base* scenario (Fig. 2; Table 2). In the *Energy Union* scenario, the minimum risk portfolio is the same than the one for the *Low Emissions* scenario (Fig. 2). Hence we conclude that it is possible to achieve the Absolute Minimum Risk both through the implementation of a single goal –the emissions reduction objective– or through the implementation of both objectives: emissions reduction and RES minimum share.

In terms of risk we can see an increase of 1.71%, and a 0.27% of increase in cost, with relation to the *Base* scenario (Table 1). In Absolute Minimum Cost portfolios the cost impact is greater, as this policy mix raises the portfolio cost in 11.61%, but it improves its risk, reducing it in a 14.4% (Table 1). This means that it is not possible to find a portfolio with lower cost than 56.10 €/MWh –while in *Base* scenario it was possible to find a portfolio with a cost of 50.27 €/MWh–. The compensation would be the already mentioned risk reduction –to 3.45 €/MWh, under 4.03 €/MWh of the *Base* scenario Absolute Minimum Cost portfolio– (Table 1).

Table 2
Portfolio mean cost and mean risk impacts over base scenario.

Scenario	Impact over base scenario	
	Cost mean	Risk mean
Low Emissions	2.03%	0.67%
High RES	4.69%	−3.11%
Energy Union	5.02%	−1.03%

Source: Own author's calculation.

3.2. Portfolio CO_2 emissions

The level of CO_2 emissions of the efficient portfolios depends on both its goal and the policy scenario contemplated. The most polluting portfolios are the Absolute Minimum Cost in absence of emissions restrictions (*Base* and *High RES scenarios*). They double the emissions limit for 2030 (Fig. 3). The reason is the participation to their limits of coal (24%) and natural gas (28%) technologies -Fig. 6-. An important conclusion can be highlighted: in *High RES* scenario, although RES reach the minimum share of 43%, portfolio emissions are much higher than the allowed limit (Table 3). This is because we looked for the lowest portfolio cost. Nuclear energy share –free emissions technology- is reduced to 5%, and coal share –with heavy emissions- is increased to the aforementioned limit of 24% (Fig. 6).

Conversely, the portfolios that minimize the risk lead to lower emission levels –171.18 gr./MWh-, but they are still far away from the 2030 emissions goal –133.41 gr/MWh- (Fig. 3). For these portfolios the share of RES technologies stands at 46%, below the necessary participation in *Low Emissions* and *Energy Union* scenarios which is 48% (Table 3). Two ideas can be drawn from this fact: looking for a minimum risk portfolio would imply the reduction of emissions, and implementing a single *High RES* policy would not ensure achieving the 2030 emissions reduction goal. This goal would only be targeted if the reduction goal is included in the implemented policy.

As stated, we included in Annex B an analysis of how each technology affects the portfolio emission factor when they individually participate at their minimum and at their maximum.

Table 3
Efficient portfolios HHI results and RES share by scenario.

Portfolio/Scenario	Absolute minimum risk portfolio		Absolute minimum cost portfolio	
	HHI	RES share	HHI	RES share
Base	13.78%	46.01%	23.67%	19.14%
Low Emissions	14.26%	48.54%	22.19%	34.57%
High RES	13.78%	46.01%	19.51%	43.00%
Energy Union	14.26%	48.54%	19.97%	43.00%

Source: Own author's calculation.

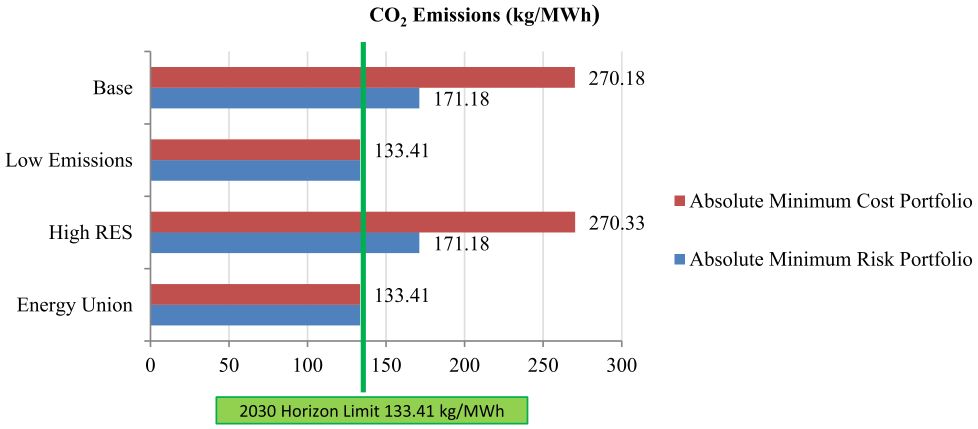

Fig. 3. Efficient portfolio CO_2 emissions by scenario.
Source: Own author's calculation.

3.3. Portfolio diversification

In the proposed analysis, two points of view are presented: achieving the minimum cost or the minimum risk for the power generation portfolio. It would mean the selection of the best combination of technologies to produce electricity which respects a social and environmental dimension. Therefore, it would be necessary to define at European Union level what would be the goal of the power generation portfolio design. To answer this question we propose to include the dimension of the level of portfolio diversification through the Herfindahl-Hirschman Index. The results confirm that the better option is every time trying to reach the minimum risk generation portfolio. The translation in terms of energy policy must be that the more diversified the portfolio and the high RES share would be, more risk of a possible disruption of supply provoked by geopolitical reasons will be reduced and higher level of European energy independence [1,2,7,41,42].

The results about portfolio diversification confirm the existence of a direct relation between this level and the assumed risk. The minimum HHI values, that show greater diversification, are reached for those portfolios that minimize the risk for each one of the studied scenarios (Table 3; Fig. 4). On the other hand, looking for an Absolute Minimum Cost portfolio would cause achieving the greatest risk and the lowest level of diversification.

The conclusion seems clear: minimizing portfolio financial risk leads to the minimization of the risk of supply disruption. The levels of the European energy security could be improved through the portfolio design. The economic and geopolitical dimensions of the portfolio would achieve good levels thanks to the increase of

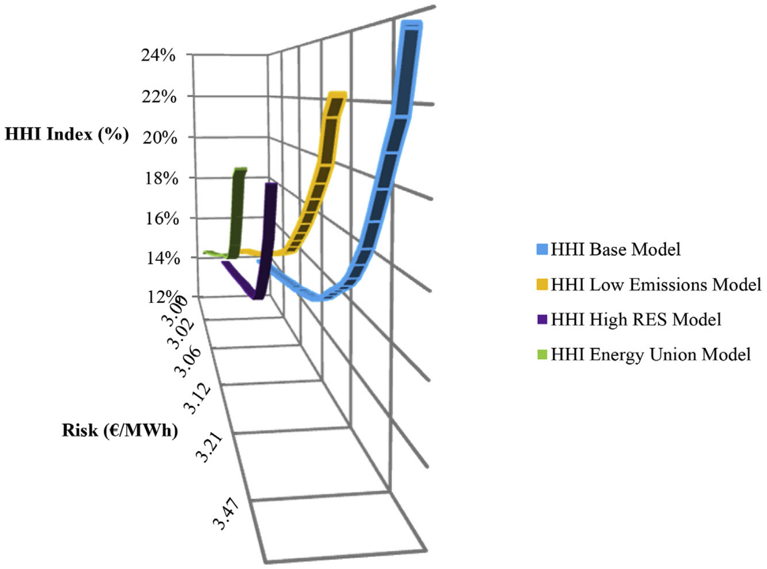

Fig. 4. Efficient portfolios HHI Index results by scenario.
Source: Own author's calculation.

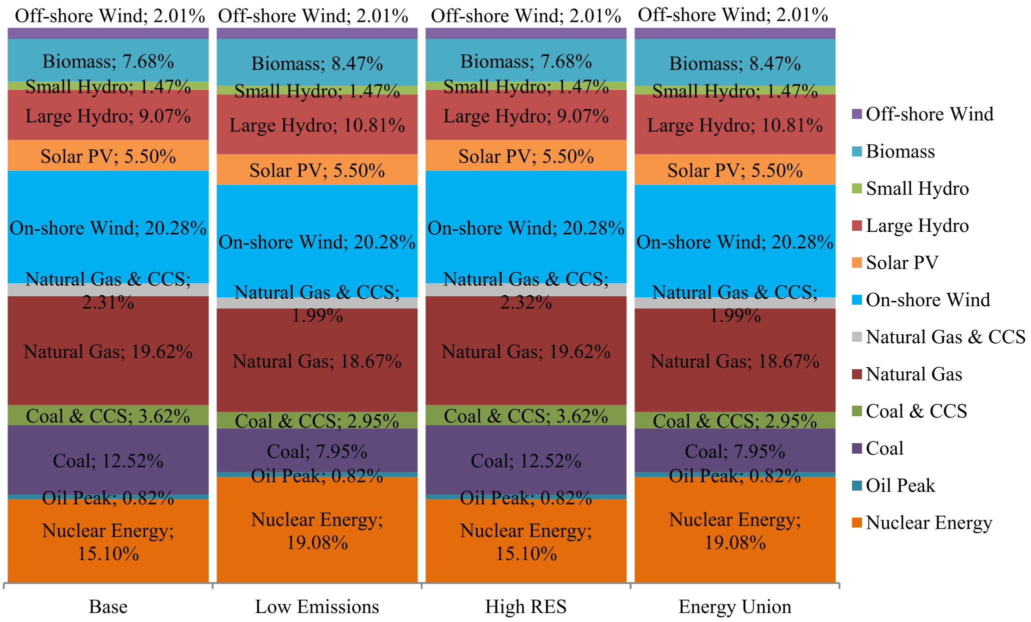

Fig. 5. Composition of the Absolute Minimum Risk portfolios by scenario (2030).
Source: Own author's calculation.

portfolio RES share, which are indigenous sources. The way to achieve the target of the European energy independence for electricity generation has in RES and in emissions limits two important pillars.

3.4. Portfolio technological change

Technological change to be achieved by the EU in 2030 will depend on the type of the target portfolio. Hence if the goal is to achieve minimum risk the EU would need the presence of all available technologies (Fig. 5). The greatest technology share in the portfolio would be on-shore wind (20%), followed by natural gas (19%), nuclear energy (15–19%) and large hydro (10%). Depending on the scenario the portfolio composition is slightly modified. In the *Energy Union* scenario all RES reach the share limit (Fig. 5). RES would be in this scenario preferred technologies. Besides, in 2030 the commercial availability of CCS technologies is needed.

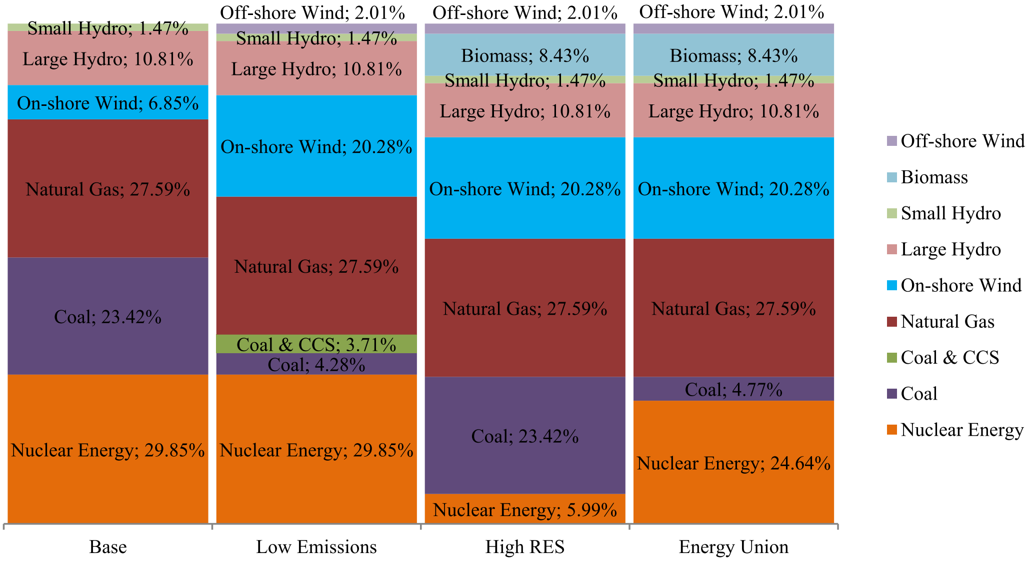

Fig. 6. Composition of the Absolute Minimum Cost portfolios by scenario (2030).
Source: Own author's calculation.

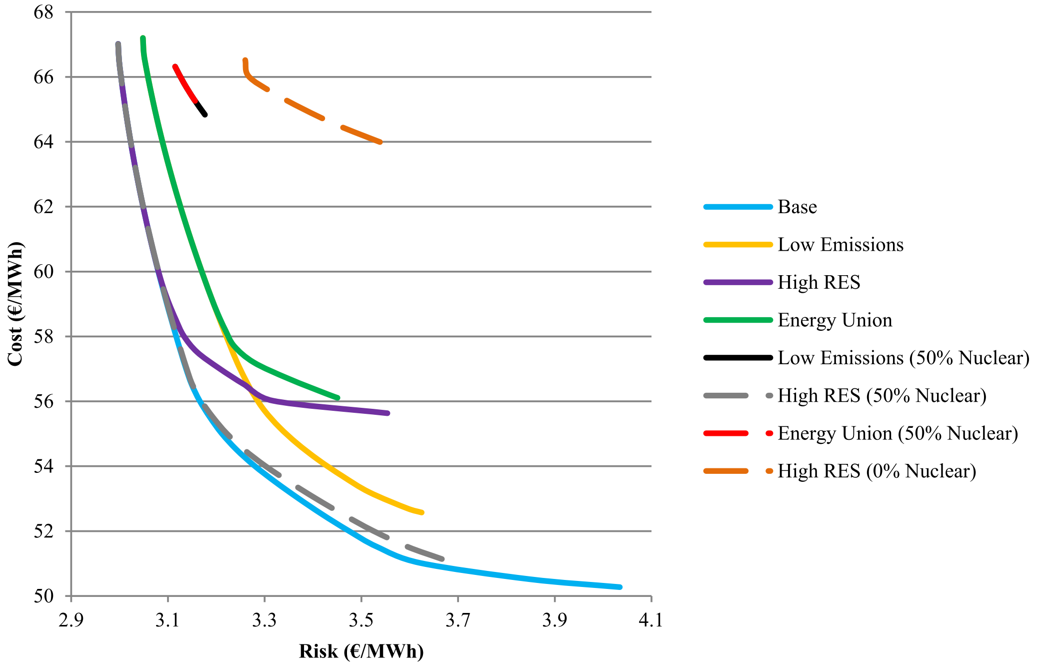

Fig. 7. Efficient portfolios including nuclear energy reduction cases by scenario.
Source: Own author's calculation.

Alternatively, selecting the Absolute Minimum Cost portfolio as target would imply a very variable composition depending on the scenario (Fig. 6). The solar PV technology would not be in any Absolute Minimum Cost portfolio due to its high costs.

In the *Low Emissions* scenario coal –with high emissions- is the most affected technology, with a final share of 4.3%. Coal & CCS would enter with a participation of 3.8%. Biomass is not participating and the rest of technologies would participate to the maximum allowed (Fig. 6).

In the *High RES* scenario all RES would be in the portfolio to their limits, with the exception of, as commented, solar PV. Nuclear energy would be reduced to a scarce share of 6% (Fig. 6). The reason is that nuclear energy would be displaced due to the high cost level for a high RES Absolute Minimum Cost portfolio. Natural gas and coal technologies would participate to their maximum allowable limits.

In the *Energy Union* scenario, the combination of both policies -and not only the emission policy- leads to: the entrance to its limit of biomass, the elimination of Coal & CCS and a nuclear energy reduction of 5% (Fig. 6). The difference with the portfolios of *High RES* lies in the substitution of 18% of coal by nuclear energy.

Table 4
Expected costs by technology.

Cost by technology (€/MWh)	Nuclear	Coal	Coal with CCS	Natural gas combined cycle	Natural gas with CCS	Oil	On-shore wind	Large hydro	Small hydro	Off-shore wind	Biomass	Solar PV
Production Costs												
Investment	9.17	8.24	14.42	9.89	20.67	23.58	26.67	26.63	29.96	28.57	20.44	170.21
O&M	10.24	9.89	21.63	9.89	20.67	16.27	22.00	11.98	12.98	33.21	9.20	29.79
Fuel	7.48	15.75	20.79	10.11	11.78	39.66	0.00	0.00	0.00	0.00	66.93	0.00
Complementary	3.15	N/A	19.07	N/A	9.25	N/A	12.03	N/A	N/A	12.03	N/A	12.03
=Total	30.04	33.88	75.91	29.89	62.38	79.50	60.69	38.62	42.95	73.81	96.58	212.03
Externality Costs												
CO_2	N/A	18.35	2.52	8.90	1.22	13.66	N/A	N/A	N/A	N/A	0.05	N/A
SO_2	N/A	0.58	0.17	0.07	0.08	0.44	N/A	N/A	N/A	N/A	1.20	N/A
NO_X	N/A	1.51	1.44	2.11	2.35	1.13	N/A	N/A	N/A	N/A	3.30	N/A
PM	N/A	0.27	0.22	0.03	0.03	0.20	N/A	N/A	N/A	N/A	5.46	N/A
Radioactivity	4.16	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Land use	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	3.43	N/A
Accident Plant	23.00	0.06	0.06	0.09	0.09	N/A	N/A	N/A	N/A	N/A	N/A	N/A
=Total	27.16	20.78	4.42	11.20	3.77	15.42	0.98	0.22	0.34	1.06	12.87	0.52
Total Generation Cost by technology												
=Total Generation Cost	57.20	54.65	80.33	41.09	66.15	94.93	61.68	38.84	43.28	74.87	109.45	212.55

Source: De-Llano et al. [26].

As discussed above, if Europe looks for the Absolute Minimum Cost portfolio in the *Energy Union* scenario the composition of the portfolio will be led by natural gas (27.6%) and nuclear energy (24.6%). RES technologies would participate to their maximum limits –except Solar PV which is not participating- and coal would have a testimonial share of 4%. On-shore wind would stand out as preferential technology with a share of 20% (Fig. 6).

4. Nuclear energy shutting down cases

Shutting down the 50% of nuclear energy would imply a high concentration both of the cost around high values (64.8–66.31 €/MWh) and of the risk around low values (3.11–3.17 €/MWh) in the *Energy Union* scenario. The efficient frontier moves upwards (Fig. 7). The HHI values would be between 15.5% and 16.5%, which indicates a level of diversification close to the minimum −13.77%–. Reducing the share of nuclear energy would force entering the solar PV and Coal & CCS with 5% each one.

Reducing nuclear participation to 50% lead to lower values for the absolute minimum cost efficient portfolio by moving down the frontier (Fig. 7) in the *High RES* scenario. If nuclear energy disappears in 2030, the *High RES* is the only feasible scenario. This scenario shows a rise in the portfolio cost (between 63.93 and 66.52 €/MWh) and a medium-level risk (between 3.26 and 3.55 €/MWh).

The model does not find any solution for the case of the total shutdown of nuclear energy in the *Energy Union* or *Low Emissions* scenarios. The emission reduction goals would not be achievable in any case with the expected development of technologies RES –free emission sources- in 2030.

5. Conclusions and policy implications

The proposed study attempts to address the effects that the new 2030 European Commission targets proposal would have over the cost and risk of the European power generation mix and the convenience of the different goals included inside the announced European *Energy Union* policy. To this end each environmental goal is considered individually and together with in order to facilitate the analysis of the different policies.

The results confirm that targeting a minimum economic risk portfolio leads to lower emissions and higher shares of RES. Besides the more diversified the portfolio and the high RES share would be, more risk of a possible disruption of supply provoked by geopolitical reasons will be reduced and higher level of energy independence and energy security.

Therefore European Union should search reaching the minimum risk generation portfolio, which means that European Union would be minimizing emissions and increasing its energy security level at the same time. It also can be outlined that the future RES development is needed in order to participate in the portfolios and to achieve the European emissions reduction goals.

In these terms, the environmental policy which can lead to the minimum electricity production risk is the *High RES* share one. Considering an emissions reduction policy -*Low Emission*- or a combination of both -*Energy Union*- implies, for both, the same reduced impact over risk (+1.7%) and cost (+0.3%). For this the best option could be any of them.

The study also confirms that it would not be necessary to implement a *High RES* policy in order to achieve a higher share than the goal of 43%: this would be reached with the Low Emissions policy (48%). In addition the implementation of a minimum share of RES policy does not necessarily lead to the reduction of CO$_2$ emissions. Therefore the *High RES* goal is not relevant in terms of policy: Including a sole Low Emissions policy it could be possible to achieve the maximization of RES share and the minimization of carbon dioxide emissions.

Consequently the EU 2030 environmental policy should consider only the emission reduction target. In terms of mean cost a *Low Emissions* policy is a cheaper option than *High RES* and *Energy Union* ones. The cost increase moves between 2% -Low Emission- and 5% -Energy Union- considering the lack of policies. Besides in terms of risk does not imply higher values.

Nuclear energy would play a relevant role in 2030 EU portfolios. A reduction of 50% of the participation of nuclear energy would force to enter into the portfolio technologies with high costs (Solar PV and Coal & CCS), *ceteris paribus.* And a zero nuclear energy share in 2030 is not possible, unless the technological limits participation for RES energy were increased. To this end the European Union should support more intensively RES development.

6. ANNEX A

Table 5
Risk by Technology.

Risk by technology (€/MWh)	Nuclear	Coal	Coal with CCS	Natural gas combined cycle	Natural gas with CCS	Oil	On-shore wind	Large hydro	Small hydro	Off-shore wind	Biomass	Solar PV
Production Costs												
Investment	2.11	1.90	3.32	1.48	3.10	5.42	1.33	10.12	3.00	2.86	4.09	8.51
O&M	0.56	0.53	1.17	1.04	2.17	3.94	1.76	1.83	1.99	2.66	0.99	1.01
Fuel	1.80	2.20	2.91	1.92	2.24	9.92	N/A	N/A	N/A	N/A	12.05	0.00
Complementary	0.29	N/A	5.00	N/A	5.00	N/A	6.07	N/A	N/A	6.07	N/A	6.07
Externality Costs												
CO$_2$	N/A	4.77	0.66	2.31	0.32	3.55	N/A	N/A	N/A	N/A	0.01	N/A
SO$_2$	N/A	3.13	3.13	3.13	3.13	3.13	N/A	N/A	N/A	N/A	3.13	N/A
NO$_X$	N/A	3.26	3.26	3.26	3.26	3.26	N/A	N/A	N/A	N/A	3.26	N/A
PM	N/A	2.65	2.65	2.65	2.65	2.65	N/A	N/A	N/A	N/A	2.65	N/A
Radioactivity	2.39	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.00	N/A
Land use	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1.07	N/A
Accident Plant	6.64	0.14	0.14	0.04	0.04	0.14	N/A	N/A	N/A	N/A	N/A	N/A
Total Generation Risk by technology												
Standard deviation	7.61	7.68	8.59	6.31	8.48	13.5	6.46	10.29	3.59	7.21	13.84	10.5

Source: De-Llano et al. [26].

Table 6
Maximum technology portfolio shares in EU Power Generation Mix.

Region	EU-27 power generation mix
Technologies	Limits (%)
Coal	23.4
Coal with CCS	Together with Natural Gas with CCS, they must not exceed 18% of the total share of Fossil fuel technologies. Together with Coal, they must not exceed 23.4%
Natural Gas Combined Cycle	27.6
Natural Gas with CCS	Together with Coal with CCS, they must not exceed 18% of the total share of Fossil fuel technologies. Together with Natural Gas, they must not exceed 27.6%
Oil	0.8
Nuclear energy	29.8
Hydro	12.3
Large Hydro	10.8
Small Hydro	1.5
Biomass	8.5
Solar PV	5.5
Wind	22.3
On-shore Wind	20.3
Off-shore Wind	2.0

Source: Authors' own calculations based on data collected from IEA [12,17], IPTS [43] [De-Llano et al. [26].

Table 7
Base scenario for each model. Tornado diagrams.

	Base Model	(50%) Nuclear	Nuclear shutdown
Nuclear	19.23%	14.92%	0.00%
Coal	10.16%	13.33%	20.13%
Coal with CCS	2.40%	3.43%	3.24%
Natural Gas	22.32%	23.39%	26.71%
Natural Gas with CCS	2.81%	2.51%	0.89%
Oil	0.60%	0.60%	0.82%
On-shore Wind	20.09%	20.28%	20.28%
Large Hydro	10.57%	10.46%	10.81%
Small Hydro	1.47%	1.47%	1.47%
Off-Shore Wind	1.95%	1.99%	2.01%
Biomass	6.25%	5.40%	8.46%
Solar Photovoltaic	2.13%	2.21%	5.19%
Base Scenario Portfolio Cost	60.05 €/MWh	59.73 €/MWh	65.08 €/MWh
Base Scenario Portfolio Emissions	161.30 kg/MWh	189.19 kg/MWh	251.19 kg/MWh

Source: Own author's calculation.

7. ANNEX B

7.1. *Cost and emissions sensibility analysis*

7.1.1. *Base scenario*

We have three different models –the base model, the model with a reduction of 50% in nuclear generation and the model with a complete nuclear shutdown– and we calculate a base scenario for each one. Using the average share of each technology in the set of results, we made up the base scenario for every analysis in this section. Then we calculate the cost and the emissions taking the maximum and the minimum share for each technology to draw the corresponding tornado diagrams. In the following Table 7 we show the base scenario shares for each model and the cost and emission values according to those shares.

7.1.2. *Base model*

For the Base model, we show the technologies cost variation –when we take into account their minimum and maximum shares obtained in the model– from the base scenario in the following Fig. 8.

As we can see, nuclear, PV and coal –without CCS– power generation will increase the cost of the portfolio at around 10% when we let them participate at their maximum share –29.85%, 5.50% and 23.42% respectively– (Fig. 8). On the other hand, when we set a minimum share for each technology, nuclear, biomass and on-shore wind power generation –with shares of 5.99%, 0.00% and 6.85%– will cause the highest reduction in the portfolio cost –again at around 10%–. It is relevant to see that even at their maximum wind share –both on and off-shore– and hydro –both large and mini– power generation will have a minimum impact on the portfolio cost (Fig. 8).

If we analyse the portfolio CO_2 emission factor –Fig. 9- and we let the coal power generation to enter at its maximum –23.42%–, we get the worst result –with 258 kg/MWh of CO_2 emitted–, reflecting the high negative impact that this technology has on the power generation CO_2 emission factor. On a second level, the gas –both with and without CCS– power generation participating at their maximum –4.10% and 27.59%– will lead the portfolio to a 180 Kg CO_2/MWh emission factor, being 133 Kg CO_2/MWh the limit in the 2030 horizon.

On the other hand, when we reduce the coal –without CCS– share to its minimum –18.67%– we get the highest reduction in the portfolio CO_2 emission factor –more than a 25% reduction–, and drive the portfolio emissions to a factor even lower than the aforementioned 133 kg/MWh limit (Fig. 9).

As expected, the RES technologies have no impact on the portfolio CO_2 emission factor (Fig. 9).

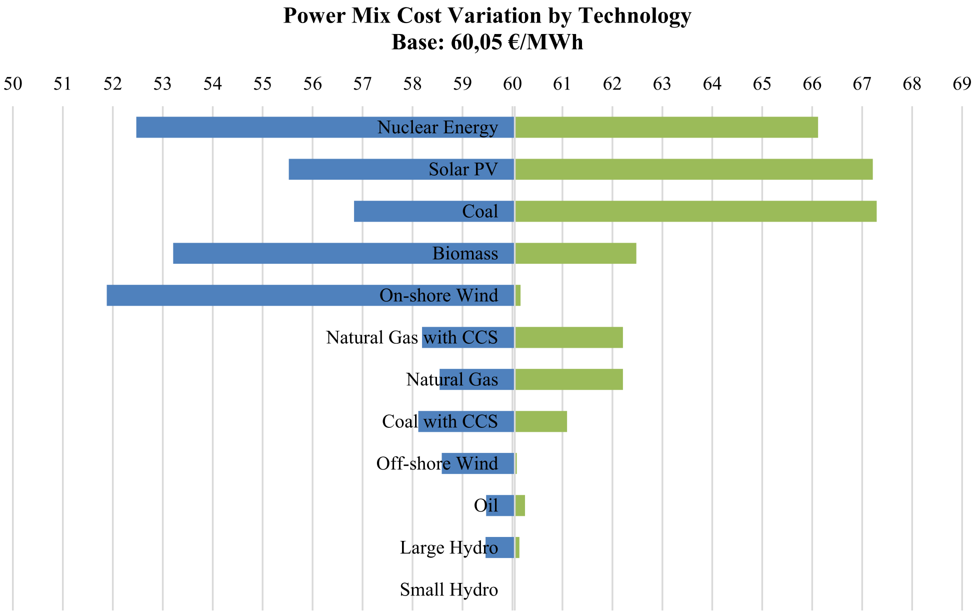

Fig. 8. Power Mix Cost Variation by Technology. Base Model.
Source: Own author's calculation.

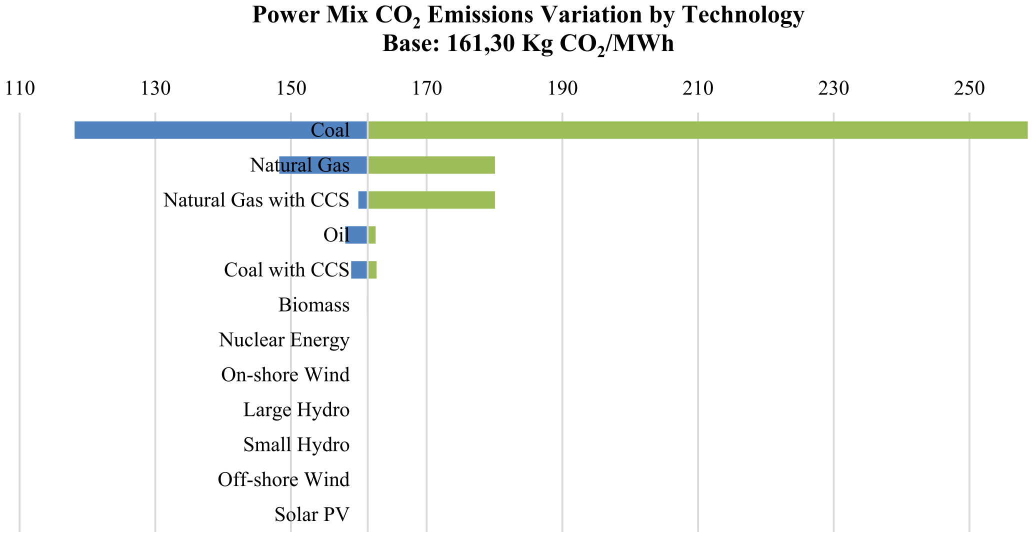

Fig. 9. Power Mix CO_2 Emissions Variation by Technology. Base Model.
Source: Own author's calculation.

7.1.3. Shutting down (50%) Nuclear Energy Scenario

We reduce the share of the nuclear power generation to a maximum of 50% of its expected capacity in the second model. As we see in Fig. 10 the variability of the portfolio cost is reduced for the RES set. PV and coal are again the technologies with a higher negative impact in the portfolio cost –at around 10%– when they participate at their maximum –5.50% and 23.42%, respectively–.

Analysing the portfolio CO_2 emissions in this model we can see –Fig. 11– that the situation is quite similar to the one that we get in the previous model –base model–, except for the fact that the portfolio CO_2 emissions are higher in the base scenario.

7.1.4. Shutting down (100%) Nuclear Energy Scenario

In the face of a complete shutdown of nuclear power generation in 2030, the higher variation in the portfolio cost would be caused by the CCS coal technology –a reduction of 5% when this technology participates at its minimum and an increase of 5% when this

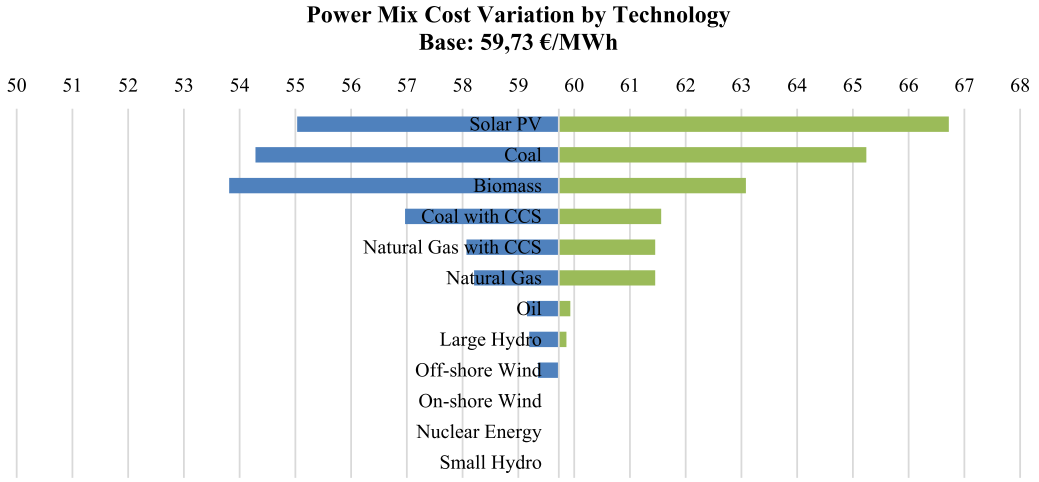

Fig. 10. Power Mix Cost Variation by Technology. Shutting down (50%) Nuclear Energy Scenario.
Source: Own author's calculation.

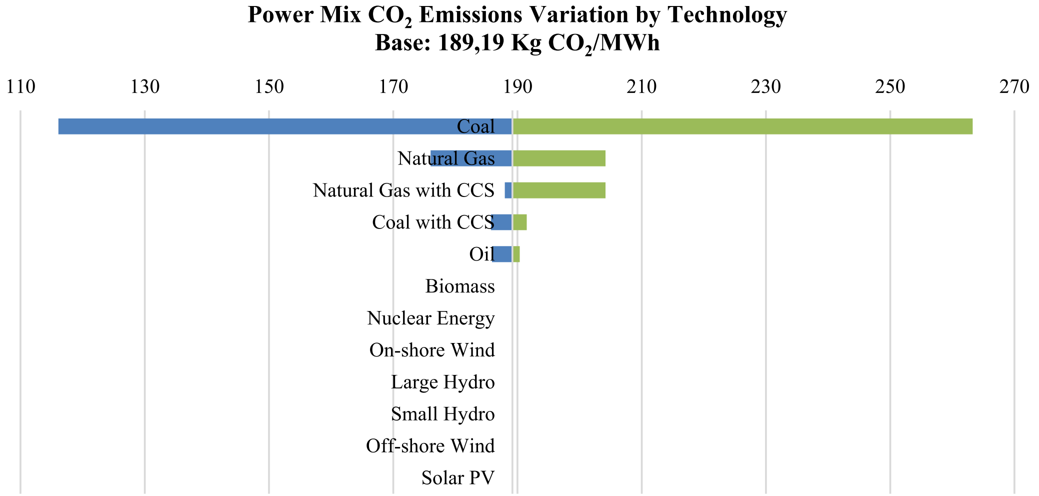

Fig. 11. Power Mix CO_2 Emissions Variation by Technology. Shutting down (50%).
Source: Own author's calculation.

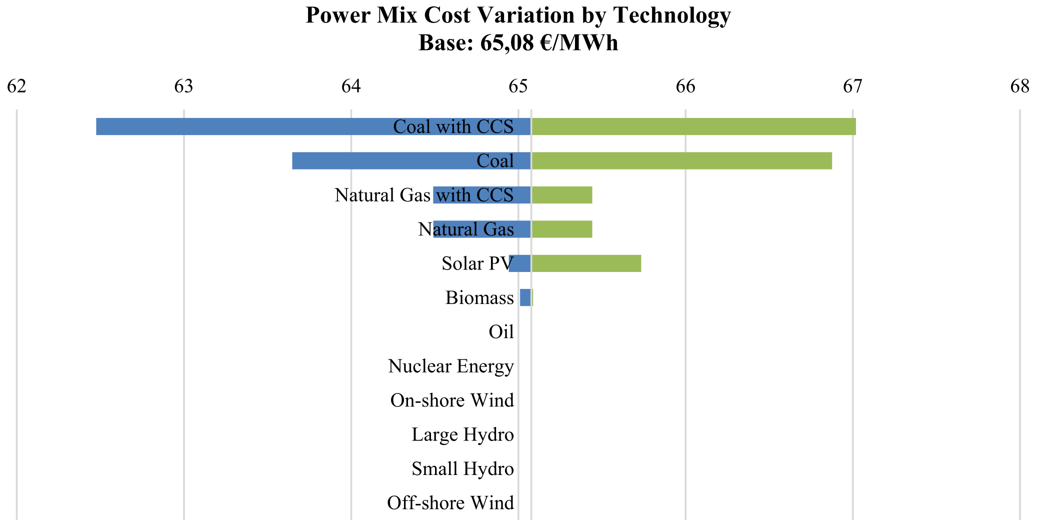

Fig. 12. Power Mix Cost Variation by Technology. Shutting down (100%) Nuclear Energy Scenario.
Source: Own author's calculation.

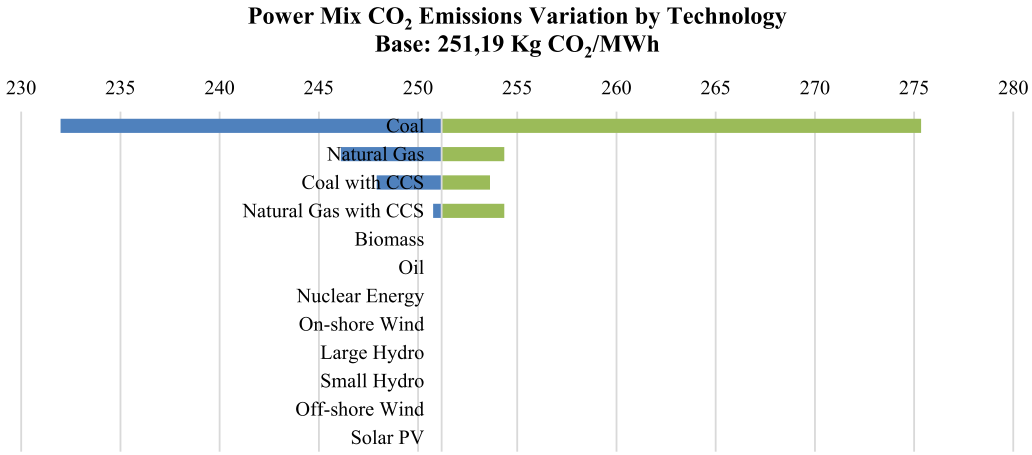

Fig. 13. Power Mix CO_2 Emissions Variation by Technology. Shutting down (100%). Source: Own author's calculation.

technology participates at its maximum–. Following, we see –Fig. 12– the coal, gas and PV power generation technologies.

Finally, regarding the portfolio CO_2 emissions variability in this 100% shutdown of nuclear power, we see in Fig. 13 how this reduction will cause the power mix to be the most pollutant. In fact if we jointly analyse Fig. 9; Figs. 11 and 13 the portfolio emissions are being increased although the factors that most affect this increase are always the same –pollutant technologies, as expected–.

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4.3 Paper 2: The effects of different CCS technological scenarios on EU low-carbon generation mix

The effects of different CCS technological scenarios on EU low-carbon generation mix

Fernando deLlano-Paz, Paulino Martinez Fernandez & Isabel Soares

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The effects of different CCS technological scenarios on EU low-carbon generation mix

Fernando deLlano-Paz[1] · **Paulino Martinez Fernandez**[1] · **Isabel Soares**[2]

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Abstract Carbon capture and storage technology (CCS), a technology to reduce the emissions in coal and gas power generation plants, will play an important role in the achievement of the European Union emissions reduction objective. In the European Union, energy policies are articulated around three different elements: measures to promote renewable energy technologies, the emissions certificates system and both energy-saving and energy-efficiency policies. The succession of directives and communications from the EU Commission on renewable technology generation share targets and the implementation of the European Emissions Market exemplify the serious EU commitment to a more environmentally friendly future. CCS technologies—together with RES technologies—are thus key to achieve the European emissions reduction target. Although the CCS commercial availability is not guaranteed—due to a slow technological development—some institutions, such as the Institute for Prospective Technological Studies, assume, for 2030 horizon, a quick development of this technology, growing until a maximum participation of an 18 % over the fossil fuels total generation. An eventual non-availability of these technologies in 2030 could increase the cost of this objective in a 70 %. Therefore, the achievement of pollutant emissions reduction targets depends on a correct design of the European generation technologies mix, which should include CCS technologies. Nevertheless, the uncertainty about the final costs and economic risk of these technologies makes a question about their future role to arise. This paper analyses the effects of different variations in the cost and risk of the CCS technologies (scenarios) over the European power technologies mix. The results confirm the need of the availability of these technologies in 2030, beyond the potential costs and risks of both options. The reason lies in

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✉ Fernando deLlano-Paz
fdellano@udc.es

[1] Department of Financial Economics and Accounting, Faculty of Economics and Business, University of A Coruña, Elviña Campus, 15071 A Coruña, Spain

[2] Economic Scientific Group and CEF-UP, Faculty of Economics, University of Porto, Rua Dr. Roberto Frias, 4200-464 Porto, Portugal

the methodological approach of portfolio theory, which allows an analysis from an efficient portfolio point of view.

Keywords Efficiency · Emissions reduction · Carbon capture and storage—CCS · Portfolio theory · Externalities

1 Introduction

One of the fundamental cornerstones of human activity for the development of society lies in the use of energy and the generation of electricity. Nowadays, this generation process is largely focused on the use of fossil fuels, which have the drawback of pollutant gas emissions. The concentration of these gases in the atmosphere is the cause of global warming on the Earth's surface and the rising sea level (Omer 2008; Panwar et al. 2011; Hernández-Escobedo et al. 2010), as well as other effects related to air pollution, acid precipitation, ozone depletion and the emission of radioactive substances. All these consequences have a negative impact on human life and on the environment.

The security of supply, the sustainability and the competitiveness are key factors for the solution of a territory's energy problem (Sierra 2011). The diversification of both the energy inputs portfolio and the importer regions encourages the reduction of those risks related to the import of resources and the energy dependence (EC 2000). The EU States are responsible for the design of environment friendly energy policies (Labandeira 2012; Labandeira et al. 2012). Energy planning allows taking action in the design of a territory's energy model from a medium-/long-term perspective. The energy planning problem can be assessed from an investment selection point of view (Awerbuch 2004), on the basis of the risk-return approach of Markowitz's (1952) financial portfolio theory. Therefore, portfolio theory can be employed to assess the efficiency of the generation technologies portfolio as if they were real assets. The proposed approach is based on the joint analysis in terms of cost and risk (variability) efficiency of all the available assets. Due to the different type of assets, real assets (power generation technologies) and—therefore—not financial assets, a non-strict compliance of the assumptions of portfolio theory on the market efficiency is assumed. With this approach, we can fully assess the potential role played by the carbon capture and storage (CCS) technologies into the technologies portfolio.[1]

The contribution of this paper lies in the analysis of the future role to be played by carbon capture and storage technologies in the 2030 European generation mix, assuming the existence of a high uncertainty on their final implementation costs and risks analysis. The proposed methodology is the Modern portfolio theory. It permits a quadratic optimisation approach that takes into account the set of technologies and their possible interrelationships. Therefore, the analysis is performed from a global perspective, and it is not individually focused in each technology. Additionally, the model includes environmental constraints regarding the European emissions reduction targets. The present work

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[1] In this study, we propose an analysis of the CCS technologies share behaviour in the efficient portfolios of De-Llano et al. (2014) and DeLlano-Paz et al. (2015) model. Thus, our aim is to see how far the cost or the risk of these CCS technologies—based on fossil fuels but with lower emissions than the traditional carbon and gas technologies—can affect their share in the power generation mix. We do not want to put priority on them over RES technologies. In fact, we firmly think that both types of technologies are key to achieve the European emissions reduction target.

considers six different scenarios, based on the modification of CCS technologies cost and risk. Four of these scenarios are set by varying the CCS technologies cost in ±1 and ±2 SD,[2,3] The other two scenarios are set by changing the CCS technologies risk: in the low-risk scenario, we assume a 50 % risk reduction (0.5 Var) and in the high-risk scenario, we assume a 150 % risk increase (1.5 Var) to cover a reasonable future risk range.

In order to achieve these objectives, in the second point of this work, we will review the EU-27 energy context, together with a brief revision of the role and projections of the CCS technologies on the horizon of 2030.[4] In the third point, we will comment the most important contributions in the literature related to the use of the portfolio theory in calculating the power generation mix and we will present the model designed. In the fourth point, we will comment the results obtained, and, finally, in the fifth point, we will draw some conclusions and policy implications of this study.

2 The EU-27 and its energy context: future role of the CCS technologies

Energy is one of the reasons of the EU's foundation. Since the signature of the Treaty of Paris (1951) and the creation of the European Coal and Steel Community (ECSC), the European Union is pursuing its energy security in the form of security of supply. In fact, the Article 194 of the consolidated version of the Treaty of the Functioning of the EU (EU 2010) points out the aim of its energy policy, which involves all member states: to ensure the functioning of the energy market, to guarantee the security of the energy supply in the EU, as well as the development of new and renewable energies and to promote energy efficiency, savings and the interconnection of energy grids.

The EU-27 energy framework is strongly conditioned by its high-energy dependency (53.4 % in 2014; Fig. 1)—which shows the reliance of the EU economy upon imports in order to meet its energy needs. It is also conditioned by a less intensive consumption[5] and an important qualitative participation of the fossil fuels—higher than 70 % of the mix of gross inland energy consumption between 2010 and 2014 in the EU-27; Fig. 2.

That is why the EU-27 efforts are focused in increasing the energy security—through the reduction of its energy dependence—and in improving the efficiency levels of the energy processes. Besides, the European Union has made an important effort in order to reduce pollutant emissions and to fight against climate change (EC 1997, 2007, 2008, 2009a, b).

EU-27 efforts to reduce the greenhouse gases emissions (EC 2009b) and to reduce the energy dependence were driven through both the development and implementation of renewable energies and the commissioning of the EU-27 European Emissions Trading

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[2] SD stands for standard deviation. The standard deviation informs about the possible variation of the asset return or cost.

[3] By doing so, and assuming normality in the CCS technologies cost, our analysis covers more than 95 %—two standard deviations up and down from the cost expected value—of the expected cost variability. The assumption of normality in the distribution of the CCS technologies cost is not a strong one from our point of view and we can see it in Awerbuch and Berger (2003), for instance.

[4] 2030 Horizon considers a CO_2 Emissions reduction goal between −54 and −68 % for electricity sector (EC 2011) and a maximum limit share for the sum of the CCS coal and the CCS Natural Gas participations of 18 % of the fossil fuel total portfolio participation (Russ et al. 2009).

[5] Energy intensity was reduced in a 15 % from 2000 to 2011 (Eurostat: tsdec 360). The energy intensity is calculated as net energy imports divided by the sum of gross inland energy consumption plus bunkers.

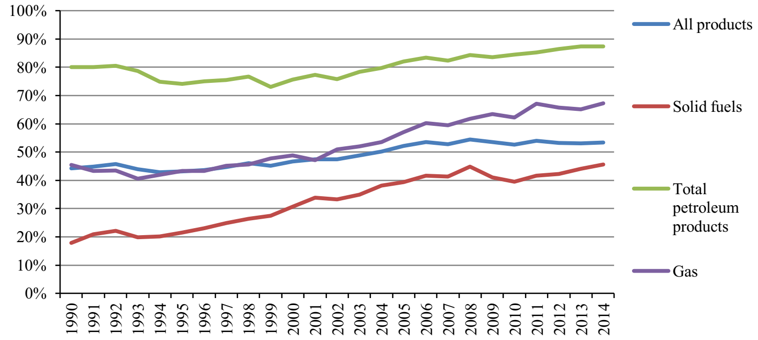

Fig. 1 EU energy dependency (1990–2014) *Source*: Own author's elaboration with data collected from Eurostat (tsdcc310)

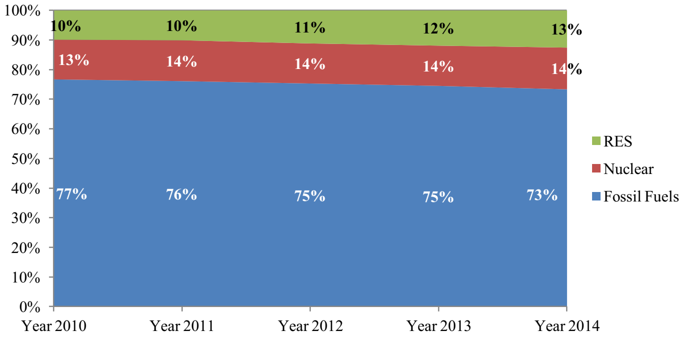

Fig. 2 EU gross inland energy consumption mix (years 2010–2014) *Source*: Own author's elaboration with data collected from Eurostat (tsdcc320)

System (EU-ETS). Power generation sector was responsible for a 31.9 % of the total of greenhouse gases emissions in 2007 and 27 % in 2012 (Eurostats, 2015).

CCS technologies are key to achieve the objectives of emissions reduction (Russ et al. 2009). This technology takes part in a worldwide 3 % both for the coal and the natural gas. This percentage is equivalent to a 2 % of the total of electricity generated (International Energy Agency—IEA 2011). The 450[6] scenario implies that, in 2035, a 60 % of the coal plants will be using CCS, which corresponds to a participation of a 9 % over the total of electricity generated. The Institute for Prospective Technological Studies (IPTS) assumes, for 2030 horizon, a quick development of this technology, growing until a maximum participation of an 18 % over the total generation coming from fossil fuels (Russ et al. 2009). Likewise, the IEA (2011) puts in 2030–2035 the commercial availability or the CCS technologies.

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[6] The IEA 450 scenario considers—with 50 per cent probability—the achievement of the rise limit of 2 degrees Celsius in average global temperatures—when compared to preindustrial levels. The "450" comes from the long-term concentration of greenhouse gas emissions limit of 450 ppm CO_2 eq.

A commercial implementation of the CCS technologies will only be possible with helping policies to cover the adverse market behaviours, as the system of emission prices (ZEP 2012). That explains why the assimilation of the emission prices and the emission reduction costs will be among the energy policies to implement in 2030, at least for new fossil fuel plants.

According to the IEA (2011), the 10 years delay in incorporate and commercially use this technology, with an emission reduction perspective similar to the one in its *450* scenario, would force an alternative investment with an 8 % higher cost than the one in the IEA *450* scenario (IEA 2011) for the years 2011–2035. Recently, the EU-27 has confirmed its commitment to this technology (ZEP 2012). The European Commission establishes the development of the CCS technologies as a complementary objective to the commitment to renewable energies inside its emission reduction policies. 2030 is the year in which it is believed that CCS will reach its commercial viability. If this technology could not be developed in order to be technically and commercially available in 2030–2035, the abatement cost of the emission reduction objective would likely be increased in a 70 % considering initial cost estimates (ZEP 2012).

3 The application of the portfolio theory to select power generation sources portfolios

The approach of Markowitz's (1952) optimisation model consists in an objective function, either to minimise the portfolio's risk subject to a fixed value for its yield, or to maximise its yield subject to a fixed risk. Furthermore, a technical restriction to force the sum of the diverse assets participation shares to be one must be added. The model allows us to obtain—through successive executions—the efficient portfolio frontier, defined by those portfolios showing the minimum risk for a given yield, or the highest yield for an a priori set risk.

The application of Markowitz portfolio theory to energy planning requires some theoretical adaptations. The most relevant one is that focused in the different nature of the assets: real assets—generation plants, for instance—versus financial assets. The model also needs to assume that the market efficiency hypothesis is not fully accomplished (Awerbuch and Berger 2003; Awerbuch and Yang 2007; Jansen et al. 2006; Hickey et al. 2010; Kruyt et al. 2009; Stirling 1998, 2007). Allan et al. (2011), among others, emphasise the limitation derived from the unrealistic assumption about the assets unlimited divisibility.

The application of the portfolio theory to the problem of a territory's energy planning is a proven methodology with great acceptance. One of the most referenced authors is Awerbuch (Awerbuch and Berger 2003; Awerbuch and Yang 2007), who proposed in a novel and explicit way an approach based in Markowitz's (1952) portfolio theory. Those models based in the costs of the different technologies are primarily relevant for this work. Among them, we can find the studies of Doherty et al. (2006), White et al. (2007), Awerbuch and Yang (2007), Awerbuch et al. (2008), Doherty et al. (2008), Rodoulis (2010), Allan et al. (2011), Zhu and Fan (2010) and Bhattacharya and Kojima (2012). In this study, we apply the model proposed in De-Llano et al. (2014) and DeLlano-Paz et al. (2015) because it includes the externality costs for each technology and, besides, it incorporates the different pollutant gases emissions targets for the European Union in 2030 horizon. Cost and risk data can be consulted in "Appendix".

3.1 Portfolio profiling: expected cost and risk

The technologies portfolio expected value is obtained from the sum of every technology expected costs weighted by its participation in the portfolio.

$$E\left(C_{\mathrm{p}}\right) = \sum_{t} x_t E(\mathrm{TC}_t)$$

$$E\left(C_{\mathrm{p}}\right) = x'c, \quad x \in \mathbb{R}^{12},\ c \in \mathbb{R}^{12}$$

Being: C_p the portfolio total cost, x_t the participation of the technology t in the portfolio p and TC_t the total generation cost for technology t (€/MWh). This total generation cost includes investment costs, O&M costs, fuel costs, plan dismantling costs, technology intermittence costs and those costs coming from externalities[7]: emissions of carbon dioxide, sulphur dioxide, nitrogen oxide and suspended particles; potential accidents in generation plants; the negative impact of biomass cultivation and the radioactivity derived from eventual leaks in the nuclear power generation processes.

The portfolio risk (σ_p) is obtained from the individual risk of each technology cost component and from its two-by-two interaction—measured by the technologies pair correlation coefficient. Each component shows a risk—its variability—that can be expressed through its standard deviation. The following expression summarises the portfolio risk:

$$\sigma_p = \left\{ \sum_{t=1}^{12} x_t^2 \sigma_t^2 + \sum_{t_1=1}^{12} \sum_{\substack{t_2 = 1 \\ t_1 \neq t_2}}^{12} \left(\sum_{\forall C_1} \sum_{\forall C_2} \sigma_{C_1 t_1} \sigma_{C_2 t_2} \rho_{C_1 t_1, C_2 t_2} \right) x_{t_1} x_{t_2} \right\}^{1/2}$$

$$\sigma_p = (x'Vx)^{\frac{1}{2}}, \quad V \in \mathbb{R}^{12\times 12},\ V_{ij} = \sigma_{t_i t_j}$$

$$\sigma_{t_i t_j} = \begin{cases} \sum\limits_{\forall C_1} \sum\limits_{\forall C_2} \sigma_{C_1 t_1} \sigma_{C_2 t_2} \rho_{C_1 t_1, C_2 t_2}, & \text{if } i \neq j \\ \sigma_t^2, & \text{if } i = j \end{cases}$$

where x_t is the participation of technology t in the portfolio p, σ_t is the standard deviation of the cost of the technology t, $C_k t_i$ is the kth cost component for technology i, and $\rho_{C_1 t_1, C_2 t_2}$ is the correlation of every one of the cost components between every two technologies. In this work, we assume as given data the correlation coefficients for the O&M costs and fuel costs between every two technologies from Awerbuch and Yang (2007). In the study, we use the historical fuel and $\mathrm{CO_2}$ prices series, taking yearly data to avoid seasonality (BP 2011; SENDECO2 2012 and Uranium Miners), for calculating our own correlation coefficients.

In the next formula, we show the expression for each technology cost[8]:

$$\sigma_t = (\sigma^2_{\mathrm{Inv}_t} + \sigma^2_{\mathrm{O\&M}_t} + \sigma^2_{\mathrm{Fuel}_t} + \sigma^2_{\mathrm{Compl}_t} + \sigma^2_{\mathrm{CO2}_t} + \sigma^2_{\mathrm{SO2}_t} + \sigma^2_{\mathrm{NOX}_t}$$
$$+ \sigma^2_{\mathrm{PM}_t} + \sigma^2_{\mathrm{Rad}_t} + \sigma^2_{\mathrm{Cult}_t} + \sigma^2_{\mathrm{Acc}_t} + 2\sigma_{\mathrm{Fuel}_t} \sigma_{\mathrm{Co2}_t} \rho_{\mathrm{Fuel}_t \& \mathrm{Co2}_t})^{\frac{1}{2}}$$

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[7] The externalities costs are those costs related to the potential damage to ecosystems and to the society (Wesselink et al. 2010; IPCC 2005).

[8] We are assuming the hypothesis of no-correlation except for the fuel costs and the $\mathrm{CO_2}$ emission prices (Jansen et al. 2006).

This approach calculates the risk for each technology by adding the cost components variances and covariances and differs from previous works (Awerbuch and Berger 2003; White et al. 2007; Allan et al. 2011). We have chosen not weighting the risks by its components participation and follow the proposal of Jansen et al. (2006). Null cost and risk for fuel and emissions are assumed for renewable technologies, according Awerbuch and Yang (2007) and Allan et al. (2011).

3.2 Mathematical formulation

Our model mathematical formulation is as follows:

$$\begin{aligned}
\mathrm{Min}\{\sigma_{\mathrm{p}}\} &= \mathrm{Min}\left\{\sum_{t=1}^{12} x_t^2\sigma_t^2 + \sum_{t_1=1}^{12}\sum_{t_2=1,t_1\neq t_2}^{12}\left(\sum_{\forall C_1}\sum_{\forall C_2}\sigma_{C_1t_1}\sigma_{C_2t_2}\rho_{C_1t_1,C_2t_2}\right)x_{t_1}x_{t_2}\right\}^{\frac{1}{2}}\\
&= \left\{\sum_{t=1}^{12} x_t^2\left(\sigma^2_{\mathrm{Inv}_t} + \sigma^2_{\mathrm{O\&M}_t} + \sigma^2_{\mathrm{Fuel}_t} + \sigma^2_{\mathrm{Compl}_t} + \sigma^2_{\mathrm{CO2}_t} + \sigma^2_{\mathrm{SO2}_t} + \sigma^2_{\mathrm{NOX}_t} + \sigma^2_{\mathrm{PM}_t}\right.\right.\\
&\quad \left. + \sigma^2_{\mathrm{Rad}_t} + \sigma^2_{\mathrm{Land}_t} + \sigma^2_{\mathrm{Acc}_t} + 2\sigma_{\mathrm{Fuel}_t}\sigma_{\mathrm{CO2}_t}\rho_{\mathrm{Fuel}_t,\mathrm{CO2}_t}\right)\\
&\quad \left. + \sum_{t_1=1}^{12}\sum_{t_2=1,t_1\neq t_2}^{12}\left(\sigma_{\mathrm{O\&M}_{t_1}}\sigma_{\mathrm{O\&M}_{t_2}}\rho_{\mathrm{O\&M}_{t_1},\mathrm{O\&M}_{t_2}}x_{t_1}x_{t_2} + \sigma_{\mathrm{Fuel}_{t_1}}\sigma_{\mathrm{Fuel}_{t_2}}\rho_{\mathrm{Fuel}_{t_1,}\mathrm{Fuel}_{t2}}x_{t_1}x_{t_2}\right)\right\}
\end{aligned}$$

$$\text{Subject to: } E(C_{\mathrm{p}}) = \sum_t x_t E(TC_t) = C_{\text{Portfolio IEA.EU}-27}$$

$$\sum_t x_t = 1$$

$$\forall t, x_t \geq 0$$

Being: $t = \{$coal, CCS coal, natural gas, CCS natural gas, oil, nuclear, onshore wind, offshore wind, solar photovoltaic, large hydro, small hydro, biomass$\}$, $x_t =$ unknown model variables, meaning the participation of technology t in the portfolio (the sum of every x_t must add up to 100 %).

The model also considers one constraint related to the maximum share for each technology. This constraint is set taking into account the forecast of installed capacity in the European Union for 2030. The model constraint expression to be included would be:

$$x_t = \text{Maximum percentage of participation of technology ``}t\text{''}$$

In order to establish the maximum share for each technology, we compute the 2030 technology maximum participation percentage (Table 1) through different scenario data coming from the sources used by the EU-27 (IEA 2011, 2012; Russ et al. 2009), following the proposal included in DeLlano-Paz et al. (2015). The final maximum share limits were chosen considering the maximum participation for each technology among the different institutional sources.

The model also considers one additional restriction related to the level of emissions of the portfolio emission factor (DeLlano-Paz et al. 2015) in order to include an environmental dimension in the model:

$$\text{Portfolio Emission Factor}_{(\mathrm{CO_2,SO_2,NOX,PM})} \leq \text{Emissions Limit}_{(\mathrm{CO_2,SO_2,NOX,PM})}$$

The portfolio emission factor is obtained by adding every pollutant gas emission factor for each pollutant technology—coal, CCS coal, natural gas, CCS natural gas, oil and

Table 1 Maximum share limits for each technology in the 2030 EU-27 power generation mix *Source*: IEA (2011, 2012), Russ et al. (2009) and DeLlano-Paz et al. (2015)

Technologies	Maximum limits (%)
Coal	23.4 (%)
CCS coal	The sum of the CCS coal and the CCS natural gas participations cannot be greater than the 18 % of the fossil fuel total participation The sum of the coal and the CCS coal participations cannot be greater than 23.4 %
Natural gas	27.6 %
CCS natural gas	The sum of the CCS coal and the CCS natural gas participations cannot be greater than the 18 % of the fossil fuel total participation The sum of the natural gas and the CCS natural gas participations cannot be greater than 27.6 %
Oil	0.8 %
Nuclear	29.8 %
Large hydro	10.8 %
Small hydro	1.5 %
Biomass	8.5 %
Solar photovoltaic	5.5 %
Onshore wind	20.3 %
Offshore wind	2.0 %

Table 2 Maximum pollutant emission portfolio limits *Source*: Own author's calculation following data collected from DeLlano-Paz et al. (2015)

Pollutant emission portfolio limits (gases and particulates)	2010	Emission limit—horizon 2030		
	Current emission factor	Reduction		
		Minimum	Medium	Intense
CO_2	287.70	157.36	133.41	109.47
SO_2	29.15	12.10	11.19	10.27
NO_X	126.79	89.40	84.72	80.05
PM	10.97	9.30	9.18	9.05

biomass—weighted by its participation in the portfolio. For the emission limits calculation, we consulted several European normative and relevant articles (EC 2001, 2008, 2011, 2012a, b; Ammann et al. 2008). The maximum portfolio emission factors are shown in Table 2.

4 Results

The model offers a set of solutions that can be drawn in a cost–risk coordinate axis (Fig. 3). The set of portfolios minimising the cost for a given risk, or minimising the risk for a given cost, is the so-called efficient portfolios frontier. This frontier is shaped as a concave curve—instead of a convex curve like the one based in financial assets yield in Markowitz's model. On the left, the curve is limited by the minimum absolute risk

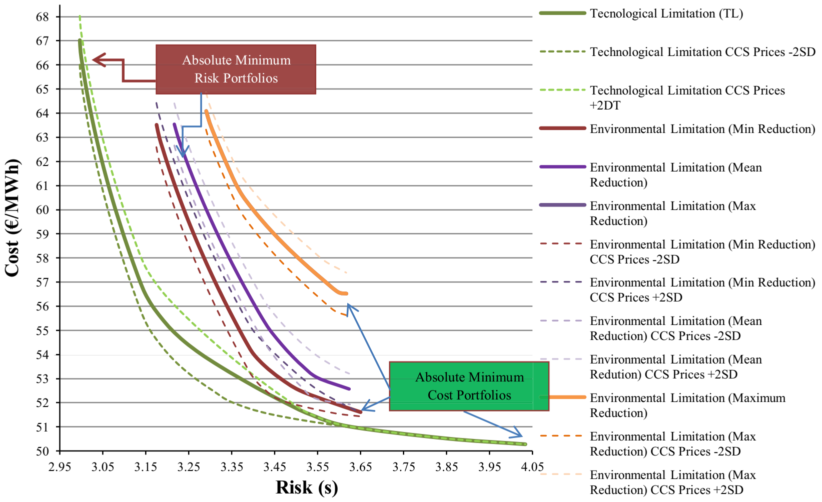

Fig. 3 Efficient portfolios frontiers according to the different models and CCS costs scenarios *Source*: Own authors' calculation

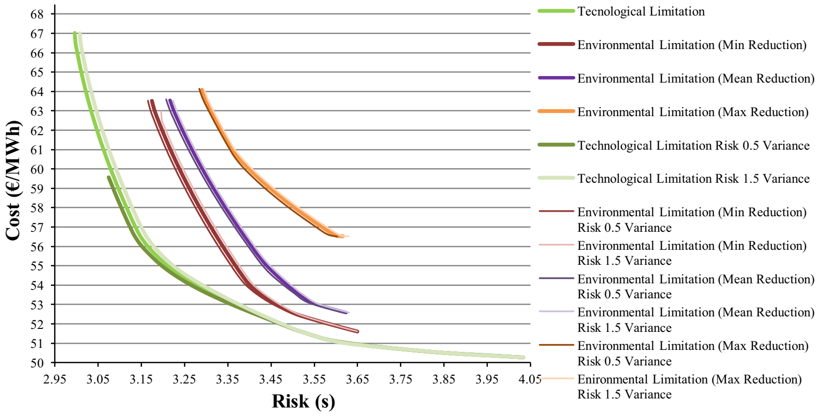

Fig. 4 Efficient portfolios frontiers according to the different models and CCS risks scenarios *Source*: Own authors' calculation

portfolio—that portfolio with the less possible risk. And on the bottom, it is limited by the absolute minimum cost portfolio—that with the less possible cost. Thus, those portfolios with a higher cost given a level of risk or with a higher risk for the same level of cost would be outside the efficient portfolios frontier. Inefficient portfolios will be over the efficient portfolios frontier.

In Figs. 3 and 4 there are four main efficient frontiers. The technological limits (TL) efficient frontier is obtained taking into account only the technology maximum participation restrictions in the mathematical model. The other three environmental limits efficient frontiers correspond with the three levels of emissions reduction scenarios, and they consider both technological constraints and those constraints related to the portfolio emission factor. As we can see in the graphs, incorporating the environmental restrictions results in an up and left movement of the efficient portfolio frontier, which means higher costs but fewer risks. Additionally in both Figs. 3 and 4 several discontinued efficient frontier lines are shown. They are related to the different modifications proposed in this study over the cost (CCS prices ± 1 or 2 SD) and risk (CCS Risk × 0.5 or 1.5). In Fig. 3 we draw the ±1 or 2 SD efficient frontiers scenarios, and in Fig. 4 0.5 and 1.5 Var efficient frontiers scenarios are represented. Both figures show the impact of considering the different modifications in CCS technologies cost and risk values over the composition of the efficient portfolios.

4.1 Impact of a change in the cost of the CCS technologies

We assess the impact of a variation in the cost of the CCS technologies by comparing the results obtained in four different scenarios: two of cost reduction—one and two standard deviations[9]—and two of cost increase—again, one and two standard deviations. The costs of the technologies per scenario would be as follows (Table 3).

The results of the impact of these changes are analysed on the basis of the absolute minimum risk and cost portfolios composition. These portfolios are efficient because it is impossible to find a portfolio with less risk or cost inside the efficient portfolios frontier. These two portfolios delimit, thus, the efficient frontier.

4.1.1 Efficient portfolios with absolute minimum risk

Modifying the CCS technologies costs causes no effect on the composition of the absolute minimum risk portfolios. The participation of the different technologies is independent of the CCS technologies cost (Fig. 5). CCS natural gas participates in all the scenarios with a share of around 2 %. Incorporating—or hardening—the emission reduction objectives has a negative effect on that quota. CCS coal would share a 3 % quota. This quota will drop to its minimum in the intense emission reduction scenario. In the same way than we saw with the CSS natural gas technology, reducing its costs has no effect in its participation.

We can see how, when we consider the emission reduction objectives, the coal participation (higher in proportion) and the natural gas participation (for emitter technologies) are being gradually reduced. The weights of the free emission technologies—nuclear, large hydro and biomass—are on the other hand increased. In fact, large hydro reaches its maximum participation share under these scenarios. These three technologies will take advantage from the emission reduction efforts. The portfolio is also participated by oil (0.82 %), onshore wind (20.28 %), small hydro (1.47 %), offshore wind (2.01 %) and solar photovoltaic (5.50 %). These technologies participate at their maximum in every case (Fig. 5).

When we reduce the cost of the CCS technologies in two standard deviations, we are able to reduce the portfolio cost in 1.5 %, compared with the basis efficient portfolio (Fig. 6). If we reduce the cost of the CCS technologies in only one standard deviation, the

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[9] For CCS Coal the Standard Deviation is 8.59 €/MWh and for CCS Natural Gas is 8.48 €/MWh (De-Llano et al. 2014).

Table 3 Costs by technology (€/MWh) and by scenario of variation of the CCS technologies cost *Source*: De-Llano et al. (2014)

Costs by technology (€/Mwh)	Nuclear	Coal	CCS coal	Natural gas	CCS natural gas	Oil	Onshore wind	Large hydro	Mini hydro	Offshore wind	Biomass	Solar photovoltaic
Strong increase "+2 SD"	57.20	54.65	97.50	41.09	83.11	94.93	61.68	38.84	43.28	74.87	109.45	212.55
Soft increase "+1 SD"			88.91		74.63							
Basis			80.33		66.15							
Soft reduction "−1 SD"			71.74		57.67							
Strong reduction "−2 SD"			63.15		49.19							

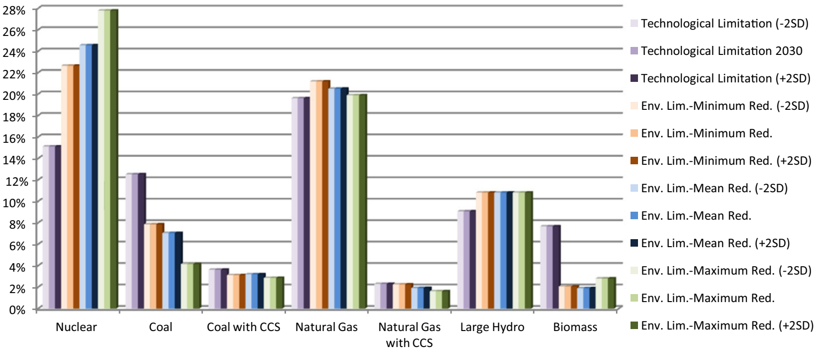

Fig. 5 Participation shares of the technologies in the absolute minimum risk portfolios by model, reduction objective and CCS technologies cost modification scenario *Source*: Own authors' calculation

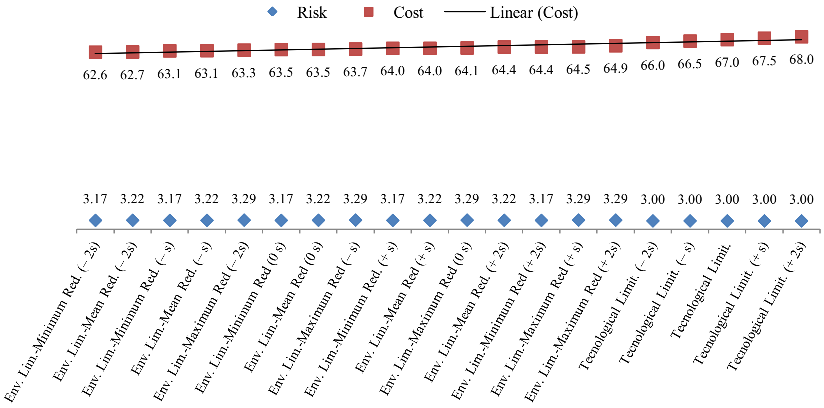

Fig. 6 Cost and risk of the absolute minimum risk portfolios. Strong and soft reduction of the CCS technologies cost *Source*: Own authors' calculation

portfolio cost gets reduced in 0.7 %. Hence, we can say that a variation of the CCS technologies cost has no significant impact on the portfolio risk.

4.1.2 *Absolute minimum cost portfolios*

Regarding the absolute minimum cost portfolios, we conclude that the CCS natural gas technologies are never participating, despite the modification of its costs.

On the contrary, the CCS coal technology will participate in those portfolios, although its participation will be affected by its cost. If its cost is small—2 standard deviations below its average–, its participation share changes from 0.00 to 2.25 % in the minimum emission reduction scenario and from 3.71 to 3.84 % in the medium emission reduction scenario (Fig. 7). Its substitutive technology would be the off-shore Wind technology.

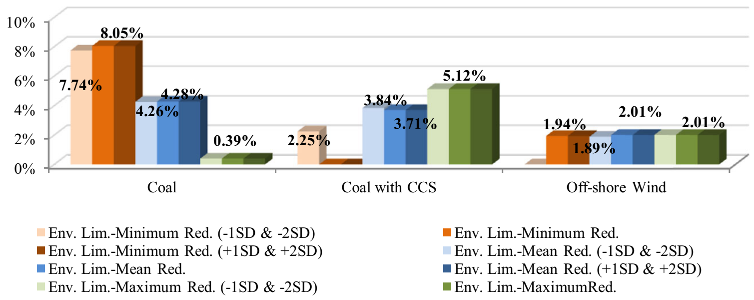

Fig. 7 Participation shares of coal, CCS coal and offshore wind in the absolute minimum cost portfolios by model, reduction objective and CCS cost modification scenario *Source* Own authors' calculation

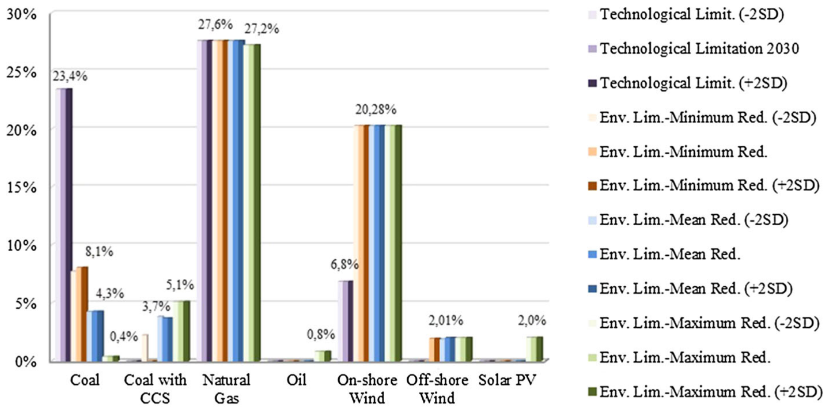

Fig. 8 Participations of the diverse technologies in the absolute minimum cost efficient portfolios by model, reduction objective and CCS technologies cost modification absolute minimum scenario *Source*: Own authors' calculation

Also the participation of this technology will reach a higher value the stronger the reduction objective is. In fact, it changes from 0.00 % participation—in the minimum reduction scenario—to a 3.71 % participation—in the medium reduction scenario—and to a 5.12 %—in the intensive reduction scenario. The technology that interchanges its participation with the CCS coal is the traditional coal technology—very pollutant—and its participation is reduced as the reduction objectives are getting harder (Fig. 7).

Technologies with zero emissions increase its weight in the absolute minimum cost portfolio when we apply the environmental model (Fig. 8). In the intense and medium reduction scenarios this is the case for the onshore wind, which reaches its maximum participation, and for the offshore wind. Solar photovoltaic only enters—with an unimpressive 2 % share—in the portfolio in the intense scenario reduction. The rest of the technologies participate as follows (Fig. 8): Nuclear at its maximum, 29.85 %, large hydro 10.85 % and small hydro 1.47 %. We can conclude that, when we speak about the minimum cost, wind and CCS coal technologies will be the preferred technologies in an

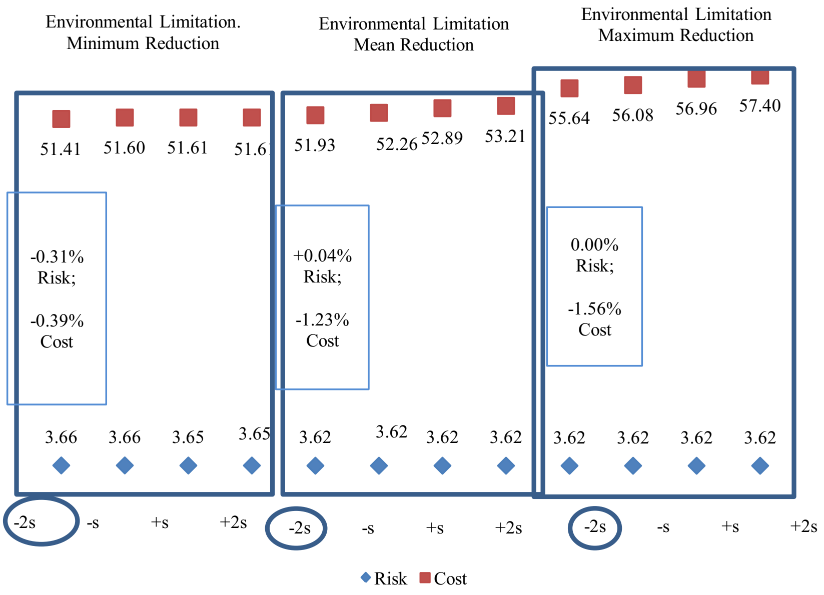

Fig. 9 Cost and risk of the absolute minimum cost portfolios. Strong and soft CCS technologies cost increase and reduction scenarios *Source*: Own authors' calculation

emission reduction scenario. Solar photovoltaic technology would only be in the portfolio when the scenario is that of intense emission reduction.

The results confirm that the more intense the reduction objective is and the higher the cost reduction, the higher will be the portfolio cost reduction (Fig. 9). Nevertheless, we can see how the impact in the final cost reduction hardly reaches values between −0.4 and −1.6 %. And the impact of the increase reaches a maximum of +1.6 % in the portfolio cost. The impact in the risk is limited to the minimum emission reduction scenarios.

4.1.3 Variation in the risk and in the cost of the portfolios caused by the variation in the cost of the CCS technologies

As we can see in Fig. 10, when we modify the CCS technologies cost we do not get an increase in the risk variability of the different portfolios, models and scenarios we deal with. Furthermore, the more intense the reduction objective is, the smaller the variation between the risk results (higher risk vs. lower risk) is, independently of the portfolio being of minimum cost or minimum risk. This causes a reduction in the length of the efficient portfolios curves.

The variability of the efficient portfolios cost results is also reduced as we consider the different reduction objective (Fig. 11). Nevertheless, a modification in the CCS technologies cost causes a higher variability in the cost of the models efficient portfolios. Despite the price modification reaches an increase of about 16€, it hardly causes small percentage increases in the value ranges (33–35; 23–25; 21–24; 13–17 %), which translates to increases or reductions in the portfolios cost of one €/MWh.

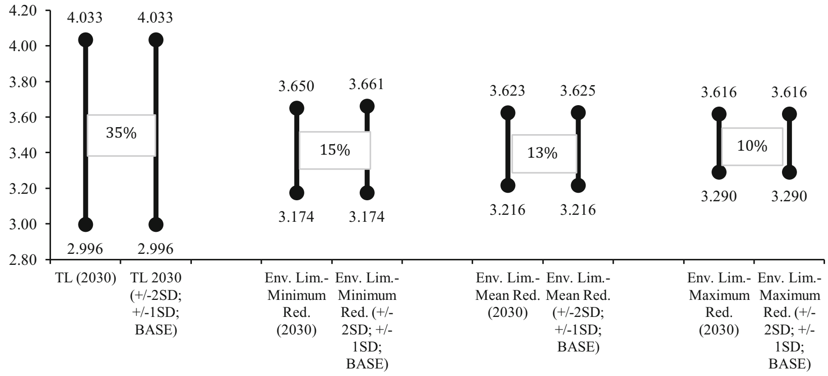

Fig. 10 Impact of the variation of the CCS technologies cost on the efficient portfolios risk variability (range in €/MWh) *Source*: Own authors' calculation

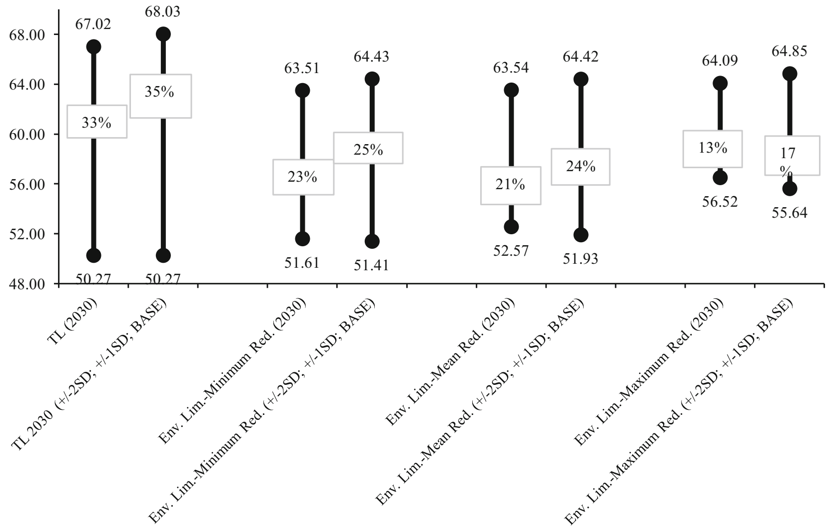

Fig. 11 Impact of the variation of the CCS technologies cost on the variability of the efficient portfolios cost (range in €/MWh) *Source*: Own authors' calculation

4.2 Impact of the CCS technologies risk variation

We analyse the impact of the CCS technologies risk variation with two different scenarios: in the first one, the risk—the CCS technologies cost variance—is reduced 0.5 times and in the second one, it is increased 1.5 times.[10]

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[10] For CCS Coal the Variance is 73.74 €/MWh and for CCS Natural Gas is 71.89 €/MWh (De-Llano et al. 2014).

Technologies risks under these two scenarios would be as in Table 4.

In the same way than we did before, the impact results are proposed on the basis of the minimum cost and risk portfolios composition.

4.2.1 *Absolute minimum risk-efficient portfolios*

When modifying the risk of the CCS technologies we cause a change in the minimum risk portfolios composition. But extracting conclusions is here a difficult task as this change is not always in the same direction.

As a general rule, in those scenarios with reduced risk for CCS technologies (0.5 Var), CCS coal technology increases its participation, while CCS natural gas reduces it (Table 5). Participation of other technologies like natural gas or biomass is slightly increased and coal see how its weight in the portfolio is reduced. Every technology experiences a movement below one point in percentage.

On the other hand, in those scenarios under the hypothesis of increased risk for CCS technologies, CCS natural gas increases its participation in the portfolio, while CCS coal undergoes both positive and negative changes depending on the scenario. Regarding the rest of technologies, coal participation is the one that varies in a bigger percentage: 2 points in the minimum emission reduction scenario (Table 5).

According to the results of our models, it seems that the participation structure of the CCS technologies is replicated both for CCS coal (3 %) and CCS natural gas (2 %). When we reduce the risk of these technologies, CCS coal increases its participation, while CCS natural gas reduces it. Generally speaking, if we increase their risk, the behaviour is the opposite. In any case the higher the intensity of the emission reduction objective, the lower the CCS technologies participation. From this fact, we can conclude that the model prefers free-emission wind technologies (nuclear and biomass), together with the reduction of the coal participation—and a slightly reduction of the natural gas—to achieve the reduction objectives.

With the exception of the technological model, modifying the risks of the technologies causes minimum impacts on the portfolio risk. Environmental model would show a variation of the absolute minimum risk portfolios of around ±0.20 %—a slight variation from our point of view. If we pay attention to the cost variation, it is barely relevant as we show in Table 6.

4.2.2 *Absolute minimum cost efficient portfolios*

Modifying the CCS technologies risk has no impact in the absolute minimum cost efficient portfolios of the different models and reduction scenarios. Technologies participation is hence the same either we consider a change in the CCS technologies risk or not.

5 Conclusions and policy implications

If the European Union seeks to generate electricity with the minimal society and economic risk, carbon capture and storage—CCS—technologies must participate in efficient technology portfolios in 2030. On the contrary, if the portfolio minimum cost is searched for, only the CCS coal technology must participate.

Table 4 Technology risks (€/MWh) by CCS technologies cost modification scenario *Source*: Own authors' calculation

Technology risk (variance)	Nuclear	Coal	CCS coal	Natural gas	CCS natural gas	Oil	Onshore wind	Large hydro	Small hydro	Offshore wind	Biomass	Solar photovoltaic
Decrease "0.5 Var"	57.80	58.97	36.87	39.77	35.95	183.30	41.69	105.79	12.92	52.04	191.43	110.27
"1 Var"			73.74		71.89							
Increase "1.5 Var"			110.60		107.84							

Table 5 Technologies participations in the absolute minimum risk portfolios by model, reduction objective and CCS technologies risk modification scenario *Source*: Own authors' calculation

Model	Nuclear (%)	Coal (%)	CCS coal (%)	Natural gas (%)	CCS natural gas (%)	Large hydro (%)	Biomass (%)	Solar photovoltaic (%)
Technological model (0.5 S)	15.52	12.86	3.19	22.15	3.26	10.42	6.48	1.54
Technological model	15.11	12.52	3.63	19.62	2.31	9.07	7.67	5.50
Technological model (1.5 S)	15.30	12.43	3.36	19.45	2.53	9.16	7.70	5.50
Environmental model—minimum reduction (0.5 S)	22.42	7.85	3.59	21.42	1.83	10.81	2.01	5.50
Environmental model—minimum reduction	22.65	7.85	3.12	21.18	2.25	10.81	2.06	5.50
Environmental model—minimum reduction (1.5 S)	21.39	10.03	3.29	20.99	2.44	10.81	0.98	5.50
Environmental model—medium reduction (0.5 S)	24.37	6.84	3.79	20.84	1.34	10.81	1.93	5.50
Environmental model—medium reduction	24.55	7.05	3.19	20.50	1.91	10.81	1.90	5.50
Environmental model—medium reduction (1.5 S)	24.62	7.13	2.97	20.38	2.13	10.81	1.88	5.50
Environmental model—intense reduction (0.5 s)	27.62	3.95	3.43	20.21	1.06	10.81	2.84	5.50
Environmental model—intense reduction	27.80	4.15	2.86	19.89	1.61	10.81	2.81	5.50
Environmental model—intense reduction (1.5 S)	27.86	4.22	2.64	19.77	1.83	10.81	2.79	5.50

Table 6 Impact of the CCS technologies risk variation on the efficient portfolios risk and cost variation (€/MWh) *Source*: Own authors' calculation

Model	Risk	Cost	% Risk variation	% Cost variation
Technological model (0.5 S)	3.07	59.57	2.62	−11.11
Technological model (1.5 s)	3.01	67.00	0.37	−0.02
Environmental model—minimum reduction (0.5 S)	3.17	63.52	−0.28	0.01
Environmental model—minimum reduction (1.5 S)	3.20	62.98	0.67	−0.84
Environmental model—medium reduction (0.5 S)	3.21	63.60	−0.26	0.09
Environmental model—medium reduction (1.5 S)	3.22	63.52	0.24	−0.03
Environmental model—intense reduction (0.5 S)	3.28	64.14	−0.20	0.08
Environmental model—intense reduction (1.5 S)	3.30	64.07	0.18	−0.03

The cost and risk of both technologies are not individually relevant. Thus, we conclude that the importance of these technologies lies in their availability in 2030. Changes in technologies costs between 10 and 20 % lead to reduced impacts over the portfolio cost (±2 %). Likewise changes in technologies risk (±50 %) cause small changes in portfolio risk (±0.20 %). The impact over the participation of these technologies in efficient portfolios due to changes in their cost and risk is diverse and it depends on the type of efficient portfolio analysed (minimum risk or minimum cost).

Therefore, the results confirm the need of the availability of CCS technologies in the near future. In this manner, its commercial implementation must be attained in 2030 in order to achieve EU more efficient portfolios. CCS coal would have an important role in efficient portfolio substituting conventional coal technology (more pollutant). Its positive effect over the low-carbon European portfolio is complemented by an important renewable energy sources share in efficient portfolios.

Appendix

See Tables 7 and 8.

Table 7 Expected costs by technology *Source*: De-Llano et al. (2014)

Cost by technology (€/MWh)	Nuclear	Coal	Coal with CCS	Natural gas combined cycle	Natural gas with CCS	Oil	Onshore wind	Large hydro	Small hydro	Offshore wind	Biomass	Solar PV
Production costs												
Investment	9.17	8.24	14.42	9.89	20.67	23.58	26.67	26.63	29.96	28.57	20.44	170.21
O&M	10.24	9.89	21.63	9.89	20.67	16.27	22.00	11.98	12.98	33.21	9.20	29.79
Fuel	7.48	15.75	20.79	10.11	11.78	39.66	0.00	0.00	0.00	0.00	66.93	0.00
Complementary	3.15	N/A	19.07	N/A	9.25	N/A	12.03	N/A	N/A	12.03	N/A	12.03
Total	30.04	33.88	75.91	29.89	62.38	79.50	60.69	38.62	42.95	73.81	96.58	212.03
Externality costs												
CO_2	N/A	18.35	2.52	8.90	1.22	13.66	N/A	N/A	N/A	N/A	0.05	N/A
SO_2	N/A	0.58	0.17	0.07	0.08	0.44	N/A	N/A	N/A	N/A	1.20	N/A
NO_X	N/A	1.51	1.44	2.11	2.35	1.13	N/A	N/A	N/A	N/A	3.30	N/A
PM	N/A	0.27	0.22	0.03	0.03	0.20	N/A	N/A	N/A	N/A	5.46	N/A
Radioactivity	4.16	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Land use	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	3.43	N/A
Accident plant	23.00	0.06	0.06	0.09	0.09	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Total	27.16	20.78	4.42	11.20	3.77	15.42	0.98	0.22	0.34	1.06	12.87	0.52
Total generation cost by technology												
Total generation cost	57.20	54.65	80.33	41.09	66.15	94.93	61.68	38.84	43.28	74.87	109.45	212.55

Table 8 Risk by Technology *Source*: De-Llano et al. (2014)

Risk by technology (€/MWh)	Nuclear	Coal	Coal with CCS	Natural gas combined cycle	Natural gas with CCS	Oil	Onshore wind	Large hydro	Small hydro	Offshore wind	Biomass	Solar PV
Production costs												
Investment	2.11	1.90	3.32	1.48	3.10	5.42	1.33	10.12	3.00	2.86	4.09	8.51
O&M	0.56	0.53	1.17	1.04	2.17	3.94	1.76	1.83	1.99	2.66	0.99	1.01
Fuel	1.80	2.20	2.91	1.92	2.24	9.92	N/A	N/A	N/A	N/A	12.05	0.00
Complementary	0.29	N/A	5.00	N/A	5.00	N/A	6.07	N/A	N/A	6.07	N/A	6.07
Externality costs												
CO_2	N/A	4.77	0.66	2.31	0.32	3.55	N/A	N/A	N/A	N/A	0.01	N/A
SO_2	N/A	3.13	3.13	3.13	3.13	3.13	N/A	N/A	N/A	N/A	3.13	N/A
NO_X	N/A	3.26	3.26	3.26	3.26	3.26	N/A	N/A	N/A	N/A	3.26	N/A
PM	N/A	2.65	2.65	2.65	2.65	2.65	N/A	N/A	N/A	N/A	2.65	N/A
Radioactivity	2.39	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.00	N/A
Land use	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1.07	N/A
Accident plant	6.64	0.14	0.14	0.04	0.04	0.14	N/A	N/A	N/A	N/A	N/A	N/A
Total generation risk by technology												
Standard deviation	7.61	7.68	8.59	6.31	8.48	13.5	6.46	10.29	3.59	7.21	13.84	10.5

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4.4 Paper 3: Pollutant versus non-pollutant generation technologies: a CML-analogous analysis

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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]

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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 technology to achieve a less risky generation mix, with less emissions and allowing a higher diversification 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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✉ Paulino Martinez-Fernandez
paulino.martinez@udc.es

[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; Panwar 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, influencing 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 represents 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 institutional-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 development, 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 emission–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, n is the number of generation technologies involved in the model.

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

Regarding the emission risk of the portfolio P, σ_P, it can be calculated as

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

In this equation, σ_i^2 represents the variance of the emission of technology i. In turn, σ_{ij} is the covariance between the emission of technologies i and j. Remind that the Pearson coefficient of correlation, ρ_{ij}, is related to the covariance through the expression $\rho_{ij} = \frac{\sigma_{ij}}{\sigma_i \sigma_j}$. 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 σ_i is the standard deviation of technology i emission.

If we denote by x 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

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

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:

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

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 $x_i = 0, \forall i \neq \text{Biomass}$. 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 emission 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 standard 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

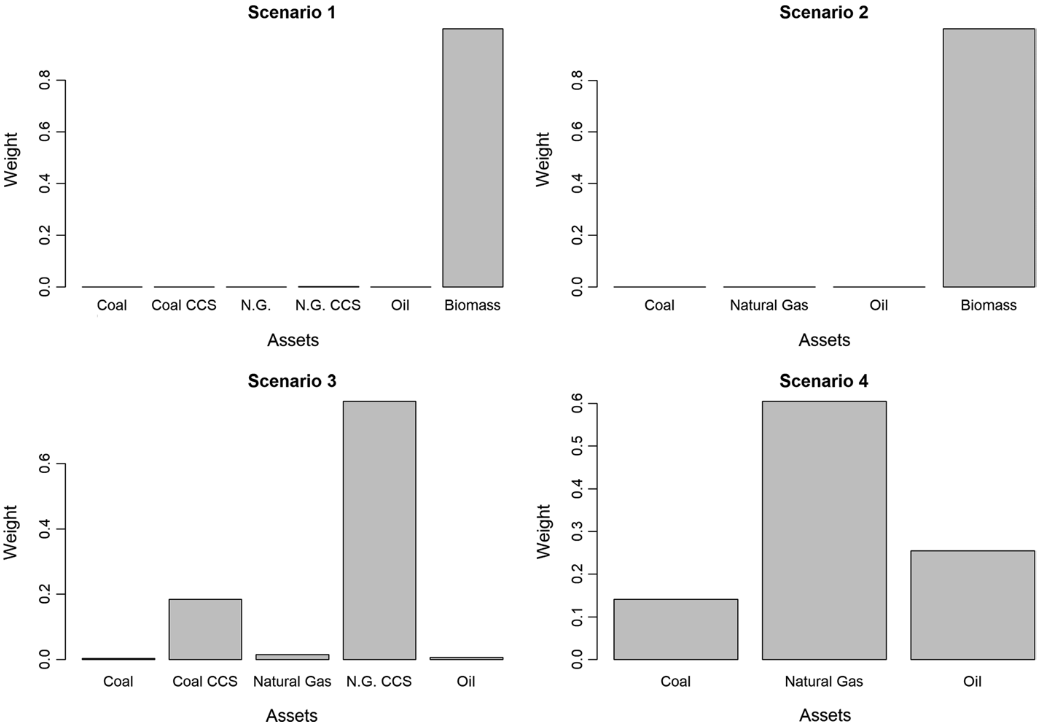


Fig. 1 GMV portfolios composition. *Source*: Authors' own calculations

can let the other technologies to enter into the solution, we can increase the level of diversification 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 portfolio—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 coincidentally, 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

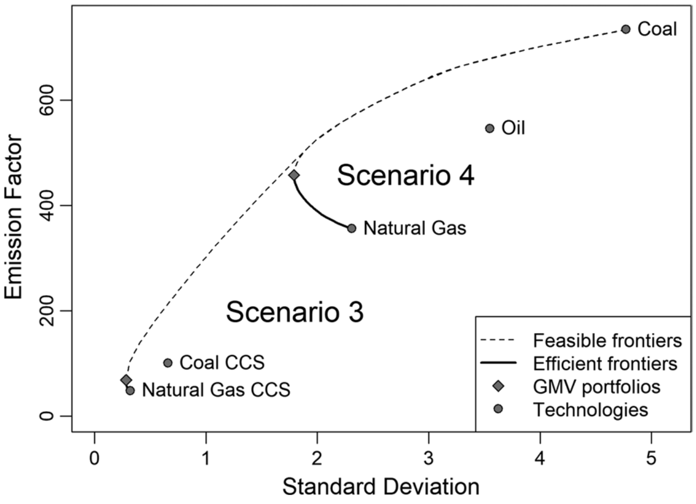
Table 3 GMV portfolios for scenarios 3 and 4

	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 without 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 origin 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



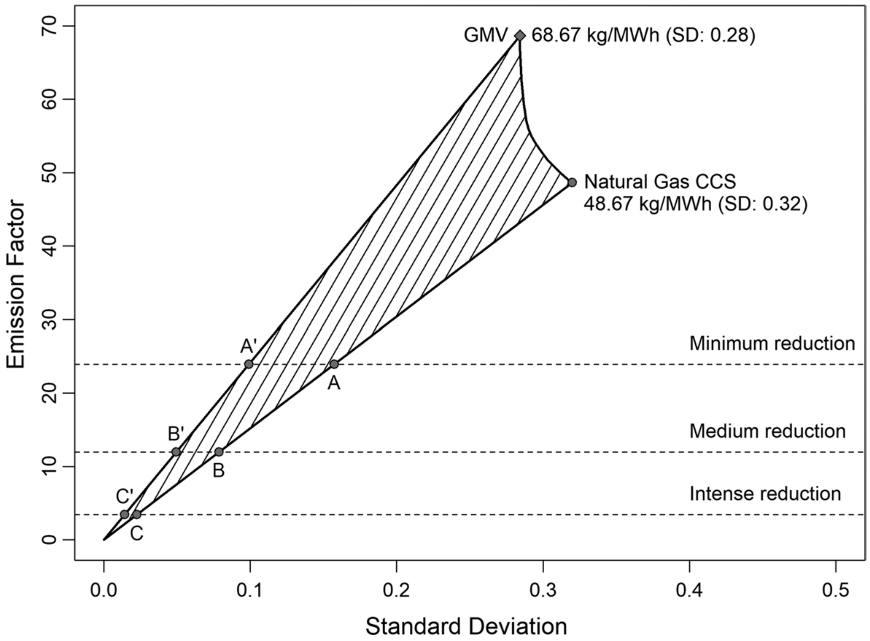


Fig. 3 Scenario 3 efficient frontier, GMV portfolio and CML-A

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 positive impact of the CSS generation technologies on the pollutant portfolio. For each one of the proposed reduction objectives—minimum, medium and intense—including CSS technologies 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 fundamental 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 dataset of real emissions observations and make our own analysis of standard deviations and correlations.

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5 Conclusions

In the works presented, we believe we have shown that MPT can be considered a robust model for the medium/long-term power generation planning for a territory. It incorporates the concept of efficiency; it is a powerful, yet flexible model that can be enriched with constraints reflecting different policy scenarios; and it allows, once the model is solved, a lot of useful information to be extracted for a decision-maker. In particular, the emission factor of the efficient portfolios and their level of diversification were used in the papers included in this compilation.

We want to stress the fact that this is a medium/long-term planning model for a territory. As stated, this is one of the harshest criticisms of applying MPT to power generation. But we are convinced that this objection can be overcome if we focus on these two characteristics —the medium/long term and a relatively vast extension— because, on that basis, power generation plants could almost be considered as fungible and completely divisible assets, in accordance with the original financial MPT. It is obvious that any generation plant cannot be built, reallocated or dismantled in the short-term. Considering the medium/long term and a state or regional level is key for the use of MPT in power generation decisions. In fact, in the two first articles presented here, we focus on the medium/long-term —2030/2050— European strategic objectives —regarding RES generation, CCS technologies, emission objectives. . . — and use them an input for our model.

In this work, we have developed a brief example of how to apply MPT to power generation, how to adapt the constraints of the model to generate new efficient frontiers, how to change the objective function from a cost risk minimization to an emission risk minimization function and, finally, how to set a path —or better yet, an area: the CML-A— to reduce the power generation CO_2 emission to an eventual zero-emission scenario. The articles included analyze the results of applying our model under diverse hypotheses, in accordance with the objectives of the EU energy policy and the aims of the specific work, and should be considered when answering the research questions originally presented.

In the following paragraphs, we will answer the research questions presented in Section 2.2:

- How do the EU power generation policies affect cost-risk efficiency, emmissions and the diversification of the power generation mix?

  According to the research contained in the first paper of this compilation, EU power generation policies can achieve acceptable cost-risk efficiency in every model studied. In our work, we included four different constrained models: the technological model —referred as base model in the paper—, the low-emission model —which includes constraints on the portfolios' emissions—, the high-RES model —with a minimum of 43% RES generation— and the European Union model — with both the emission constraints and the RES constraints.

  All the models show similar results. As explained in the paper, on the left side of the efficient frontier —i.e., the part corresponding to the portfolios with less risk, including the GMV— the technological model and the high-RES model virtually overlap. The same happens for the low-emission and the Energy Union models, but with a slight increase in the risk — efficient frontiers are displaced to the right. On the right part of the efficient frontier —less cost and more risk—, the technological and the low-emission models present a lower cost than the high-RES and the European Union models.

In the article, we conclude that the EU can increase the efficiency of the power generation mix by considering only emission reduction objectives. Indeed, in a scenario like this, RES power generation technologies will participate at their maximum allowed levels without the need for setting specific participation limits. RES participation in power generation, due to its indigenous character, is one of the most important ways to improve energy security by reducing the energy dependence. Furthermore, low-emission policies are on average cheaper to implement than explicit high-RES participation policies, although in the left side of the efficient frontier, the cost of the portfolios in the low-emission model are a bit higher than the cost of the portfolios of the high-RES model.

Another conclusion we can draw from our work is that aiming for risk minimization, instead of cost minimization, will render more diversified generation portfolios. In other words, efficient portfolios built around the GMV portfolio are less concentrated than efficient portfolios built around the GMC portfolio, the former showing lower HHIs than the latter. This is yet another way of improving energy security. Diversification is an important issue to consider when designing power generation policies, especially if RES generation technologies have an important weight, as this ameliorates the problems derived from the RES intermittence.

– How does an intense RES participation in the mix affect these variables?

  Implementing a high-RES participation policy can lead to acceptable cost-risk efficiency of the power generation mix. Even so, as stated above, implementing low-emission policies would have the same effect on cost-risk efficiency, and will cause the RES technologies to participate at their technological maximum allowed levels. Thus, policy-makers can achieve reasonable efficiency of the power-generation mix and, at the same time, increase the RES participation —and, subsequently, increase the diversification, reduce the EU energy dependence and reduce the emissions— by developing low-emission policies.

  In particular, in the attached article, we see that the GMV in the high-RES model coincides with the GMV of the technological model, meaning that its cost-risk efficiency, the emission factor and the technologies diversification are not affected by the constraints imposed on the model by the RES participation policies. Regarding the GMC, the cost is increased by more than 10% —as compared to the technological model GMC cost— but the risk decreases by almost 12%. Generation technologies diversification is also positively affected — 19.51% *versus* 23.67% in the technological model. However, the portfolio emission factor remains more or less the same.

– How would these factors affect a stronger commitment to emmision reduction?

  High-RES policies and low-emission policies have similar effects on the generation cost-risk efficiency. Our high-RES model shows a similar cost, but a lower risk than the low-emission model on the left part of the efficient frontier and, particularly, in the GMV. In the right side of the efficient frontier, the situation is reversed: with a similar risk, the low-emission model shows lower costs.

We said that a stronger commitment to emission reductions leads to both a reduction in EU emissions and an increase in the RES generation technologies up to their technological maximum allowed levels. But this does not mean that both models are interchangeable in terms of policies. Above we explained the differences in the models when the policies seek to either reduce the cost or reduce the risk or, in other words, when the policies seek to either move towards the GMC or move towards the GMV. Effects can also be seen in the emission factor and in the technologies diversification index.

Regarding the emission factor, the high-RES model shows higher emissions than the low-emission model, because the former resorts to fossil fuel generation, while the latter shows preference for nuclear energy generation. Bear in mind that once the high-RES constraint —43% of RES generation— is reached, the model selects the rest of the technologies on a cost-risk basis. In the low-emission model, the constraints affect every iteration of the model (see Section 3.5) and consequently, non-pollutant technologies are shown preference.

With regard to portfolio diversification, our high-RES model results in portfolios that are a bit more diversified than the low-emission model portfolios. The reason is the same as the one that explains the differences in emission: once the high-RES constraint is reached, the model operates on the entire set of technologies, but only on a cost-risk basis, while the low-emission model selects only non-pollutant technologies, once the emission limit is reached.

- Is nuclear phase-out an option for the EU? What would the effects be on the cost and the emissions of the generation mix?

  In the first article included in this compilation, we investigate a couple of scenarios that have to do with the nuclear generation phase-out. The first scenario sets a 50% reduction in the technological limit for nuclear energy generation. The second one completely shutdowns the nuclear power generation.

  According to our research, nuclear power generation will likely play an important role in EU power generation. In the first of the scenarios, a 50% reduction in nuclear generation will cause a significant increase in the average generation cost, as costly technologies that were far from their limits must enter to compensate the reduction in nuclear power generation. It would also trigger a significant decrease in the average generation risk. The values of the cost and the risk become much more concentrated as the models' efficient frontiers shrink. The diversification is a bit lower, but quite similar to the one in the models without nuclear phase-out. All the GHG emission factors are increased, but the PM emission is reduced.

  When considering a complete shutdown of nuclear generation, the RES constraint is activated, meaning that the model tries to substitute nuclear generation with RES generation. Again, costly technologies enter on the efficient frontier, increasing the generation cost. Both the risk and the cost under this scenario are a bit higher than in the previous one. Emissions are increased for every GHG and for PM.

- Some institutions, like the Institute for Prospective Technological Studies (IPTS), assume a maximum participation of 18% for CCS technologies over the generation based on fossil fuels. How will this assumption affect the European generation portfolio?

  In terms of the CCS technologies —based on coal and natural gas, but with much less CO_2 emission—, and on the basis of the result of our works, we can affirm that energy policies must empower their development, as they are of paramount importance for ensuring the implementation of the EU 2030 energy strategy. Their commercial availability must be granted in 2030 to fulfill the emission objectives and to improve the generation efficiency. Moreover, our analyses prove that CCS cost and risk variations have a reduced impact on the generation portfolio cost and risk. We consider this proof to be quite important for a technology that is still in its early stages of development.

  In the second article included in this compilation, we focus on our technological and environmental models with constraints adapted to both the 2020 EU objectives and the 2030 EU objectives and even with emission limits for the portfolios. We also test the model against a variation of ±1 and ±2 standard deviations in CCS costs and against a variation of ±50% in the CCS cost risk, which allows us to draw conclusions about the eventual commercial availability of the CCS technologies and to answer detailed questions about this issue.

  To include the IPTS hypothesis in the model —indeed in line with the hypotheses of other institutions like the International Energy Agency (IEA), which establishes the commercial availability of CCS technologies in 2030/2035— we set a constraint in the technological model to reflect the fact that the joint participation share of the coal and natural gas CCS technologies must be at most 18% of the joint participation shares of coal, natural gas and oil. The flexibility of the model allows us to test it against new scenarios like this one.

  - Is this assumption compatible with European energy targets for 2030?

    European energy 2030 targets consider a CO_2 reduction of between 54% and 68% for the electricity sector, among other objectives, as part of a more general objective of a 40% reduction in GHG emissions. Our work is focused on this target, and in fact we define an environmental model which includes emission constraints for GHG and PM in three different scenarios: minimum, medium and intense reduction.

    The European generation cost and risk will of course be affected by the commercial availability and implementation of CCS technologies. There is good reason why the cost and risk of the CCS technologies are higher than the cost and risk of coal and gas natural generation technologies. Even so, if we compare the European efficient frontier for the 2020 horizon —without CCS technologies— with the European efficient frontier for the 2030 horizon —already including CCS technologies— we can see how the frontier shifts to the left —indicating less risk— and somewhat downwards —indicating less cost—, as shown in Figure 16 — not included in the published version of the article. Of course, this effect is not caused by the CCS technologies themselves, but by the European energy strategy.

- Which would be the effects of underestimating or overestimating the cost and risk of CCS technologies?

  In Section 4.1 of the article that accompanies this document, we focus our analysis on studying how the changes in the CCS technologies' costs and risks will affect their participation in the power generation mix and, if they participate, how the cost and risk of the portfolio will be affected.

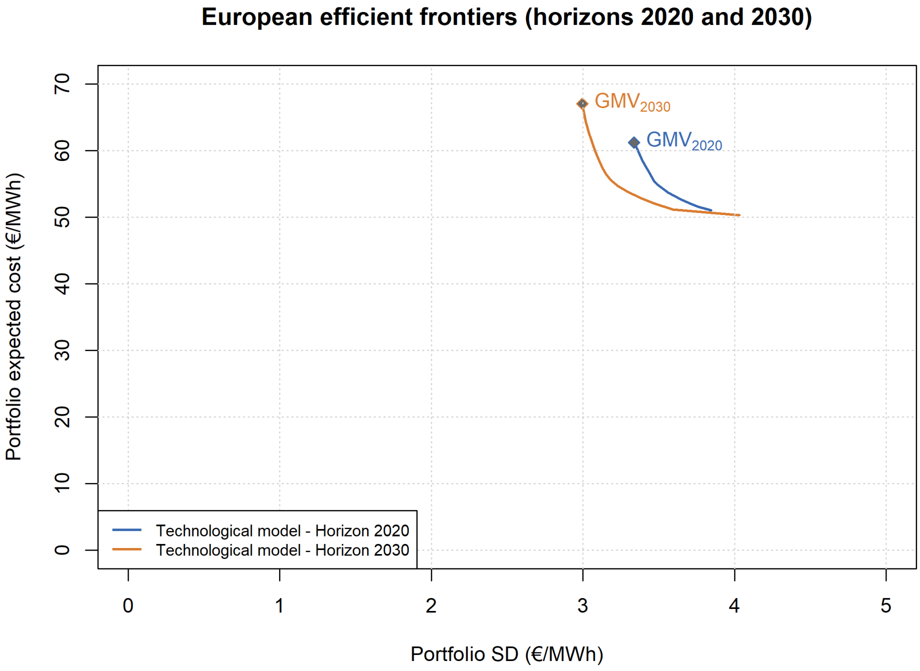

Figure 16: European efficient frontiers

Apart from the fact that they are more expensive and riskier than their primary technologies, we can affirm that, in general, CCS technologies integrate quite smoothly into the efficient portfolios, if we look at how the efficient frontiers of the models considered change in the face of changes in the CCS technology cost and risk. In fact, the change in cost, risk and composition of the portfolios in the efficient frontier is very small, as explained in the article.

But the effects of the CCS technologies being implemented in the CO_2 emission factor of the generation portfolio are quite positive. They can replace other more pollutant technologies, mainly, their primary technologies: coal and natural gas. This is explained by the fact that CCS technologies are able to reduce the emission factor of their primary technologies by nearly 90%. Table 8 shows the CO_2 emission factor for the CCS technologies as compared to that of their primary technologies. These effects explain why we conclude in the article that CCS technologies must be available in 2030 in order to achieve the European low-carbon objectives.

- Will CCS technologies have a role to play in terms of environmental policies?

  As mentioned above, the implementation of CCS will globally reduce the emission factor of the efficient portfolios. They participate in the GMV portfolio in every

Table 8: CCS technology CO_2 emission factor

	CO_2 emission factor (kg/MWh)		
	Without CCS	With CCS	Variation
Coal	734.09	101.00	-86.24%
Natural gas	356.07	48.67	-86.33%

scenario considered, meaning that, when the policy-makers' objective is to reduce the generation risk, CCS technologies must be taken into account. On the other hand, natural gas with CCS does not participate in any GMC portfolio. In turn, coal with CCS participates in every environmental scenario, if the emission reduction is medium or intense, even though it does not participate if the emission reduction is minimal or if it is not considered — as in the technological scenarios.

So far, we conclude that if the European energy policy seeks to reduce risks —it prefers less risk, even if the cost is higher— both CCS technologies will enter in the efficient portfolios, also contributing to reducing the European generation emission factor. If the objective of the European energy policy is to minimize the cost, then coal with CCS will participate if the policy also entails strong emission reduction objectives. If the environmental objectives are set aside or if they show a weak commitment to emission reduction, then none of the CCS technologies will participate in the efficient portfolios.

- MPT has proven to be a useful methodology for application to power generation. But would it be also possible to apply CAPM theory to power generation?

  Considering the generation emission risk in our objective function, we were able to transform the original cost-risk problem of MPT applied to power generation into an emission-risk problem. By classifying the generation technologies as pollutant or non-pollutant, we introduced an analogy with the risk-free asset of MPT and CAPM. Our risk-free asset is, in fact, the emission risk-free subset of technologies, i.e., the set of non-pollutant generation technologies.

  In the third article included in this compilation, we combine this non-pollutant generation technology set with the efficient frontier of the pollutant technologies on an emission-risk coordinate plane, and we derive the CML-A area or the place on the plane where any combination of pollutant technologies efficient portfolios and non-pollutant technologies efficient portfolios can be found. The convexity of our efficient frontier —from either a cost-risk or an emission-risk perspective— makes it impossible to determine a tangency point —the market portfolio of the CAPM—, so we had to account for any portfolio on the efficient frontier. This is the reason why, when applying MPT to power generation, we cannot obtain a CML, but rather a CML-A area instead. In any case, we consider that CAPM can be also applied to power generation, and the results are in line with the results obtained so far: RES technologies will play an important role in the near future for EU power generation and the commercial availability of CCS technologies is vital for an efficient implementation of the EU energy strategy.

- How do we select the CAPM risk-free reference in power generation?

  Financial markets have a risk-free asset —a Treasury bond, for instance— to support the evolution of MPT. This risk-free asset is also fundamental for the development of CAPM. When talking about power generation, we do not have a risk free generation technology at our disposal. Some works (Awerbuch, 2000; Awerbuch & Berger, 2003; Escribano Francés et al., 2013) reason that, from a certain point of view, RES generation technologies can be considered risk-free generation assets. This approach considers the fact that RES technologies are not dependant on any fuel, the prices of which are subject to some degree of variability and, consequently, risk. We took a different approach in the third article included in this compilation. We changed the usual cost-risk approach taken when applying MPT to power generation, to an emission-risk approach. This allows us to build not merely a risk-free asset, but a risk-free portfolio of non-pollutant technologies. As we did not have any information about emission risks and correlations, we decided to use the cost risk as a proxy for the emission risk and simulate the correlations on the basis of the expected emission and the assumed risk.

  As mentioned throughout this work, the main issue here is the fact that the emission-risk efficient frontier is convex. This fact prevents us from determining a single efficient power generation portfolio with the same characteristics as the financial market portfolio. We decided to use the entire pollutant technologies efficient frontier instead, and to determine not a line —like the CML— but rather an area of combinations between a pollutant efficient portfolio and a non-pollutant one that offers less emissions and risk than the efficient frontier itself: the CML-A.

  The CML-A is the area delimited by the GMV portfolio of the pollutant set of technologies, its GMC portfolio and the origin of coordinates of a risk-emission plane. The set of non-pollutant technologies combinations are precisely located in the origin of coordinates itself, as they lack emissions, and consequently, emission risk.

  Every combination of a pollutant efficient portfolio and any efficient portfolio of non-pollutant technologies will fall inside the CML-A. Our study focus on those combinations on the lines joining the GMV portfolio and the GMC portfolio with the origin of coordinates, as these combinations show less risk for a given level of emission — the ones on the line connecting the origin of coordinates and the GMV portfolio— or less cost for a given level of risk — the ones on the line connecting the origin of coordinates and the GMC portfolio.

- Would the application of CML in power generation be useful to a policy-maker?

  We answer this question with an application example in both the third article and in the Section 3.3 of this compilation. If a policy-maker wants to set, say, a specific emission factor for power generation, he will minimize the risk if he chooses the point on the line connecting the origin of coordinates and the GMV pollutant portfolio that corresponds to that emission factor. Inversely, if he wants to set a specific level of emission risk for power generation, he would choose the point on the line connecting the origin of coordinates and the GMC pollutant portfolio corresponding to that level of risk, as this point minimizes the portfolio emission factor.

- From the CAPM perspective, are CCS technologies still being considered for power generation?

  The diverse emission factor of the pollutant generation technologies considered in the article —coal, coal with CCS, natural gas, natural gas with CCS, oil and biomass— forced us to set up different scenarios taking out those technologies showing the least emission factors. In the first scenario, the entire set of pollutant technologies was considered, but biomass accounted for nearly 100% of the GMV generation portfolio, with only a symbolic participation of CCS technologies and an even smaller participation of coal and natural gas without CCS — oil does not participate at all. The GMC portfolio in Scenario 1 is formed only by biomass. In Scenario 2, we took out the CCS technologies, and the situation became even worse from a diversification point of view: biomass participates at a level greater than 99.99% in the GMV portfolio, with natural gas assuming the rest of the generation; and the GMC portfolio is once again formed only by biomass. Thus, in Scenario 3 we took biomass out of the pollutant technology set,and the resulting GMV portfolio was then composed by CCS technologies at a level greater than 97% — 18.38% coal with CCS and 79.09% natural gas with CCS. Natural gas with CCS is the only pollutant technology in the Scenario 3 GMC portfolio. Scenario 4 takes out both the biomass and CCS technologies and its results are much more diversified than the results of the previous scenarios, as the emission factors and risks of the remaining technologies are very similar, although only natural gas participates in its GMC portfolio. Hence, we can affirm that CCS technologies, together with biomass, will be of vital importance in a low-carbon Europe. Models presented in the third article do not include technological constraints for the pollutant models and technologies considered. This results in the fact that the preferred pollutant technologies are biomass and CCS technologies, and the rest of the pollutant technologies are considered only if they are set aside. This situation is obviously unreal and cannot be applied in practise, but it clearly highlights the great potential of CCS technologies in a cleaner future.

Finally, we would like to emphasize again the difficulty of obtaining a clean dataset to input in the model. We have received some criticism about this, and we would like to make it clear that our conclusions are drawn on the basis of the current information about generation costs and risks. Of course, the logic of the model is uncoupled from the input dataset. Thus, as new information becomes available, it would be easy to re-run the program and analyze the differences with the previous results.

As we attempted to show with these conclusions, we consider the research objectives presented at the beginning of this compilation to have been fulfilled. MPT is both a powerful and versatile tool for designing Energy Policies with regard to power generation. The evolution in the field of Finance from MPT to CAPM can be replicated in the field of Energy, but considering the issue of the convexity of the efficient frontier. RES generation technologies and CCS will be key to improving the cost-risk efficiency of the European power generation mix. To facilitate that improvement, CCS generation technologies must be available in 2030.

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A Resumo

A.1 Introdución

Neste traballo preséntase a compilación de tres artigos publicados en revistas indexadas de ámbito e prestixio internacional con revisión por pares. Os tres artigos foron publicados durante a miña etapa de elaboración da tese de doutoramento e son o resultado da investigación realizada nese período. Neste anexo, achégase un resumo desta compilación.

A seguridade enerxética ten que ser o obxectivo de calquera política que tente regular a xeración de electricidade dun territorio. A estes efectos, entendemos por territorio unha extensión grande dabondo e con entidade administrativa: un país, unha rexión. Así, a política enerxética pode verse coma un conxunto de ferramentas a medio e longo prazo que procuran a devandita seguridade enerxética.

En liña coa actual política enerxética da Unión Europea (UE), podemos definir a seguridade enerxética como o acceso á electricidade sen interrupcións, a un custo razoable e co menor impacto medioambiental posible. Nos artigos que se achegan o territorio de aplicación é a propia UE e manéxanse os tres factores da definición: a minimización do número de interrupcións, a minimización do custo —e do risco, entendido como a variabilidade dese custo con respecto ó valor agardado— e a redución do impacto medioambiental da xeración de electricidade.

En efecto, un dos xeitos más eficientes de minimizar o risco de interrupción do subministro eléctrico é mediante a diversificación das tecnoloxías de xeración. É por iso que, nos artigos presentados, ofertamos os resultados en clave de diversificación/concentración, usando normalmente o índice de Herfindahl-Hirschman (HHI), que mide a concentración nunha escala de cero —mínima concentración ou máxima diversificación— a un — máxima concentración ou mínima diversificación. Tamén usamos ocasionalmente o índice de Shanon-Wiener (SWI) que mide a diversificación — canto maior sexa o valor do índice, maior será a diversificación. Usualmente, os resultados dos nosos modelos presentan unha diversificación maior nas carteiras de menor risco —e maior custo— e unha meirande concentración nas carteiras de menor custo — e maior risco. O mesmo sucede cando, en troques de minimizar o risco-custo, minimizamos os pares risco-emisión: as carteiras con menores emisións tenden a estar máis concentradas que as carteiras con menor risco de emisión. Outros tipos de diversificación que melloran a seguridade enerxética, e que non se tratan directamente nos traballos presentados, son a diversificación das fontes primarias de enerxía e a diversificación das orixes da enerxía importada. Neste punto, convén salientar que a UE é un territorio cunha forte dependencia enerxética e o uso de tecnoloxías de xeración renovable pode axudar a reducir a devandita dependencia, dado o seu carácter doméstico.

Nos traballos presentados o custo é unha variable fundamental do modelo. Constitúe, de feito, un dos inputs do modelo — xunto co risco, ou variabilidade dese custo, e as correlacións entre os custos das diferentes tecnoloxías de xeración. O cálculo dos custos de xeración eléctrica abórdase na Literatura dende unha perspectiva financeira: o *levelized cost of energy* ou LCOE defínese como o prezo que iguala a soma financeira dos custos que debe afrontar unha planta de xeración eléctrica cos ingresos que esa planta obtén da venda da electricidade xerada.

De xeito máis detallado, podemos calcular o custo de electricidade como a soma dos custos de construción da planta, dos de finanzamento, dos de operación e mantemento da planta, dos de combustible —se houber—, dos de emisións —se cómpre— e, finalmente, dos de desmantelamento — se foran precisos. Considéranse ingresos da planta o producto da electricidade xerada polo prezo desa electricidade. No equilibrio financeiro, ese precio é o LCOE propiamente dito.

Verbo do respecto ó medio ambiente, consideramos á UE o líder mundial na loita contra o cambio climático. As súas políticas enerxéticas están orientadas á redución de emisións e a incorporación de enerxías renovables no que se refire á xeración de electricidade. O factor de emisión das carteiras de xeración é un dato que sempre presentamos nos artigos que acompañan a esta tese. Consideramos ese dato como fundamental para alguén que queira deseñar como debe ser a xeración enerxética a medio prazo nun determinado territorio. No terceiro traballo incluído neste compendio mesmo presentamos un exemplo de utilización por parte do regulador do modelo presentado nese artigo.

A.2 Metodoloxía

Nos artigos incluídos neste compendio, usamos a metodoloxía proposta por Harry Markowitz (Markowitz, 1952) para a selección de carteiras eficientes de activos financeiros. O propietario dunha carteira de activos financeiros tenta maximizar o rendemento da mesma, pero este obxectivo non pode considerarse único xa que existe un intercambio entre rendemento e risco —entendido como a variabilidade daquel rendemento— que fai que canto meirande sexa o rendemento, meirande sexa tamén o risco. Noutras palabras, se un inversor quere maximizar o rendemento, ten que asumir un maior risco e, se quere minimizar o risco asumido, ten que renunciar tamén ó rendemento. Por esta razón, o obxectivo ten que considerarse doble: maximizar o rendemento dado un nivel de risco asumible polo inversor ou minimizar o risco para un nivel de rendemento aceptable.

A teoría moderna de carteiras ou MPT —do inglés, *Modern Portfolio Theory*— afronta ese doble obxectivo cun problema de optimización cuadrática. Dados n activos financeiros e coñecidos tanto os seus rendementos esperados —medidos, por exemplo, pola media dos rendementos históricos—, os seus riscos —medidos pola desviación típica ou calquera outra expresión da variabilidade dos rendementos esperados— e as súas correlacións ou covarianzas, temos que o rendemento esperado da carteira pode expresarse como a media dos rendementos dos activos ponderada pola súa participación relativa na carteira — véxase a ecuación 1; pola súa banda, o risco da carteira tamén pode expresarse en función dos riscos dos activos que a compoñen, pero neste caso hai que ter en conta que a soma de variables aleatorias ten que ter en conta a covarianza ou correlación entre as mesmsa — véxanse as ecuacións 2 e 3.

A MPT propón a minimización do risco da carteira suxeita inicialmente a dúas restricións: a soma das participacións relativas dos activos ten que ser 1 —a carteira está completa— e o rendemento esperado da carteira ten que ser igual a un dado — véxase a ecuación 4. A solución deste problema proporciona unha curva que contén as carteiras eficientes de activos. A MPT postula que unha carteira eficiente é aquela que presenta o menor risco para un nivel de rendemento dado ou, alternativamente, a que presenta o meirande rendemento esperado para un nivel de risco dado.

Cando aplicamos a MPT ó deseño da xeración eléctrica temos que ter claro que o facemos pensando no medio ou longo prazo e para un territorio relativamente extenso. Isto é así debido ás hipóteses da propia MPT que, ó estar pensada para carteiras de activos financeiros, asume a funxibilidade e completa divisibilidade dos mesmos. Evidentemente, os activos de xeración eléctrica non son funxibles nin divisibles, pero dende unha perspectiva a medio ou longo prazo e para un territorio máis ou menos extenso, poden considerarse como tales (Awerbuch, 2000; Awerbuch & Berger, 2003).

Outra das adaptacións necesarias cando aplicamos a MPT á xeración eléctrica, é o feito de que as tecnoloxías non poden presentar participacións negativas cando se resolve o modelo. En Finanzas, os activos financeiros si poden presentalas —sempre que a soma de tódalas participacións sega sendo un— e indican unha posición curta no activo correspondente. Esta adaptación inclúese no modelo por medio dun conxunto de restricións polas que a participación de cada tecnoloxía ten que ser igual ou meirande que cero.

Por outra banda, o problema financeiro da MPT preséntase nun espazo risco-rendemento, namentres que —cando aplicamos a MPT á xeración eléctrica— é usual cambiar a dimensión do rendemento por outra. Nos artigos incluídos neste compendio, ó aplicar a MPT á xeración eléctrica, usamos o custo de xeración por tecnoloxía. No terceiro artigo, ademáis do custo por tecnoloxía, tamén usamos o factor de emisión de CO_2 das tecnoloxías poluíntes.

Verbo do custo de xeración, este adoita ser calculado coma un *levelized cost of energy* ou LCOE. É esta unha aproximación financeira ó cálculo do custo de xeración que consiste en igualar financeiramente os ingresos dunha determinada planta de xeración cos custos da mesma. Noutras palabras, iguálase o valor descontado dos ingresos —produción por prezo— co valor descontado dos custos —custos de capital, custos de operación e mantemento da planta, custos de combustible, custos das emisións e custos de desmantelamento da planta— e despéxase o prezo que é o LCOE propiamente dito — véxanse as ecuacións 6, 7 e 8.

Pola súa parte, o risco de xeración calcúlase por agregación dos riscos das diferentes compoñentes do custo. Esa agregación ten que ter en conta as posibles correlacións entre os diferentes custos. En realidade, para a meirande parte dos custos, asúmese a hipótese de non correlación, pero, como podemos comprobar vendo as ecuacións 9 e 10, si que temos en conta a correlación entre os custos de combustible e os custos de emisións.

Ademais, cando falamos do risco de xeración, temos que ter tamén en conta que pode haber correlacións entre as compoñentes do custo das diferentes tecnoloxías. Nos artigos adxuntos a este traballo asúmese que a única compoñente do custo que presenta correlación entre as diferentes tecnoloxías é o custo de operación e mantemento, hipótese usual na Literatura (Awerbuch & Berger, 2003; Awerbuch & Yang, 2007; de-Llano Paz, 2015; de-Llano Paz et al., 2014).

Habería que facer unha mención especial ó risco das tecnoloxías de xeración renovables (RES). A xeración mediante RES xoga un papel fundamental na estratexia enerxética europea xa que permite, por unha banda, reducir a sen dúbida elevada dependencia enerxética do vello continente de fontes enerxéticas foráneas; por outra banda, permite elevar o nivel de diversificación da carteira de xeración e, por último, contribúe a reducir as emisións da xeración eléctrica. As tecnoloxías de xeración mediante RES teñen sido tratadas de diferentes xeitos na Literatura. Dende autores como Awerbuch e Berger (2003) que asumen que estas tecnoloxías carecen de risco por presentar unicamente custos de operación e mantemento, cunha variabilidade tan pequena como para asumila nula, até autores como Arnesano et al. (2012) para os que o risco da xeración

RES, especificamente da xeración eólica e fotovoltaica, provén da súa intermitencia: ó seren tecnoloxías cunha dispoñibilidade parcial, o seu factor de capacidade debe ser considerado unha fonte de risco similar ó risco de variabilidade dos custos de combustible.

A.3 Contribución científica

Incluímos neste compendio tres traballos. Todos fan unha análise de diferentes aspectos da xeración eléctrica aplicando a MPT. Como entradas do modelo, usamos o custo de xeración de cada unha das tecnoloxías consideradas —en xeral teremos en conta a nuclear, o carbón, o carbón con captura e almacenamento de carbono (CCS), o gas natural o gas natural con CCS, o petróleo, a eólica, a hidráulica, a pequena hidráulica, a eólica *offshore*, a biomasa e a solar fotovoltaica (PV)— e o seu risco, medido este por algún tipo de variabilidade do custo — nomeadamente, a desviación típica ou a varianza. Na liña da actual estratexia enerxética europea, estes traballos afondan na vertente medioambiental das políticas enerxéticas.

O primeiro artigo analiza catro diferentes escenarios no horizonte 2030: o escenario tecnolóxico, o escenario de redución de emisións, o escenario de alta participación das RES e o escenario UE — que supón a consideración conxunta dos escenarios de redución de emisións e do de alta participación das RES.

Nos artigos, normalmente un escenario supón un conxunto de restricións adicionais ó problema de optimización da MPT. Por exemplo, no primeiro artigo, o escenario tecnolóxico supón a inclusión de límites de xeración por tecnoloxía ou conxunto de tecnoloxías similares ós presentados na táboa 4. Estes límites veñen dados pola propia natureza da xeración eléctrica —que, salvo en sistemas moi pequenos, non debe depender dunha única tecnoloxía de xeración— e polos obxectivos, políticas e estratexias do regulador.

No escenario de redución de emisións incluímos, ademais das restricións tecnolóxicas, restricións relacionadas coa emisión de CO_2 — véxase a táboa 5. Os límites para estas restricións toman como referencia os obxectivos europeos de redución de emisións. No escenario de alta participación das RES, forzamos a que polo menos un 43 % da xeración eléctrica sexa con orixe en RES. O modelo EU incorpora, como diximos anteriormente, tanto os límites de redución de emisións como os de participación das RES.

O segundo artigo incluído neste compendio estuda o efecto da incorporación das tecnoloxías CCS —actualmente, en desenvolvemento— á carteira de xeración europea. As tecnoloxías CCS permiten a captura da meirande parte das emisións de CO_2 nas plantas de carbón e gas natural, pero aínda non é posible saber cales serán os seus custos cando estean dispoñibles para o seu uso comercial. Nin sequera se sabe con absoluta certeza se estarán dispoñibles para o seu uso comercial, aínda que tanto a EU coma outros organismos e institucións internacionais —*Institute for Prospective Technological Studies* (IPTS), *International Energy Agency* (IEA), etc.— apostan pola súa dispoñibilidade para 2030. No artigo, e dada a incerteza do actual estado destas tecnoloxías, estudamos o efecto na carteira de xeración europea —concretamente, no seu custo, no seu risco e no seu factor de emisión— dunha variación de ±1 e ±2 desviacións típicas no seu custo, e o dun cambio de ±50 % no seu risco. O estudo do efecto das variacións no risco e no custo das tecnoloxías CCS no risco e no custo da carteira de xeración é levado a cabo mediante restricións tecnolóxicas e o estudo do efecto no factor de emisión impleméntase mediante restricións medioambientais de redución de emisións mínima, media e intensa.

A MPT evolucionou en Finanzas cara o modelo de valoración de activos de capital ou CAPM — do inglés, *Capital Assets Pricing Model.* Xa a MPT tiña suposto a entrada no modelo dun activo libre de risco —un bono do estado, por exemplo— que podería combinarse con calquera carteira eficiente para producir o mesmo rendemento có da carteira a un menor risco. Dada a concavidade da fronteira eficiente de activos financeiros, pode incrementarse a pendente da liña que representa as combinacións entre o activo sen risco e a fronteira eficiente até un punto no que chega a ser tanxente á fronteira eficiente — véxase a liña vermella da figura 3. Nesa circunstancia, a carteira eficiente que serve como punto de tanxencia ten unhas propiedades especiais —é a carteira eficiente que presenta unha mellor relación de intercambio entre rendemento e risco— e por iso coñécese como a carteira do mercado — o punto M na figura 3.

Cando se aplica a MPT á xeración de electricidade, tal e como diximos anteriormente, é usual cambiar os pares risco-rendemento da MPT orixinal por pares risco-custo. Isto causa que a fronteira eficiente pase a ser convexa e sexa imposible determinar un punto de tanxencia no suposto de que puideramos atopar un activo de xeración sen risco. Algunhas aplicacións da MPT á xeración de electricidade optan por manter unha fronteira eficiente cóncava —por exemplo, utilizando a inversa do custo na vez do custo propiamente dito— pero, no terceiro artigo deste compendio, decidimos cambiar dende un plano risco-custo a un plano risco-emisións no que tamén quedaba moito máis clara a existencia de activos de xeración sen risco: calquera tecnoloxía de xeración non poluínte. Aínda así, a fronteira eficiente seguía a ser convexa e iso impediunos determinar unha liña como a liña do mercado de capitales ou CML —do inglés, *Capital Market Line*— que recollese as posibles combinacións entre o activo sen risco e a carteira do mercado. En troques, decidimos formar unha área co activo sen risco e os puntos extremos da fronteira eficiente que recollese calquera combinación entre un activo non poluínte —e, polo tanto, sen risco— e unha carteira eficiente. Chamamos a esa área a área análoga á CML ou área CML-A. Pensamos que pode servir coma ferramenta para o regulador á hora de deseñar as sucesivas carteiras de xeración cara a un futuro sen emisións na xeración eléctrica.

Nos artigos incluídos nesta compilación tentamos dar resposta ás seguintes preguntas:

- Como afectan á eficiencia custo-risco, ás emisións e a diversificación da carteira de xeración as políticas da UE referentes á xeración eléctrica?
- Algunhas institucións, como o IPTS, asumen unha participación máxima das tecnoloxías CCS do 18 % da xeración en base a combustibles fósiles. Como afecta esa asunción á carteira de xeración europea?
- A aplicación da MPT á xeración eléctrica vén demostrando ser práctica e útil. Podería ser posible tamén a aplicación do CAPM á xeración eléctrica?

A.4 Modelos utilizados

Dadas n tecnoloxías de xeración, sexa $x \in \mathbb{R}^{n\times 1}$ o vector que contén as participacións relativas —descoñecidas— de cada tecnoloxía no *mix* de xeración eléctrica dun territorio. Dados os custos medios de xeración para cada tecnoloxía, $c \in \mathbb{R}^{n\times 1}$ e a matriz de varianzas-covarianzas deses custos, $S \in \mathbb{R}^{n\times n}$, partimos o problema a resolver nos tres pasos que explicamos a continuación.

Os riscos do custo de xeración —a súa variabilidade— veñen recollidos na matrix S que, na súa diagonal, contén as varianzas do custo de xeración.

1. Calcular a carteira de mínimo risco global ou GMV — *Global Minimum Variance*. Para isto, resolvemos o problema presentado na ecuación 11. Nesta ecuación, a primeira restrición é a de positividade das participacións —non admitimos participacións negativas na xeración eléctrica— e a segunda é a completiva — a soma das participacións das tecnoloxías consideradas ten que ser igual á unidade.

2. Calcular a carteira de mínimo custo global ou GMC — *Global Minimum Cost*. No terceiro artigo, e por mor do cambio risco-custo a risco-emisións, calcularemos tamén a carteira de mínimas emisións global ou GME — *Global Minimum Emission*. O problema preséntase na ecuación 12, na que tamén vemos as restricións de positividade e a completiva.

3. Calcular un subconxunto de m carteiras eficientes entre a carteira GMV e a carteira GMC. Para isto, engadimos unha restrición adicional ó problema do paso 1 anterior: a restrición de custo. En realidade, o que facemos é calcular m valores específicos de custo, k^*, equidistantes entre o custo da carteira GMV e o custo da carteira GMC para resolver os m problemas de optimización e determinar a fronteira eficiente.

A verdadeira flexibilidade do modelo está precisamente na posibilidade de definir diferentes funcións obxectivo e de incluir restricións adicionais —en termos de igualdade ou desigualdade— que limiten os posibles resultados. Así, ademais do modelo recén descrito, ó que chamaremos modelo base pola súa función de referencia, utilizamos nos artigos adxuntos a este traballo tres tipos de modelos adicionais construídos sobre este: os modelos tecnolóxicos, os modelos medioambientais e os modelos de emisións.

O obxectivo dos modelos tecnolóxicos é o de achegar ós resultados ó mundo real mediante a inclusión de restricións que limiten as participacións das tecnoloxías consideradas. Recollemos o valor concreto dos límites interpretando as políticas enerxéticas e as recomendacións de diferentes institucións e organismos —nomeadamente, a UE. Estes límites contribúen á mellora da seguridade enerxética mediante a diversificación das tecnoloxías de xeración.

Os modelos medioambientais e de emisións tentan recoller os obxectivos presentados nas estratexias de deseño da xeración eléctrica europea. A diferencia entre eles estriba en que os modelos medioambientais son similares ós tecnolóxicos no senso de que as restricións que definen son sobre as participacións relativas das tecnoloxías consideradas, aínda que agora os límites definidos supoñen participacións mínimas, namentres que os límites dos modelos tecnolóxicos son participacións máximas. Os modelos de emisión incorporan restricións sobre os factores de emisión de gases de efecto invernadoiro —CO_2, SO_2 e NO_x— e materia particulada —*particulate matter* ou PM— das carteiras que compoñan a solución do modelo.

A.5 Conclusións

Neste apartado daremos resposta ás preguntas presentadas no apartado A.3 anterior.

- Como afectan á eficiencia custo-risco, ás emisións e a diversificación da carteira de xeración as políticas da UE referentes á xeración eléctrica?

No primeiro artigo desta compilación, utilizamos un modelo tecnolóxico de referencia —ó que, no artigo, referímonos como modelo base—, un modelo de baixas emisións —que incorpora restricións sobre os factores de emisión das carteiras eficientes que entren na solución do modelo—, un modelo de alta participación das RES —que impón unha participación mínima do 43 % das tecnoloxías RES— e o que chamamos o modelo europeo — que incorpora conxuntamente as restricións do modelo de baixas emisións e do modelo de alta participación das RES. De acordo cos resultados dos modelos considerados, a UE conservaría un nivel aceptable de eficiencia risco-custo en calquera dos escenarios.

Todos os modelos amosan resultados similares. De feito, na parte esquerda da fronteira eficiente —aquela preto da carteira GMV— o modelo tecnolóxico e o de alta participación das RES practicamente solápanse. O mesmo sucede —cun lixeiro incremento de risco— para os modelos de baixas emisións e europeo. Na parte dereita da fronteira eficiente —preto da carteira GMC— os modelos tecnolóxicos e de baixas emisións presentan un menor custo cós modelos de alta participación das RES e europeo.

No artigo concluímos que a UE pode incrementar a eficiencia da xeración eléctrica considerando unicamente obxectivos de redución de emisións. De feito, estes obxectivos provocan *per se* unha elevada participación das RES na xeración eléctrica, o cal —por mor do carácter doméstico deste tipo de tecnoloxías— incrementa a seguridade enerxética reducindo a dependencia enerxética. Ademais, a implementación de políticas de redución de emisións é —en media— máis barata que a de políticas de participación mínima das RES. Por outra banda, os resultados dos modelos de emisións presentan menores factores de emisión cós resultados dos modelos medioambientais. Isto era de esperar xa que as restricións de emisións están presentes nos tres pasos apuntados do modelo no apartado A.4 anterior, namentres que unha vez se acade o límite mínimo do 43 % de participación das RES na xeración eléctrica, o modelo pasa a optimizar a función nunha base de risco-custo estrita. A contrapartida é que os modelos de redución de emisións son menos diversificados que os modelos de alta participación das RES.

No artigo, tamén estudamos se a UE pode prescindir da xeración nuclear. Isto facémolo presentando dous escenarios: un que limita a participación nuclear á metade do seu límite tecnolóxico e outro no que completamente prescindimos da xeración nuclear. En calquera caso, os resultados apuntan a que a xeración nuclear seguirá tendo un papel importante na UE. De prescindir do 50 % da súa xeración, entrarían —para cubrir esa falla— tecnoloxías de maior custo incrementando o custo de xeración, pero diminuíndo o risco. Esta situación cambia se prescindimos da xeración nuclear na súa totalidade, escenario no que se verán incrementados tanto o risco coma o custo de xeración.

Nas conclusións do artigo tamén pode verse que a minimización do risco de xeración resulta en carteiras máis diversificadas que a minimización do custo, o cal supón, de novo, un xeito de incrementar a seguridade enerxética.

- Algunhas institucións, como o IPTS, asumen unha participación máxima das tecnoloxías CCS do 18 % da xeración en base a combustibles fósiles. Como afecta esa asunción á carteira de xeración europea?

As conclusións do segundo artigo apuntan a que a UE debe apoiar o desenvolvemento das tecnoloxías CCS posto que están chamadas a xogar un papel de capital importancia na implementación da estratexia europea no horizonte 2030. Esa importancia vén da man tanto dos obxectivos de reduccón de emisións coma dos de incremento da eficiencia. Nembargantes, o estado actual das tecnoloxías CCS non pode garantir a súa dispoñibilidade nin os seus custos e riscos esperados actuais en 2030. Por isto, o segundo artigo dos incluídos neste compendio analiza que sucedería se os custos e riscos esperados destas tecnoloxías variasen. En liña coa asunción do IPTS engadimos ó noso modelo tecnolóxico unha restrición conforme a que as tecnoloxías CCS deberán participar polo menos nun 18 % da xeración conxunta de carbón sen CCS, gas natural sen CCS e petróleo.

Os obxectivos da UE para 2030 inclúen unha redución do 40 % nas emisións de gases de efecto invernadoiro. Para o CO_2 esa redución concrétase nunha baixa de entre o 54 % e o 68 % das súas emisións, a cal é considerada mediante a inclusión de tres escenarios de redución de emisións mínima, media e intensa, e as súas correspondentes restricións.

O artigo conclúe que os efectos das variacións no custo —±1 e ±2 desviacións típicas— e no risco —±50 %— apenas afectan ás fronteiras eficientes consideradas. Se nos fixamos noutros aspectos, como as emisións, veremos que a inclusión na carteira de xeración das tecnoloxías CCS ten efectos moi positivos, o desplazar estas tecnoloxías a outras máis poluíntes.

Se analizamos a composición das carteiras GMV e GMC dos diferentes modelos presentados no artigo, veremos que as tecnoloxías CCS están presentes en calquera das GMV, indicando que, se o regulador quere reducir o risco de xeración, ten que contar con estas tecnoloxías. Por outra banda, o gas natural con CCS non participa en ningunha carteira GMC, e o carbón con CCS participa sempre que a redución de emisións sexa media ou intensa, quedando fóra dos escenarios cunha redución de emisións pouco comprometida.

Como, en calquera caso, semella que a UE vai manter e mesmo incrementar os seus compromisos medioambientais, conclúese que as tecnoloxías CCS deberán estar dispoñibles en 2030 para axudar a consecución deses compromisos.

- A aplicación da MPT á xeración eléctrica vén demostrando ser práctica e útil. Podería ser posible tamén a aplicación do CAPM á xeración eléctrica?

  Considerando a redución do risco das emisións na función obxectivo do noso modelo, podemos transformar o problema risco-custo orixinal da MPT aplicada á xeración de electricidade nun problema risco-emisións. Isto permítenos separar en dous grupos as tecnoloxías consideradas: un grupo estaría composto polas tecnoloxías poluíntes e outro polas non poluíntes. A MPT financeira dispón de activos financeiros sen risco —os emitidos polos diferentes estados— pero non podemos atopar unha tecnoloxía de xeración sen risco de custo — aínda que como comentamos no apartado A.2 deste resumo, hai autores que identifican ás tecnoloxías RES coma tecnoloxías de xeración sen risco. Coa transformación apuntada —e ó sermos capaces de obter un subconxunto de tecnoloxías sen emisións e, evidentemente, sen risco de emisións— replicamos a existencia dun activo sen risco da MPT e do CAPM. Temos que aclarar que ó non dispor de riscos de emisión, no artigo utilizamos ós riscos do custo coma *proxy* do risco de emisións.

Presentado o problema de optimización coma un problema de minimización do risco das emisións somos capaces, utilizando o subconxunto de tecnoloxías poluíntes, de elaborar unha fronteira eficiente na que están as carteiras de xeración que presentan o menor risco para un nivel de emisións determinado ou o menor factor de emisión para un risco determinado. No plano de coordenadas risco-emisións, calquera carteira non poluínte —e, en concreto, tamén as carteiras eficientes— estará na orixe de coordenadas. Isto permítenos delimitar un área —á que denominamos área análoga á CML ou CML-A— que ten a característica de presentar, para cada nivel de emisións, un menor risco que calquera carteira eficiente de tecnoloxías poluíntes. No artigo mesmo presentamos un exemplo de aplicación para o regulador que quere limitar ben o factor de emisión ben o risco da carteira de xeración europea. Se o regulador quere limitar o risco de emisións da carteira europea, poderá escoller a carteira que, situada na liña que une a orixe de coordenadas coa carteira GME da fronteira eficiente, posto que é a que —dentro das carteiras da CML-A— menor factor de emisión presenta para o risco considerado. Por outra banda, se o regulador quere limitar o factor de emisión da carteira europea de xeración, escollerá a carteira que, para ese nivel de emisións, estea situada na liña que une a orixe de coordenadas coa carteira GMV da fronteira eficiente, pois esa carteira presentará o menor risco para ese factor de emisión de entre as carteiras da CML-A.

Queremos tamén salientar o feito de que as tecnoloxías CCS, xunto coa biomasa, son as tecnoloxías preferidas á hora de determinar a fronteira eficiente das tecnoloxías poluíntes. De feito, no artigo, presentamos diferentes escenarios prescindindo desas tecnoloxías porque, cando son consideradas, deixan sen participación ás demais. Polo seu extremadamente baixo factor de emisión, a biomasa acapara prácticamente o 100 % da xeración na carteira GMV cando é considerada. Se a quitamos do modelo, entón son as tecnoloxías CCS as que asumen máis do 97 % da xeración na carteira GMV. Calquera destas situacións non ten aplicación na práctica, nun campo onde a diversificación é de vital importancia para a seguridade enerxética, pero si serven para suliñar, de novo, o potencial das tecnoloxías CCS no futuro europeo.

Con estas conclusións consideramos cubertos os obxectivos desta tese por compendio de artigos. A MPT pode considerarse unha potente e versátil ferramenta para o deseño de políticas enerxéticas no que se refire á xeración de electricidade. A evolución dende a MPT ó CAPM pode replicarse no campo da enerxía, tendo en conta a convexidade da fronteira eficiente neste ámbito. Por último, tanto as tecnoloxías RES como as CCS están chamadas a xogar un papel tremendamente importante á hora de mellorar a eficiencia da carteira de xeración europea. A UE non pode deixar de apostar pola dispoñibilidade das tecnoloxías CCS no 2030 para facilitar esa mellora.