Analysis and Application of Modern Portfolio Theory to the German Electricity Mix

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Abstract

This study contextualizes the current characteristics of the German electricity mix, what energy sources it uses and how much they are used in order to generate power, or what is the price that the final consumer pays for its electrical needs compared to other neighboring nations, among other relevant aspects.

In the second and main part of the paper, in order to predict what will be the evolution of the aforementioned sector, something relevant due to Germany´s front runner position in the current energy transition towards a cleaner and sustainable energy, that will potentially help us to understand the evolution of the majority of the advanced economies. The methodology that will be used is the modern portfolio theory, and applying the appropriate restrictions, a forecast of the electricity mix composition for the years 2030, 2040 and 2050 and the implications that it has in terms of power prices, pollution and health will be made. By 2030, 65% of the electricity produced in the country will be generated by RES and Biofuels, by 2040, 65%-82%, and by 2050 this proportion will reach 80%-90%. Also, conventional energy sources are expected to be less important as time passes. In contrast, all green energy sources will be improved drastically, being way more competitive in terms of production costs than fossil fuel sources. Indeed, onshore wind will become the single largest energy source, generating 31%-65% of power in the country, followed by solar (13%-28%).

Key words: German electricity mix, Markowitz optimization portfolio model, German energy transition, Modern portfolio theory, Renewable energy sources.

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1. INTRODUCTION

Germany is the largest national energy consumer in Europe and 6th largest energy consumer worldwide. Its Gross Inland Consumption (GIC) in 2018 was 314.43 million tonnes of oil equivalent (Mtoe), representing 21.3% of the total energy consumption in the European Union (EU) (energy conversion units can be consulted in (Annex A).

It is also the largest national electricity market in Europe, with a production of 641.59 terawatt hour (TWh) in 2018, 7,728.21 kilowatt hours (kWh) per capita, which was 17.4% more than the EU-27 average (EU-27: 6,583 kWh/person) and comparable to the 93.6% of the Organization for Economic Co-operation and Development (OECD) average per capita electricity consumption (8,256 kWh/person).

In 2017, the median German household consumed an average of 3,171 kWh of electricity at 30.5 euro cents per kWh, spending a grand total of 80.59 euros monthly (697.07 euros yearly) on electricity bills. Germany had the second highest price of residential electricity in EU only after Denmark.

Germany´s carbon dioxide (CO_2) emissions for the year 2017 summed up to 0.7 Gigatonnes (Gt), being the most CO_2 polluting country in Europe and the 6th in the world. In per capita terms, every German resident polluted 8.7 tonnes yearly, being the largest per capita polluters in the European Continent and the 8th in the world. Among all the greenhouse gases (GHG) emitted every year in Germany, roughly 80% is CO_2, and 35% are produced by the energy sector.

Its huge size within the European energy market has granted Germany the leading role in the EU green energy transition and energy market integration, being a reference in innovation patents, green energy production, legislation and for heavily investing in renewable energy sources (RES) since the beginning of the century.

The regulator is well aware of Germany´s position in the European framework, thus, in 2010 it initiated the so called Energiewende (energy transition) by passing the Energiekonzept (energy concept) Document, that sets the energy policy of the country until 2050 in terms of RES, energy efficiency, electricity production and GHG emissions.

Its main objectives are: improving the energy efficiency of the country by reducing the consumption of energy in all sectors, developing the use of RES (predominantly solar and wind) for electricity production and cutting down GHG emissions by at least 80% by 2050.

Besides of this low carbon energy transition, Germany has followed a phase-out policy regarding nuclear power, expecting to shut down the 8 remaining power plants in the country by 2022.

The main piece of Green Energy Legislation is the German Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz or EEG), a series of laws passed between the years 2000 and 2017, that aim to boost the development of green energy sources in the country by financing part of the generation cost of these technologies through levies included in the final electricity prices.

However, Germany´s lack of energy supply sufficiency is perhaps one of the biggest threats to the European Energy Common Market. Germany imports more than half of its energy, mainly oil (being the 5th largest oil consumer worldwide) from Russia, Norway and the United Kingdom. But also imports vast amounts of natural gas, giving the country the spot of world's largest importer of natural gas. As a consequence of this energy deficit, the country drives out resources that could have been used in the European territory, giving influence to suppliers of fossil fuels against the EU model such as Russia, and at the same time, waking the demand of euros by using United States dollars in order to pay more than 80% of all energy imports that the EU makes (Guarascio & Zhdannikov, 2019).

Nevertheless, because of its massive coal deposits, Germany has a long-lasting tradition of using coal, and it is nowadays the 4th largest consumer of coal in the world. However, the same does not happen from the production side. Due to the efforts of the national regulator to put Germany in the path of an environmentally friendly way of producing energy, the production of coal in the country is more expensive than importing it from countries such as China or Colombia, causing the domestic coal mining to be almost completely phased out.

As a result of this transition seen in the last years, Germany has been called “the world’s first major renewable energy economy”, achieving on 8 May 2016 a renewable energy supply of the 87.6% of Germany’s national electricity consumption under extremely favorable weather conditions (Coren, 2016).

These data contrast with the huge energy deficit that Germany has got, and is a clear example of the common European Energy Market, transitioning from an external dependent fuel-based model to a European Interconnected Electricity Market grounded on RES.

However, this quick transition, shutting down all nuclear energy plants by 2022 and encouraging the generation of energy through RES, is not enough to supply all energy necessities of the country, having to heavily rely on gas fossil fuels while facing this energy transition (Kunz & Weigt, 2014).

2. ELECTRICITY MIX

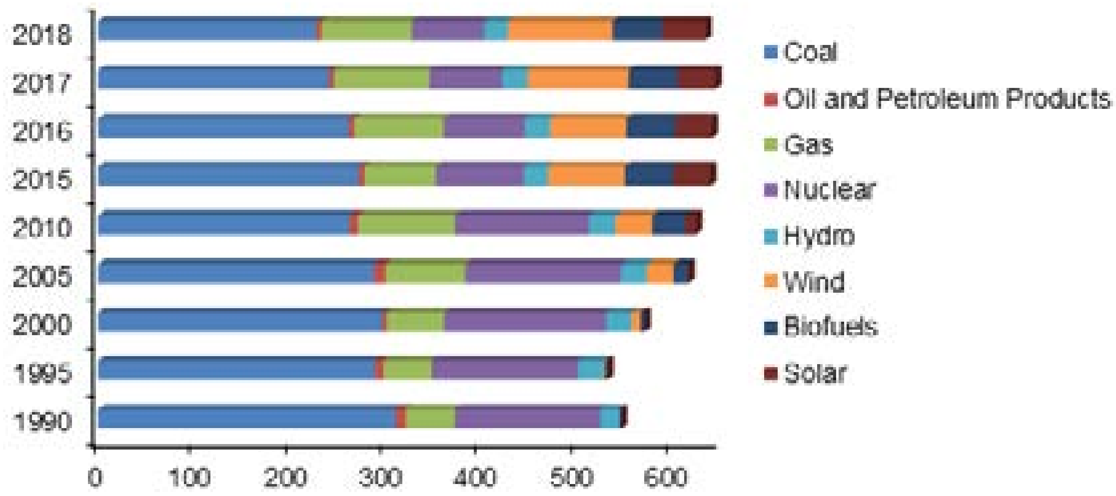
The proliferation of Germany´s RES has been outstanding in the last decades, especially since the beginning of the century when the first EEG was passed, which led to a greener energy production. As can be observed in Figure 1, almost all RES and biofuels have increased significantly in the electricity production. Among the environmentally friendly sources, hydro and biofuels seems to be stuck in the amount of electricity produced yearly over the last decade, however, solar (mainly PV) and wind seem to be unstoppable, growing at large rates since the year 2000.

The importance of Conventional Energy Sources (predominantly coal and gas) for the electricity production is still large, however, the amount of electricity generated by them in last decades is downwards, being particularly remarkable the production cut of nuclear sources. Nevertheless, gas is the only fossil-powered energy source that has gained importance in the electricity production both in relative and absolute terms.

Figure 1

Germany´s Electricity Mix Composition (1990-2018)

(In TWh)



Source: Author´s own elaboration employing data from Directorate-General for Energy European Commission (2020).

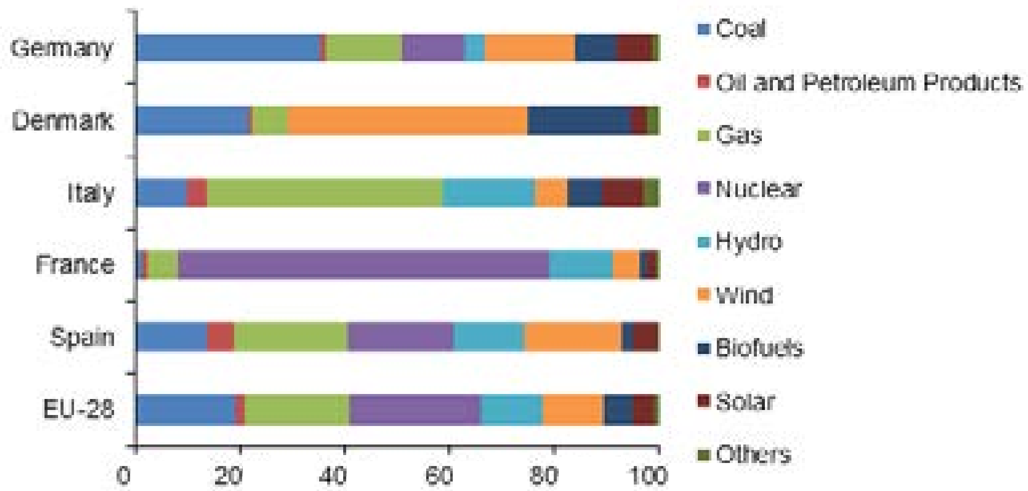
Compared to other European nations, Germany´s green energy production is above the EU-28 average, nevertheless there are some countries that are much more advanced in this regard. Denmark is the best example, producing more than 70% of their electricity through RES and biofuels. Even some major economies such as Spain or Italy are more settled in the environmentally friendly electricity production (Figure 2).

It is worth noting on which energy source each country relies. France has a strong dependence on nuclear, having the cheapest household electricity price among the big economies of the EU (though emission cost and energy production risks are not internalized in this price). Italy heavily leans on gas due to the multiple gas pipelines that flow towards the country from locations as diverse as Russia, Azerbaijan, Libya or Algeria. Denmark has got a wide network of wind farms across the country due to its geographical location and climatological features. And Germany, due to its large coal deposits and its long coal mining tradition still relies on this fossil fuel despite its transition towards a greener model.

Figure 2

EU´s Countries Electricity Mix (2018)

(Percentage)



Source: Author´s own elaboration employing data from Directorate-General for Energy European Commission (2020).

3. ELECTRICITY PRICES

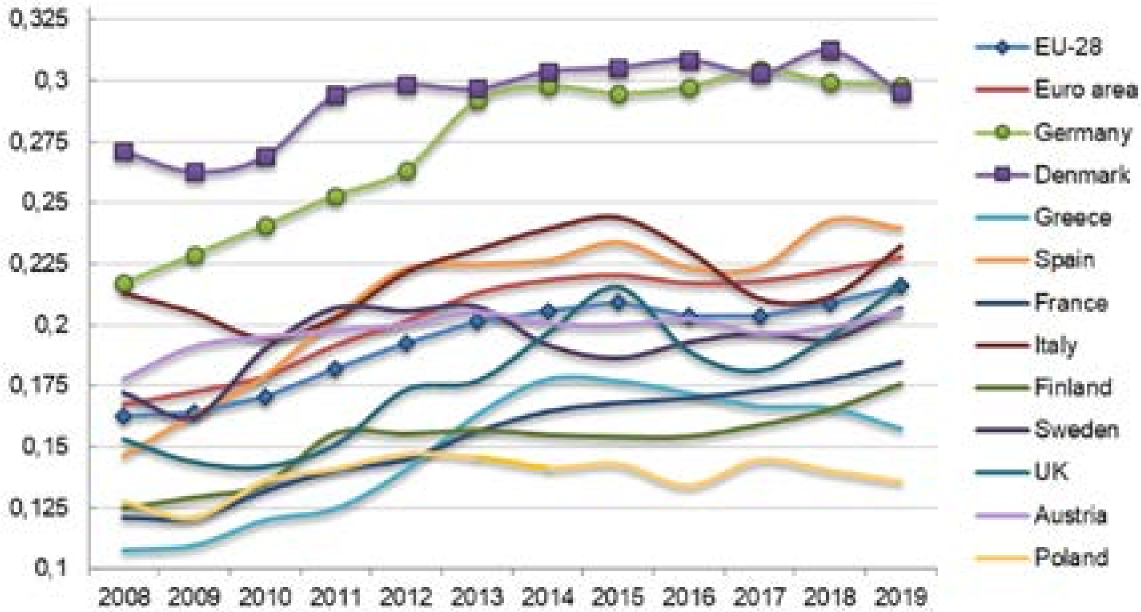
The electricity prices in Germany over the last decades have been the second highest in the EU after Denmark. In addition a sudden increase in electricity prices has occurred in the last years because of the nuclear phase-out and energy transition surcharge policies of the authorities.

Nominal electricity prices for the period 1998-2019 in Germany has increased by 78% (33% in real terms), above the average of the EU-28 (being the country with the biggest prices increase over the period 2008-2019 as seen in Figure 3). Even though the EU has set ambitious goals in terms of renewable electricity production and regulation, Germany´s determination of being a front runner in green energy production and going beyond the European milestones has the consequence of this rise, being 53% of the electricity bills taxes and levies (which have been increased in a higher percentage than the inflation rate over the last years), part to subsidize the so called Energiewende (Bode & Groscurth, 2006).

Figure 3

Evolution of Germany´s Household Electricity Price (2008-2019)

(In euros/kWh)



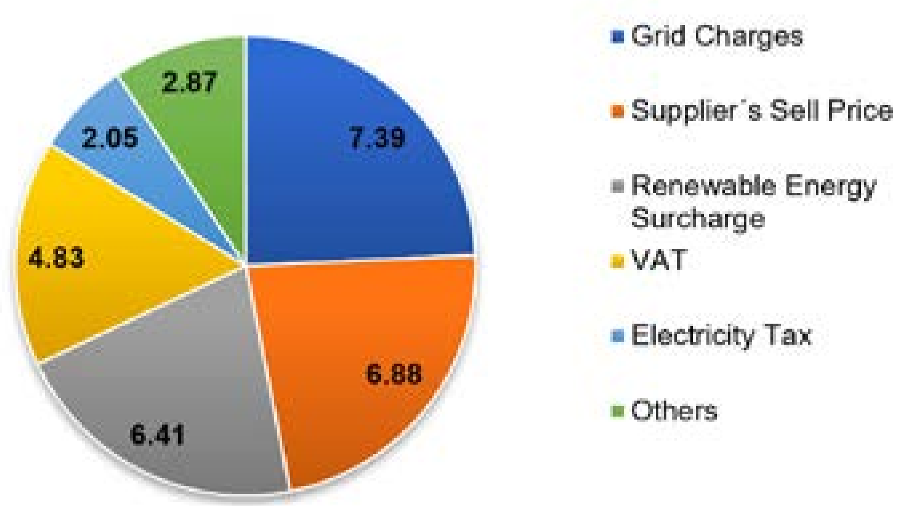
Source: Eurostat (2020).

The average price of household electricity in the consumption band 2,500 kWh-5,000 kWh in the year 2019 was 0.3043 euros/kWh.

Most of the price charged (24%) comes from the grid cost at 0.0739 euros/kWh, *i.e.* the fees of using the network to deliver the electricity, which is slightly more than the supplier's sale price of electricity (including its cost and markup) at 0.0709 euros/kWh (23%). The eenewable energy surcharge takes 21% of the price at 0.0641 euros/kWh, which is used to subsidize the energy transition by offering long-term contracts to renewable energy producers. The price also includes taxes paid to the government: value added tax at 0.0486 euros/kWh (16%) and electricity tax at 0.0205 Euros/kWh (7%). Other surcharges to finance the energy transition represent 9% of the price at a rate of 0.0287 euros/kWh. (Figure 4).

However, it is worth noting how the difference between electricity prices and bills for households affects the energy transition. By contrast, German industry

Figure 4
Germany´s Household Electricity Price Composition (2018)
(In euro cents/kWh)



Source: Author´s own elaboration Employing data from Bundesverband der Energie- und Wasserwirtschaft (2019).

in general bears a less heavy burden in moving towards a more efficient way of power use, because a portion of the fees and surcharges is waived for part of the industry, therefore lacking the same strong incentive as households.

4. MARKOWITZ´S MODEL AND ITS APPLICATION IN THE ENERGY PLANNING

Choosing how the electricity will be produced over the medium and long term in a country is a problem of investment selection and a major consideration in today’s energy and environmental planning. This decision must be made aiming for the least cost (economic and social), a sustainable production, minimizing the dependence on external resources, reducing air pollution, diversifying production among Conventional and RES, meeting the regulator´s agenda taking into account the life expectancy and the future electricity production of each energy source and granting energy security to the nation.

However, selecting one portfolio between infinite investment possibilities that has got an unpredictable behavior is too risky and uncertain, hence Modern Portfolio Theory can lead a country to pick the best option when it comes to producing electricity.

4.1 Modern portfolio theory

Modern portfolio theory (1952) was originally conceived to make the most efficient portfolio in terms of expected portfolio cost and expected portfolio risk regarding financial investments. The outcome of Markowitz´s approach is the so-called efficient portfolio frontier, a range of portfolios that offer the best risk to return or the best risk to cost possible. It makes the investment selection much easier; the investor will only consider the portfolios located in the efficient frontier instead of endless investment possibilities.

Portfolio theory is highly suited regarding energy planning. Selecting the right way of producing electricity is comparable to investing in financial securities, managing the risk and maximizing the return under a set of unpredictable outcomes. Likewise, individual technology cost and return are not the key issues, instead, the total portfolio cost and portfolio return are truly important.

Along the efficient portfolio frontier, some alternatives may have better returns while others may have tinier risks. But all combinations are considered to have the most optimal return-risk and cost-risk relationships (Awerbuch and Berger, 2003). As seen in Figure 5, when it comes to comparing risk to cost, the upper part of the frontier gathers the more secure or stable portfolios while the lower section offers more potentially profitable investment portfolios.

Several authors (Awerbuch, Jansen & Beurskens [2009], Rodoulis [2010], DeLlano *et al.* [2015], Marrero, Puch & Ramos-Real [2015] and Awerbuch & Yang [2007]) have applied the Cost-Risk analysis for different purposes, opting to define models based on the costs of the technologies and the risks associated with them. Hence, the efficient portfolio frontier the authors had generated is cost-risk focused.

Moreover, a series of variables, such as the maximum price or the maximum share of each energy technology, will be restricting the model to meet all the goals

Figure 5

Risk to Return and Cost to Risk Efficient Frontiers

Source: DeLlano-Paz *et al.* (2017).

mentioned in the previous point, the consequences of which will be a change in the composition and shape of the efficient portfolio frontiers.

4.1.1 Expected Portfolio Cost

The Expected Portfolio Cost is defined as the sum of the yields of all the assets of the portfolio.

In terms of modern portfolio theory applied to electricity production, the yield of an asset is given by the inverse of the electricity generation cost, measured in monetary units spent per unit of power generated.

Expected portfolio cost is the weighted average of the individual expected generating cost for energy sources:

$$EPC = X_1 E(LCOE_1) + X_2 E(LCOE_2) + \cdots + X_t E(LCOE_n) \qquad [1]$$

- X_1, X_2 ... X_t = *Fractional shares of the energy technologies in the electricity mix.*
- $E(LCOE_1)$, $E(LCOE_2)$… $E(LCOE_n)$ = *Expected levelized costs of energy per MWh.*

Levelized cost of electricity

The levelized cost of electricity (LCOE) is the ratio of the total lifetime expenses versus the total electricity output measured in monetary units of a given energy asset, in terms of present value.

$$LCOE = \frac{\sum_{t=1}^{T} \frac{Inv_t + O\&M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{Elect_{tt}}{(1+r)^t}} \qquad [2]$$

- *Inv_t = Investment expenditures including financing in the year t*
- *$O\&M_t$ = Operations and maintenance expenditures in the year t*
- *F_t = Fuel expenditures in the year t*
- *$Elect_t$ = Electricity generation in the year t*
- *r = Discount rate*
- *T = Life of the system*

The expenses that the LCOE includes are the investment expenditures of the energy assets (including the interest paid each year if the investment is financed through a line of credit), operations and maintenance expenditures, the expenses that the technology must carry out in its production, fuel expenditures, how much fuel the energy source use to generate electricity over its lifepath, and additionally, this formula might include CO_2 emissions as an expense since CO_2 emission rights are not free in the EU.

4.1.2 Expected Portfolio Risk

The expected portfolio risk in the electricity mix is the expected year-to-year variation in the levelized cost of electricity. It is also the weighted average of each individual technology levelized cost variances, affected by their expenses´ correlation coefficients:

Expected portfolio risk (for a 2-period time frame)

$$EPR = \sigma_P = X_1^2\sigma_1^2 + X_2^2\sigma_2^2 + 2X_1X_2\rho_{12}\sigma_1\sigma_2 \qquad [3]$$

- X_1 & X_2 = *Fractional Shares of each technology in the portfolio*
- σ_1 & σ_2 = *LCOE´s standard deviations of technologies 1 and 2*
- ρ_{12}= *Correlation coefficient of O&M and fuel expenses of technologies 1 and 2*

The standard deviations of the LCOE are crucial to determine the level of risk that an electricity asset implies, because it measures how volatile the electricity production costs are: the more they fluctuate, the more uncertain it is to produce with this energy source, and therefore, riskier.

The correlation coefficients, ρ, measure the relationship between operation & maintenance expenses of different energy sources as well as the co-movements of fuel expenses among technologies. Moreover, it is a measure of diversity: a lower ρ among portfolio components creates greater diversity, which reduces portfolio risk. For example, fuel-powered sources are strongly correlated in their expenses, so having a balanced portfolio using RES and conventional energy sources will reduce the overall portfolio risk (Awerbuch and Yang, 2007).

4.2. Germany´s Efficient Portfolio Frontier Forecast

The main objective of this paper is to make an accurate and realistic forecast about how electricity will be produced in Germany by 2030, 2040, and 2050. In order to make this estimation, modern portfolio theory will be used.

Understanding how the electricity mix will look like is relevant when it comes to understand what will be the leading technologies for the next years, how much will it cost to produce power, what will be the expected investment trends among the different technologies and what will be the impact that electricity generation has on public health. Moreover, due to the front runner position of Germany as the biggest energy market in Europe and for its vast energy innovation, the outcome of this model is going to be also relatable to the path that the EU will follow for the next decades.

Following the aforementioned principles of Awerbuch, Yang, Rodoulis and DeLlano-Paz, the model´s forecast will be obtained through the next formula:

Objective function:

$$Min\ \{\sigma_p\}$$

Subject to:

$$\begin{gathered} E\,(C_p) = C \\ C < 90.9\ Euros/MWh\ ;\ \forall p \\ X_n \leq Maximun\ Fractional\ Share\ of\ each\ technology\ n;\ \forall n \\ \textstyle\sum_N X_n = 1\ \in N\!: X_n \geq 0 \end{gathered} \qquad [4]$$

4.2.1. Markowitz´s Model Data

The following data will be employed to make the efficient portfolio frontier forecast of Germany:

Levelized cost of electricity

Europe's LCOE for the 2020-2050 horizon, as seen in Table 1, will be assumed to be the same as the German ones because no data was found forecasting the expected future LCOE of the country.

Also, they do not include the effects of CO_2 pricing, making the fossil energy sources more competitive than that they are. The LCOE data of the EU reference scenario 2016 made by the European Commission does not consider this effect and the CO_2 emission fees for such a distant time frame are still unknown, so it is impossible to consider its consequences in this paper.

The LCOE of coal is calculated as the weighted average of lignite and hard coal in the electricity production in Germany for the year 2018, being 36.44% hard coal and 63.56% lignite.

Table 1

Europe´s LCOE 2020-2050

(In euros/MWh)

	2020	2030	2040	2050
Coal	58.19	60.10	61.65	63.47
Gas	84.00	91.00	95.00	97.00
Grand scale hydropower	135.00	135.00	135.00	135.00
Mini-Hydropower	108.00	106.00	104.00	101.00
Onshore wind	89.00	80.00	75.00	72.00
Offshore wind	123.00	105.00	95.00	90.00
Solar Center and North of Europe	108.00	95.00	89.00	84.00

Source: European Commission (2016).

All data is collected from the EU reference scenario 2016 made by the European Commission except for biofuels (International Renewable Energy Agency, 2012), which states that the LCOE for the year 2012 is 96.58 Euros/MWh, and since no projection of this variable was found in the elaboration of this paper, no change from the 2012 observation will be assumed for the 2020-2050 horizon.

LCOE Variances and Standard Deviations

Using the LCOE mentioned above, variances and standard deviations have been calculated for each energy sources (Table 2).

Table 2

Germany´s LCOE Variance and LCOE Standard Deviations 2020-2050

(In euros/MWh)

	Variances	Standard Deviations
Coal	5.06	2.25
Gas	32.92	5.74
Grand scale hydropower	0.00	0.00
Mini-Hydropower	8.92	2.99
Onshore wind	55.33	7.44
Offshore wind	212.25	14.57
Solar Center and North of Europe	107.33	10.36

Source: Author´s own elaboration employing Data from European Commission (2016).

Correlation Coefficients

In order to measure part of the co-movements of the LCOE aforementioned, the covariances of operation & maintenance expenses (Table 3) and fuel expenses (Table 4) for each energy source will be used.

Table 3

Operation & Maintenance Correlation Coefficients by Energy Source

	Coal	Gas	Onshore Wind	Grand Scale Hydro	Mini-Hydro	Offshore Wind	Bio-fuels	Solar
Coal	1	0.25	-0.22	0.03	0.03	-0.22	0.18	-0.39
Gas	0.25	1	0	-0.04	-0.04	0	0.32	0.05
Onshore wind	-0.22	0	1	0.29	0.29	1	-0.18	0.05
Grand scale Hydro	0.03	-0.04	0.29	1	1	0.29	-0.18	0.3
Mini-Hydro	0.03	-0.04	0.29	1	1	0.29	-0.18	0.3
Offshore wind	-0.22	0	1	0.29	0.29	1	-0.18	0.05
Biofuels	0.18	0.32	-0.18	-0.18	-0.18	-0.18	1	0.25
Solar	-0.39	0.05	0.05	0.3	0.3	0.05	0.25	1

Source: DeLlano-Paz (2015).

Table 4

Fuel Correlation Coefficients by Energy Source

	Coal	Gas	Biofuels
Coal	1	0.92	-0.53
Gas	0.92	1	-0.15
Biofuels	-0.53	-0.15	1

Source: DeLlano-Paz (2015).

Health Index

Every year thousands of people die prematurely and suffer from severe and minor illnesses caused by air pollution. The forecast also aims to represent the spillovers of transitioning towards a RES based production scheme.

According to Markandya & Wilkinson (2007), the deaths, serious and minor illnesses caused by electricity generation per TWh by energy source in Europe are the following (Table 5):

Table 5
Health Effects of Electricity Generation in Europe by Energy Source
(Cases/TWh)

	Deaths	Serious Illness	Minor Illness
Hard coal	24.5	225	13,288
Lignite	32.6	298	17,676
Oil & petroleum products	18.4	161	9,551
Gas	2.8	30	703
Nuclear	0.052	0.22	0
Biomass	4.63	43	2,276

Source: Markandya and Wilkinson (2007).

Thus, according to the European Commission data of electricity production by polluting energy sources, the health effects in Germany for the year 2018 were (Table 6):

Table 6
Electricity Produced by Polluting Energy Source in Germany (2018)
(In TWh)

Hard coal	82.57
Lignite	144.05
Oil & petroleum products	5.19
Gas	94.24
Nuclear	76.01
Biomass	50.88

Source: Author´s own elaboration employing data from Directorate-General for Energy European Commission (2020).

And taking these generation values and multiplying them to the cases per TWh stated in the Table 5, we get the deaths, serious illness and minor illness of the electricity production in Germany in 2018 (Table 7):

Table 7
Air Pollution Effects by Electricity Source in Germany (2018)

	Deaths	Serious Illness	Minor Illness
Hard coal	2,022.97	18,578.25	1,097,190.16
Lignite	2,691.78	24,605.86	1,459,507.32
Oil & petroleum products	1,519.29	13,293.77	788,626.07
Gas	231.20	2,477.10	58,046.71
Nuclear	4.29	18.17	0.00
Biofuels	382.30	3,550.51	187,929.32
Total	6,851.82	62,523.66	3,591,299.58

Source: Author´s own elaboration employing data from Markandya and Wilkinson (2007).

4.3. Constraints

In order to make a realistic forecast, several constraints must be used to meet all the regulations and efficiency targets.

4.3.1. Energy Mix´s Composition

To have a diversified, realistic and environmentally friendly electricity, thresholds must be used for the maximum share that a portfolio can use for a specific energy technology. By doing so, the model is not depending mainly on an energy source, and therefore, the risk associated with those sources (such as lack of wind in the case of windmill powered energy sources, systematic risk…) is spread out among all technologies.

- Nuclear power will be limited to 0% due to the firm phasing out policy that the German legislator has carried out during the last decades and the announced cease of all nuclear power plants in the country by 2022.

- Due to its minor role in the power production (especially for the next decades) the model will not include oil & petroleum products.

- In order to achieve the goals stated in the German Climate Action Programme 2030 (Clean Energy Wire, 2019) the weight of RES must be at least of 65% for the years 2030 and 2040, and 80% for 2050.

- Among the conventional energy sources each technology will have the weight forecasted in the EU reference scenario 2016, *e.g.* In the case of Gas the EU Reference Scenario 2016 predicts a weight of 18.63% in the total electricity mix, but in order to meet the German Climate Action Programme 2030 targets, the maximum weight of coal for 2030 will be 11.18% (being the 18.63% of the power generated by conventional energy sources).

- RES have the same thresholds of conventional energy sources but with the difference that the maximum production limit is 100% larger than it would be if it was a fossil fuel source.

The model´s thresholds are compiled in Table 8:

Table 8

Germany´s Maximum Electricity Generation Share by Energy Source (2030-2050)

(Percentage)

	2030	2040	2050
Coal	23.82	17.82	10.47
Oil & petroleum products	0	0	0
Gas	11.18	17.18	9.53
Nuclear	0	0	0
Grand scale hydropower	8.96	9.19	9.83
Mini-Hydropower	2.68	2.75	2.94
Biofuels	26.09	29.57	31.15
Onshore wind	50.16	48.51	65.19
Offshore wind	12.54	12.13	16.30
Solar	29.57	27.85	34.59

Source: Author´s own elaboration employing data from European Commission (2016) and Clean Energy Wire (2019).

Nevertheless, the fact that an energy generation source in the mix is limited to the threshold mentioned before suggests a strong preference of that source in the energy portfolio, in other words, the energy source(s) that reaches the threshold is (are) considered to be the most efficient within the mix and cannot be used as much as the model would have to if that restriction did not exist. If the model limits the share of the source in the minimum risk portfolio or the minimum generation cost of electricity portfolio, the source will be the most efficient in terms of risk or cost. However, if the source is limited by the threshold in every portfolio along the efficient portfolio frontier, this source of power will be most efficient, being the one with a lower risk and cost.

Thus, it can give an idea of what will be the leading energy production technology for the next years as well as to where the stream of investments will flow.

4.3.2. Uniqueness Constraint

As a simplified estimation, it will be assumed that the country produces exactly 100% of the power it consumes, having neither shortages nor surplus of electricity and no power trade with other countries. The sum of all fractional share of energy technologies will be equal to 1, and no technology can have a negative share in the electricity production.

4.3.3. Energy Poverty

Having an accessible electricity supply is one of the main concerns of the German and European authorities (as stated in the *European Green Deal*, European Commission, 2019), for this reason, the model must set a certain limit for the electricity price.

The purpose of having an affordable electricity household price is to reduce the country´s energy poverty. The price of the electricity is directly related with energy poverty of any nation, however, in the German case after running a correlation analysis (made by the authors of this project), no clear correlation was observed between those variables, neither comparing the share of energy poverty in every percentile of the income distribution (in terms of arrears on utility bills and inability to keep home adequately warm) with the electricity household price, nor comparing the electricity household price with the share of energy poverty of the four energy poverty indicators (arrears on utility bills, high share of energy expenditure in income, Inability to keep home adequately warm and Low absolute expenditure). The fact that this relation is not clear is explained by several variables such as the price of other energy inputs charged in the utility bills (such as gas or oil), the change in the subsidies granted to low-income households or the change in the energy efficiency of homes (among other variables).

The threshold for the portfolio power generation cost is defined as 110% of the total cost of the 2018 portfolio (Table 9). All portfolios that have higher power costs, even if they are located in the fficient portfolio frontier will be erased from this model.

Table 9

Germany´s Electricity Production Portfolio (2018)

Nuclear	11.84
Coal	35.53
Gas	14.68
Oil	0.80
Onshore wind	13.70
Grand scale hydro	3.61
Mini-Hydro	0.87
Offshore wind	3.42
Biofuels	7.90
Solar	7.65
RES total	37.15
Risk	2.66 euros/MWh
Cost	82.64 euros/MWh

Source: Author´s own elaboration employing data from Directorate-General for Energy European Commission (2020).

4.4. Markowitz´s Model Outcomes

After running the model, three forecasts were generated, one for each time frame (2030, 2040 and 2050).

4.4.1. 2030, 2040 & 2050 Efficient Frontiers Comparison

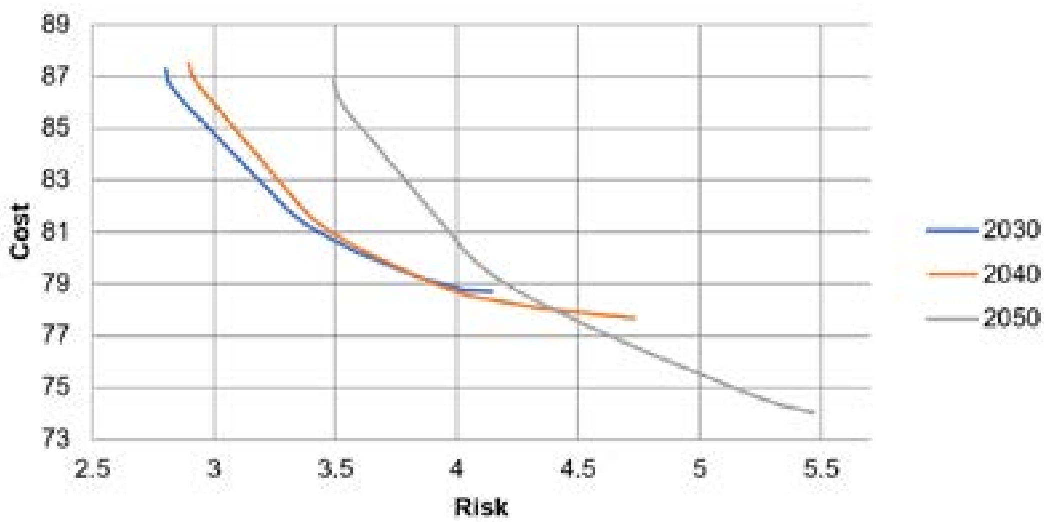
Only a minor improvement can be observed from 2030 to 2040, green energy sources are more competitive and offer a new range of cost-efficient portfolios (Figure 6).

By 2050, most of the power produced in the country is generated through green energy sources, that even though they cannot be as risk averse as the frontiers of 2030 and 2040, they can lead to a much lower production cost. Notwithstanding, this problem is expected to disappear in the decades beyond 2050, considering the risk is defined as the change of production costs, since a sudden drop in generation prices is likely to happen from 2030 to 2050 and it is expected to stabilize as the time passes, which will be considered as a much more stable and inexpensive frontier (and therefore more efficient) than the previous ones.

Figure 6

2030, 2040 & 2050 Efficient Portfolio Frontier

(In euros/MWh)



Source: Author´s own elaboration.

conventional energy sources, especially coal, are strong components throughout the 30 years of study since CO_2 emission fees are not included in the calculus. Otherwise, the competitiveness of these sources will be highly reduced since the emissions are heavily taxed in the EU, especially as time passes. Subsequently, the weight of this sources in the electricity mix may not be as large as it is in the model.

4.4.2. 2030 Efficient Frontier

As seen in the Table 10, all portfolios for this scenario sticks to the minimum share of RES in the electricity mix (65%), this may indicate that the RES are not mature enough to meet such a strong requirement and they need more years to be competitive regarding the production cost.

Coal and gas are the most efficient energy sources in terms of cost and risk, they both are limited by the maximum threshold throughout all portfolios, indicating that is the preferred technology for this horizon (Annex B).

Table 10

Germany´s 2030 Efficient Portfolios: RES, Risk and Cost

	RES Total (%)	Risk (Euros/MWh)	Cost (Euros/MWh)
Portfolio 1	65.01	2.80	87.26
Portfolio 2	65.01	2.81	86.76
Portfolio 3	65.01	2.85	86.26
Portfolio 4	65.01	2.90	85.76
Portfolio 5	65.01	2.95	85.26
Portfolio 6	65.01	3.00	84.76
Portfolio 7	65.01	3.06	84.26
Portfolio 8	65.01	3.11	83.76
Portfolio 9	65.01	3.16	83.26
Portfolio 10	65.01	3.21	82.76
Portfolio 11	65.01	3.21	82.26
Portfolio 12	65.01	3.31	81.76
Portfolio 13	65.01	3.38	81.26
Portfolio 14	65.01	3.47	80.76
Portfolio 15	65.01	3.58	80.26
Portfolio 16	65.01	3.71	79.76
Portfolio 17	65.01	3.83	79.26
Portfolio 18	65.01	4.03	78.76
Portfolio 19	65.01	4.14	78.71

Source: Author´s own elaboration.

When it comes to green energy sources, Solar seems to be constantly over all portfolios. Biofuels, hydro and offshore wind are slanted towards risk efficient portfolios and onshore wind towards cost efficient portfolios.

4.4.3. 2040 Efficient Frontier

By 2040, RES and Biofuels are still not as developed. The share of RES in almost all portfolios is the minimum required by the German Climate Action

Table 11

Germany´s 2040 Efficient Portfolios: RES, Risk and Cost

	RES Total (%)	Risk (Euros/MWh)	Cost (Euros/MWh)
Portfolio 1	65.00	2.89	87.55
Portfolio 2	65.00	2.91	87.05
Portfolio 3	65.00	2.94	86.55
Portfolio 4	65.00	2.99	86.05
Portfolio 5	65.00	3.03	85.55
Portfolio 6	65.00	3.08	85.05
Portfolio 7	65.00	3.12	84.55
Portfolio 8	65.00	3.17	84.05
Portfolio 9	65.00	3.21	83.55
Portfolio 10	65.00	3.26	83.05
Portfolio 11	65.00	3.30	82.55
Portfolio 12	65.00	3.35	82.05
Portfolio 13	65.00	3.40	81.55
Portfolio 14	65.00	3.47	81.05
Portfolio 15	65.00	3.56	80.55
Portfolio 16	65.00	3.66	80.05
Portfolio 17	65.00	3.77	79.55
Portfolio 18	65.01	3.89	79.05
Portfolio 19	67.82	4.04	78.55
Portfolio 20	72.32	4.33	78.05
Portfolio 21	82.18	4.74	77.68

Source: Author´s own elaboration.

Programme 2030. However, a slight improvement can be seen in the last three cost extreme portfolios that show the technology is competitive enough (in terms of cost) to be preferred over conventional energy sources in the model (Table 11).

Coal is still the most efficient energy source in terms of cost and risk, nevertheless, gas is not always preferred by the model in all portfolios, in low cost points it is substituted by green energy sources.

Offshore wind is consolidated as a stable electricity sources in all portfolios and hydro and biofuels still have low risk bias behavior (Annex C).

4.4.4. 2050 Efficient Frontier

2050 is the year when a big improvement in RES can be observed. Even though the required production by green energy sources is now 80%, the extreme cost portfolios exceed this mark, pushing over 90% of the electricity generation in the country (Table 12).

Table 12

Germany´s 2050 Efficient Portfolios: RES, Risk and Cost

	RES Total (%)	Risk (Euros/MWh)	Cost (Euros/MWh)
Portfolio 1	80.00	3.49	86.83
Portfolio 2	80.00	3.50	86.33
Portfolio 3	80.00	3.53	85.83
Portfolio 4	80.00	3.58	85.33
Portfolio 5	80.00	3.62	84.83
Portfolio 6	80.00	3.67	84.33
Portfolio 7	80.00	3.71	83.83
Portfolio 8	80.00	3.76	83.33
Portfolio 9	80.00	3.80	82.83
Portfolio 10	80.00	3.85	82.33
Portfolio 11	80.00	3.89	81.83
Portfolio 12	80.00	3.94	81.33
Portfolio 13	80.00	3.98	80.83
Portfolio 14	80.00	4.02	80.33
Portfolio 15	80.00	4.08	79.83
Portfolio 16	80.00	4.14	79.33
Portfolio 17	80.00	4.23	78.83
Portfolio 18	80.00	4.33	78.33
Portfolio 19	80.00	4.44	77.83
Portfolio 20	80.00	4.55	77.33
Portfolio 21	80.88	4.67	76.83
Portfolio 22	82.59	4.79	76.33
Portfolio 23	84.30	4.92	75.83
Portfolio 24	86.02	5.05	75.33
Portfolio 25	87.73	5.18	74.83
Portfolio 26	89.53	5.32	74.33
Portfolio 27	89.53	5.47	74.03

Source: Author´s own elaboration.

Onshore wind has gained a lot of importance in the electricity mix, being by far the largest energy source and coal is still the most efficient energy source in terms of cost and risk (Annex D).

4.4.5. Health Index Evolution

In order to calculate the health effects of the power production of the efficient frontier the share of each technology in each portfolio will be multiplied by the projected production (Table 13) and by the health cases per TWh of the Table 5.

Table 13

Germany´s Projected Electricity Production (2030-2050)

Year	TWh
2030	610.83
2040	617.69
2050	647.22

Source: European Commission (2016).

The outcome of this factor will be a spread of maximum and minimum cases per efficient frontier. Nevertheless, even if we consider the worst-case scenario, in which we select the upper part of the spread and compare it to the cases of

Table 14

Projected Air Pollution Effects by Electricity Source in Germany

Year		Deaths	Serious illness	Minor illness
2030	Minimum	4,505	41,536	2,387,203
	Maximum	4,808	44,355	2,536,425
	Arithmetic mean	4,754	43,850	2,509,690
2040	Minimum	3,264	29,876	1,769,809
	Maximum	3,464	31,981	1,827,305
	Arithmetic mean	3,747	34,758	1,941,402
2050	Minimum	2,008	18,384	1,089,016
	Maximum	2,542	23,587	1,309,825
	Arithmetic mean	2,363	21,887	1,228,433

Source: Author´s own elaboration employing data from Markandya & Wilkinson (2007).

2018 the results are clear that in each and every time frame deaths, serious illness and minor illness are reduced, achieving by 2050 a 3-factor reduction in all cases (Table 14).

5. CONCLUSIONS

The electricity production´s future in Germany seems changing for the next decades, it is expected that renewable energy sources and biofuels will become the main technologies to generate power, bringing many positive externalities such as a drop in electricity prices, a more secure and stable energy mix, an electrification of the economy, an environmentally friendly production and a healthier lifestyle.

According to the Markowitz model of the paper, by 2030, 65% of the electricity produced in the country will be generated by RES and biofuels, by 2040, 65%-82% will be green power, and by 2050 this proportion will reach 80%-90%. As the energy transition advances in the timeframe of study, conventional energy sources are expected to be less important and even disappear from the electricity mix as it happens with nuclear power. In contrast, all green energy sources will be improved drastically, being way more competitive in terms of production cost than fossil fuel sources, indeed, onshore wind will become the single largest energy source, generating 31%-65% of power in the country, followed by solar (13%-28%).

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ANNEXES

Annex A

Table 15

Energy Units Conversion Table

	Watt hour (Wh)	Kilowatt Hour (kWh)	Megawatt Hour (MWh)	GigaWatt Hour (GWh)	Terawatt Hour (TWh)	Tonnes of oil Equivalent (toe)	Million Tonnes of oil Equiva-lent (Mtoe)
Watt hour (Wh)	1	0.001	0.000001	0.000000001	1E-12	8.59845E-08	8.59845E-14
Kilowatt Hour (kWh)	1,000	1	0.001	0.000001	0.000000001	8.59845E-05	8.59845E-11
Megawatt Hour (MWh)	1,000,000	1,000	1	0.001	0.000001	0.085984523	8.59845E-08
GigaWatt Hour (GWh)	1E+09	1,000,000	1,000	1	0.001	85.98452279	8.59845E-05
Terawatt Hour (TWh)	1E+12	1,000,000,000	1,000,000	1,000	1	85,984.52279	0.085984523
Tonnes of oil Equivalent (toe)	11,630,000	11,630	11.63	0.01163	0.00001163	1	0.000001
Million Tonnes of oil Equivalent (Mtoe)	1.163E+13	1.163E+10	11,630,000	11,630	11.63	1,000,000	1

Source: Author´s own elaboration.

Annex B

Table 16

Germany´s 2030 Efficient Frontier Portfolios

(In percentage

	Coal	Gas	Onshore wind	Offshore wind	Grand scale hydro	Mini-Hydro	Biofuels	Solar
Portfolio 1	23.82	11.17	24.11	5.88	8.96	2.68	10.73	12.65
Portfolio 2	23.82	11.17	26.63	4.76	8.96	2.68	10.09	11.89
Portfolio 3	23.82	11.17	29.15	3.63	8.96	2.68	9.46	11.13
Portfolio 4	23.82	11.17	29.77	3.71	7.92	2.68	9.59	11.35
Portfolio 5	23.82	11.17	30.37	3.78	6.87	2.68	9.73	11.58
Portfolio 6	23.82	11.17	30.97	3.86	5.82	2.68	9.87	11.81
Portfolio 7	23.82	11.17	31.57	3.94	4.77	2.68	10.01	12.03
Portfolio 8	23.82	11.17	32.18	4.02	3.72	2.68	10.15	12.26
Portfolio 9	23.82	11.17	32.78	4.10	2.67	2.68	10.29	12.49
Portfolio 10	23.82	11.17	33.38	4.18	1.62	2.68	10.43	12.72
Portfolio 11	23.82	11.17	33.98	4.26	0.57	2.68	10.57	12.94
Portfolio 12	23.82	11.17	35.46	3.79	0	2.68	10.36	12.72
Portfolio 13	23.82	11.17	37.98	2.67	0	2.68	9.72	11.96
Portfolio 14	23.82	11.17	40.50	1.55	0	2.68	9.08	11.20
Portfolio 15	23.82	11.17	43.02	0.43	0	2.68	8.44	10.44
Portfolio 16	23.82	11.17	45.19	0	0	1.52	8.15	10.15
Portfolio 17	23.82	11.17	47.37	0	0	0	7.83	9.81
Portfolio 18	23.82	11.17	50.18	0	0	0	2.87	11.96
Portfolio 19	23.82	11.17	50.18	0	0	0	0	14.83

Source: Author´s own elaboration.

Annex C

Table 17

Germany´s 2040 Efficient Frontier Portfolios

(In percentage

	Coal	Gas	Onshore wind	Offshore wind	Grand scale hydro	Mini-Hydro	Biofuels	Solar
Portfolio 1	17.82	17.18	24.15	5.88	9.19	2.75	10.36	12.67
Portfolio 2	17.82	17.18	26.76	5.06	9.19	2.75	9.22	12.02
Portfolio 3	17.82	17.18	28.81	4.49	8.94	2.75	8.43	11.59
Portfolio 4	17.82	17.18	29.35	4.58	7.98	2.75	8.54	11.81
Portfolio 5	17.82	17.18	29.88	4.66	7.03	2.75	8.66	12.02
Portfolio 6	17.82	17.18	30.42	4.75	6.07	2.75	8.77	12.24
Portfolio 7	17.82	17.18	30.96	4.84	5.12	2.75	8.89	12.45
Portfolio 8	17.82	17.18	31.49	4.92	4.17	2.75	9.00	12.67
Portfolio 9	17.82	17.18	32.03	5.01	3.21	2.75	9.12	12.88
Portfolio 10	17.82	17.18	32.57	5.10	2.26	2.75	9.24	13.09
Portfolio 11	17.82	17.18	33.10	5.19	1.30	2.75	9.35	13.31
Portfolio 12	17.82	17.18	33.64	5.27	0.35	2.75	9.47	13.52
Portfolio 13	17.82	17.18	35.49	4.79	0	2.75	8.79	13.19
Portfolio 14	17.82	17.18	38.10	3.97	0	2.75	7.66	12.53
Portfolio 15	17.82	17.18	40.70	3.15	0	2.75	6.53	11.87
Portfolio 16	17.82	17.18	42.76	2.77	0	1.75	6.00	11.72
Portfolio 17	17.82	17.18	44.40	2.73	0	0	5.92	11.95
Portfolio 18	17.82	17.16	47.00	1.91	0	0	4.79	11.31
Portfolio 19	17.82	14.35	48.51	1.47	0	0	3.56	14.29
Portfolio 20	17.82	9.86	48.51	0.80	0	0	1.04	21.96
Portfolio 21	17.82	0	48.51	5.82	0	0	0	27.85

Source: Author´s own elaboration.

Annex D

Table 18

Germany´s 2050 Efficient Frontier Portfolios

(In percentage

	Coal	Gas	Onshore wind	Offshore wind	Grand scale hydro	Mini-Hydro	Biofuels	Solar
Portfolio 1	10.47	9.53	31.21	7.60	9.83	2.94	12.04	16.38
Portfolio 2	10.47	9.53	33.62	6.94	9.83	2.94	10.68	15.99
Portfolio 3	10.47	9.53	36.03	6.28	9.83	2.94	9.32	15.60
Portfolio 4	10.47	9.53	36.93	6.21	9.12	2.94	9.11	15.69
Portfolio 5	10.47	9.53	37.43	6.30	8.23	2.94	9.22	15.90
Portfolio 6	10.47	9.53	37.92	6.39	7.33	2.94	9.32	16.11
Portfolio 7	10.47	9.53	38.42	6.47	6.43	2.94	9.42	16.32
Portfolio 8	10.47	9.53	38.92	6.56	5.53	2.94	9.52	16.53
Portfolio 9	10.47	9.53	39.42	6.65	4.63	2.94	9.63	16.74
Portfolio 10	10.47	9.53	39.92	6.74	3.73	2.94	9.73	16.95
Portfolio 11	10.47	9.53	40.42	6.82	2.83	2.94	9.83	17.16
Portfolio 12	10.47	9.53	40.92	6.91	1.94	2.94	9.93	17.37
Portfolio 13	10.47	9.53	41.42	7.00	1.04	2.94	10.04	17.58
Portfolio 14	10.47	9.53	41.92	7.08	0.14	2.94	10.14	17.79
Portfolio 15	10.47	9.53	44.03	6.54	0	2.94	9.00	17.50
Portfolio 16	10.47	9.53	46.44	5.88	0	2.94	7.64	17.10
Portfolio 17	10.47	9.53	48.85	5.22	0	2.94	6.28	16.72
Portfolio 18	10.47	9.53	51.26	4.56	0	2.94	4.91	16.33
Portfolio 19	10.47	9.53	53.08	4.36	0	1.74	4.39	16.42
Portfolio 20	10.47	9.53	54.64	4.37	0	0	4.25	16.73
Portfolio 21	10.47	8.65	56.79	4.00	0	0	3.41	16.68
Portfolio 22	10.47	6.94	58.68	3.91	0	0	3.06	16.94
Portfolio 23	10.47	5.23	60.58	3.82	0	0	2.71	17.20
Portfolio 24	10.47	3.52	62.48	3.73	0	0	2.35	17.46
Portfolio 25	10.47	1.81	64.37	3.64	0	0	2.00	17.72
Portfolio 26	10.47	0	65.19	3.72	0	0	0.63	19.99
Portfolio 27	10.47	0	65.19	0	0	0	0	24.34

Source: Author´s own elaboration.