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Energy market analysis of integration of the variable renewable energy sources (VRES) into the EU energy systems

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Executive Summary

This report discusses the issue of system costs as one of the key factors contributing to the increase in energy transition costs, assuming the continued implementation of the scenario of rapid development of variable energy sources such as wind and solar farms. In this report we have presented different types of system costs, the reasons behind their occurrence, and the impact these costs have on electricity retail prices in Europe. To depict the impact of currently neglected costs on the competitiveness of energy sources, we have drawn up a comparison of total levelized costs of electricity generation (T-LCOE) for technologies available in 2020 and 2050, including system and environmental costs. Based on this report, three key conclusions have been made:

- The level of penetration of weather-dependent sources in electricity production determines the amount of additional system operations and maintenance costs. Developing large amounts of variable power outputs shifts the cost of green energy supply to all market participants and end users – even at penetration of 30-40%, even half of the total cost of wind and solar generation is socialized.
- The additional cost generated by variable sources, after reaching the system's maximum flexibility, starts to grow exponentially due to increasing difficulties in maintaining energy supply stability. In extreme cases, such as in countries with a high share of electricity from variable energy sources, retail prices can be twice as high.
- Comprehensive optimization of the sector's operating costs requires considering private, system, environmental and climate costs, as well as the macroeconomic and geopolitical impact of the technologies discussed. Disregarding a portion of cost when developing a strategy would result in adopting a suboptimal solution in terms of social and cost-related matters, disrupting Europe's economic development.

Introduction

Pursuing the objectives of the Paris Agreement, in December 2019 the European Council adopted the goal of achieving EU climate neutrality in 2050.[1] The importance of these objectives is underlined by the European Commission's (EC) political and legislative program — the European Green Deal— which replaces the Europe 2020 Strategy as a major long-term strategic initiative for the EU.[2] In the medium term, the European Commission has acted to increase the greenhouse gas emission reduction target for 2030 from 40% to at least 55% of 1990 levels.

Such ambitious objectives, outlined for the next decade, and the declaration of their even more extensive implementation in the next twenty years, calls for an enormous energy transition of the entire European community. It will be crucial to maintain low electricity prices within the European community as without this it would be impossible to offer competitive product and service prices in both local and international markets. Nevertheless, it is also important to contain the increasing costs borne by end users especially in the context of a high level of energy poverty. For this reason, in order to achieve a sustainable and decarbonized economy it is important to seek cost-effective and social centered strategic directions for the development of the electricity sector. The main driver for the EC is to reduce greenhouse gas emissions by limiting generation electricity based on fossil fuels and developing renewable energy sources (RES). Setting mandatory RES objectives is aimed at accelerating the necessary economic transformations and reducing the energy sector's negative impact on the environment and climate. However, considering the increasingly small number of available generation technologies that are able to maintain an economically viable reliability of power supply and system stability, finding the optimal direction of development becomes an extremely difficult task.

Another important challenge is the economic recession following the COVID-19 epidemic. The European economic slowdown we are now observing will require great efforts and commitment of its Member States to restore the regional economic potential. The EC's response to the expected recession is the EU Recovery and Resilience Facility aimed at stimulating new investments.[3] The new facility will mobilize €750 billion in grants and loans to support the recovery of the EU economy, including its green and digital transformation. Large infrastructure investments in the energy sector of the recovery period are to stimulate GDP growth and enable the economy to transition to a new, less environmentally and climate-damaging path. Additional support for green energy, similar to previous schemes, also aims to improve the competitiveness of the European economy by reducing wholesale electricity prices.

However, an excessively dynamic development of RES can rapidly tilt the balance of economic benefits towards losses and deterioration of price competitiveness of products and services offered in the EU. The reason behind this is the increasing retail prices of electricity charged to households and small and medium businesses, which do not enjoy any of the allowances energy-intensive enterprises have, nor have a strong enough position to negotiate more favorable energy purchase contracts. This is due to several factors. For example, the operation of variable RES (VRES), such as wind or solar farms, requires a high level of system flexibility and maintenance of costly power reserves, necessary to ensure the possibility of balancing the system under changing weather conditions. Additionally, the growing production of unstable and unpredictable energy changes the load profile of the system, thereby deteriorating operating conditions and economic effectiveness of other power-producing technologies. Another significant factors include the instability of network operation, as well as the increasingly frequent loopflows and measures required to counteract these challenges – such as redispatching or countertrading – as well as growing generation dispersion. All these factors contribute to increasing financial outlays required not only to develop power system flexibility, but also to ensure proper development and maintenance of transmission and distribution networks. These conditions determine the system costs, which are becoming increasingly apparent in the observed trends in retail electricity prices and are growing continuously despite the downward trend in average wholesale prices.

Wind and solar technologies help reduce greenhouse gas emissions and improve the quality of the environment. In addition, a systematic decrease in investment costs related to these technologies effects lower prices on the wholesale market offered by current and future renewables investments. Nevertheless, the decision to increase the RES target, while ignoring the negative effects associated with RES operations, may lead to an uncontrolled increase in energy costs. The comparison of total levelized costs of electricity (T-LCOE) (Figure 1) gives a comprehensive overview of changes that may await the energy market in absence of coordination between the development of wind and solar sources and the overall system development. Despite a significant decrease in investment and operating expenses by 2050, high system costs, stemming from the growing volume of unstable and unpredictable generation, offset the benefits of technological progress. A further increase of VRES over 50% could lead to counterproductive effects, in particular reduction of the European economy's competitiveness.

1 https://ec.europa.eu/clima/policies/international/negotiations/paris_en
2 https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en
3 https://ec.europa.eu/info/live-work-travel-eu/health/coronavirus-response/recovery-plan-europe_en

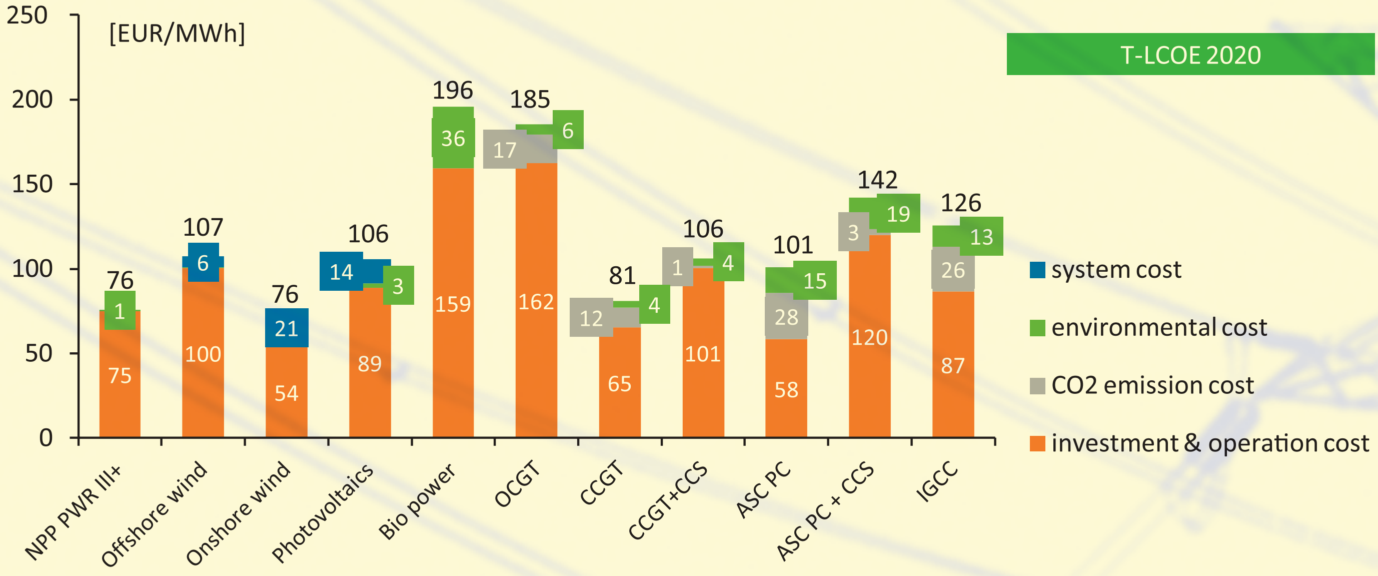

FIGURE 1 Average discounted total levelized cost of electricity per technology (T LCOE) in 2020. [EUR/MWh]; fixed prices of 2018; variable energy sources (wind and solar) considered individually in hypothetical power systems where they contribute to the net electricity generation at the level of the EU average of 2019 (offshore wind farms — 2.3%, onshore wind farms — 12.2%, photovoltaics – 5%); WACC = 6% for each technology, own elaboration based on [24][25][26][27][28] and system cost curves (Annex 1)

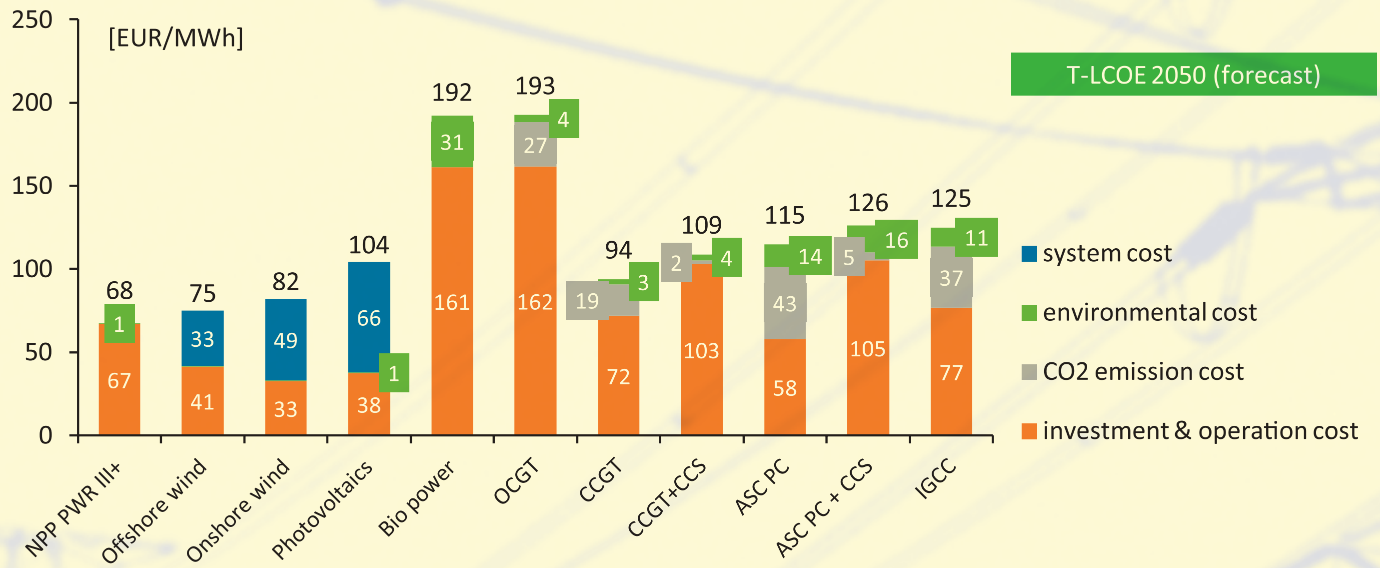

FIGURE 2 Average discounted total levelized cost of electricity per technology (T LCOE) in 2050. [EUR/MWh]; fixed prices of 2018; variable energy sources (wind and solar) considered individually in hypothetical power systems where they significantly contribute to the net electricity generation (offshore wind farms — 50%, onshore wind farms — 50%, photovoltaics – 30%); WACC = 6% for each technology, own elaboration based on [24][25][26][27][28] and system cost curves (Annex 1)

What are system costs?

A power system operates as a communicating vessels system in which generation, transmission, distribution and consumption of electricity are interdependent. The important factors that determine how a system is managed are the operating parameters of the existing generation base and long-term plans for power system development. These determine how the balance of power and electricity production will be ensured. Differentiation of technologies in terms of operation flexibility, stability and predictability of generation, average annual capacity factor, failure rate, or an option to select a convenient location directly impacts the cost of the system operation as a whole. The greater the deviation of the properties of the generating source from the parameters allowing for safe system operation, the higher the costs generated in its other areas.

The lowest system costs are generated by dispatchable sources, i.e. sources that allow — generally speaking — to produce energy "on demand" according to customer demand profile. These energy sources are characterized by a high annual capacity utilization factor and can be installed in convenient network nodes, close to energy demand centers.

System maintenance costs increase significantly for variable sources such as wind and solar technologies. Factors that hinder safe and economically efficient system management are the unpredictability of operation and uncertainty of supply, location constraints caused by limited areas with good wind and sun conditions, and asynchronous operation reducing the physical inertia available in the system.

This results in significant system costs that are naturally overlooked by investors during economic assessments of variable sources. These costs must be borne by distribution and transmission system operators and owners of dispatchable power plants. Ultimately, the system costs are passed onto end users through increased costs of operating balancing markets, higher costs of transmission and distribution tariffs, as well as new charges that stem from the need to ensure the security of supply, such as capacity mechanisms. These costs are

- **costs related to changes of system load profile (profile costs), including**
  - costs of changing the degree of utilization of available power plants (including cost of premature closure of existing generation units)
  - costs of maintaining a correspondingly larger power reserve
  - costs related to overproduction of electricity within the system (storage, negative prices, power-to-gas development)

- **costs of transmission and distribution infrastructure extension, including**
  - costs of strengthening and expanding the network to increase transmission and distribution
  - costs of losses occurring during energy transmission and distribution
  - connection construction costs — often included in power plant construction costs, although not in every case (the cost of connections of offshore wind farms is sometimes borne by the TSO e.g. of Germany, Denmark and Netherlands)

- **costs of balancing and system flexibility, including**
  - costs of the balancing market
  - overload management costs, including redispatching and countertrading[4]
  - costs of maintaining RES-specific spinning reserve (including secondary and third-degree reserves)
  - costs of demand management services (e.g. DSR services, dynamic zone tariffs)

The largest cost component is the profile costs, associated with a permanent change in the efficiency of the use of available generation assets [31]. The development of variable technologies, which enjoy priority network access, restricts the number of available working hours for technologies responsible for safe system operations. The systematic shortening of working hours and increasing volatility of wholesale electricity prices make it difficult to maintain dispatchable source profitability, thus increasing the uncertainty of full depreciation of assets. This translates into a growing risk of stranded costs within the sector, resulting from premature closure of existing generation units.

Growing investment uncertainty also increases the pricing of planned investments risk in non-variable sources. This is evidenced by increasing difficulties in obtaining both external financing from banks (debt) and internal financing in power companies (equity). This leads to a continuous increase of weighted average cost of capital (WACC) of new dispatchable system power plants. In turn this serves as an incentive to pursue higher margins on the energy market or to a more and more frequent postponement of investment decisions until the state guarantees support e.g. via capacity mechanisms. In both cases, the increased risk translates into an increased cost of financing the power plants necessary to secure unstable RES generation, increasing the total cost of energy produced with the power system discussed.

The increasing phenomenon of unscheduled power flows within the European electrical power system is an additional cost for electrical power systems. The main reason for this is the so-called "loopflows", which are physical flows along a power line located in a specific price zone (e.g. Poland or the Czechia), caused by transactions for which both source and power take-off are located in other zones (e.g. Germany or Austria) [30]. A good example of this is the situation at the Polish-German synchronous border between 2014 and 2016. The unpredictability of generation obtained with wind

4 Redispatching – a measure triggered by one or more transmission system operators by changing the generation or load pattern in order to change physical energy flows and reduce congestion [21]. Countertrading – international exchange on the market, initiated by transmission system operators, carried out between two market areas in order to reduce transmission congestion between them [21].

and solar sources in the north of Germany, which is the source of variable power flows at the borders, forced the Polish TSO to take appropriate countermeasures such as large-scale redispatching. In 2015 alone, PSE's expenses resulting from the need to secure the operation of the Polish-German interconnection exceeded EUR 100 million [30], accounting for approximately 6 % of the total operating costs incurred by TSO this year. These additional costs had to be borne by the Polish end users, while relieving German and Austrian end customers who did not have to bear the costs of using foreign network for loopflows. It was only the installation of phase shifters at the border that made it possible to reduce the obviously growing problems with system balancing. Nevertheless, the cost of phase shifters investment, although less than the growing costs of dealing with loopflows, increased the burden Polish end users had to bear. Similar problems, although having less impact on available transmission capacities and redispatching costs, occur at other European borders, leading to the installation of similar devices in other parts of the European transmission system [30].

The impact of the development of variable energy sources on the energy market and the EU power system

The rapid development of wind and solar generation in Europe, in addition to the continuous reduction of greenhouse gas emissions and improvement of environment quality, brings serious challenges in terms of maintaining the stability of operation of interconnected power systems. Subsidizing RES and placing it in preferential position on the energy market significantly hinders the financing of dispatchable power plants. This creates a serious risk of shortages of operational power reserve which are necessary for the proper operation of every electrical power system. What is more, in many cases the network infrastructure, originally constructed during the times of centralized, conventional power generation, is not adapted to the growing dynamics of energy demand and supply. Disregarding the impact of wind and solar energy on the functioning of the power system in the sector development strategies results in a significant — although usually neglected — increase in system costs.

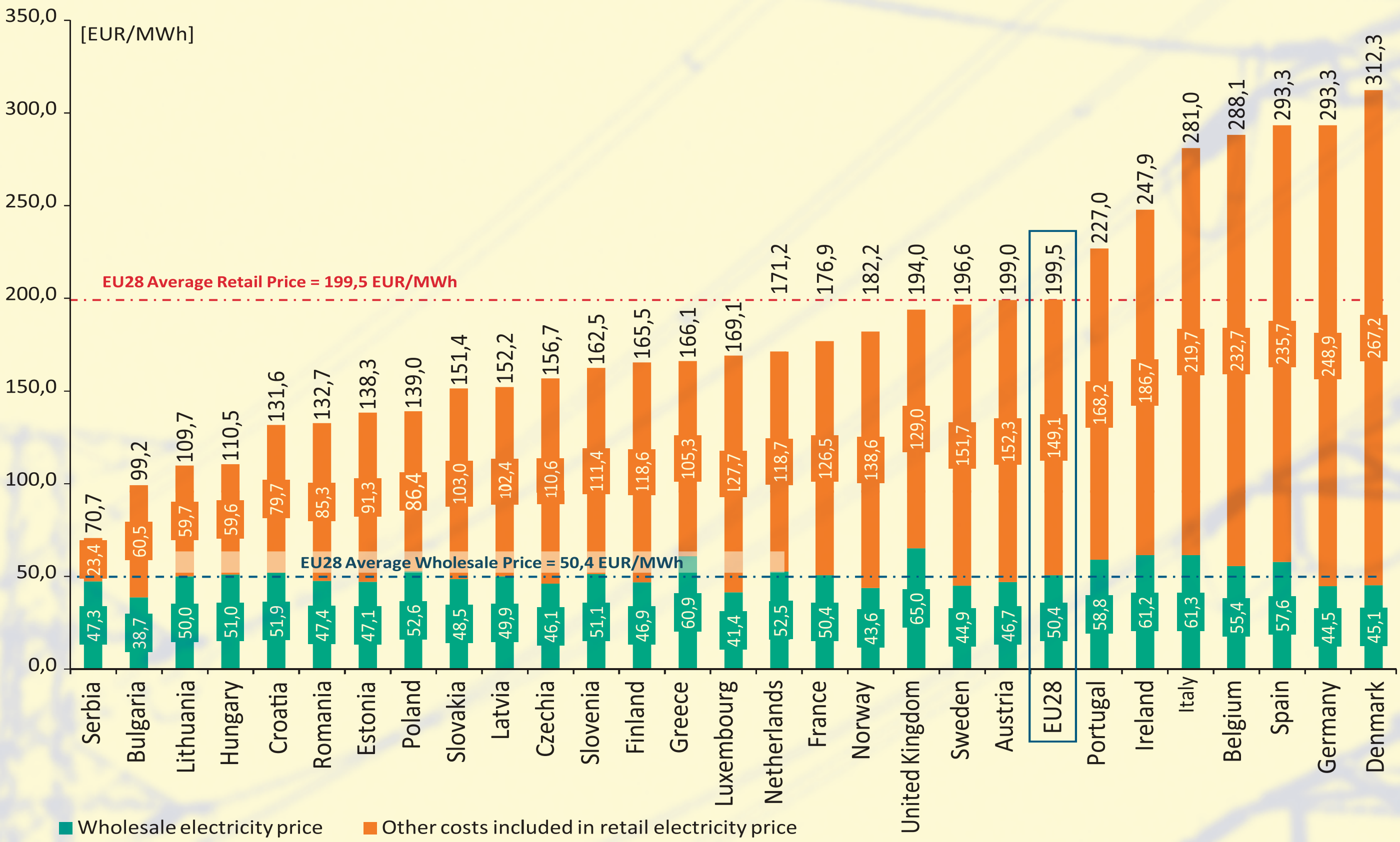

FIGURE 3 Differences between wholesale and retail prices of electricity in selected European countries in 2018 — average households with energy consumption of 2500 – 5000 kWh/year; own elaboration based on wholesale prices [15][16][17][18]], other -[11],

This becomes especially apparent when comparing retail and wholesale electricity prices in particular European countries. The actual share of wholesale energy cost in the prices quoted to end users varies between 20-50% (Figure 3). Such a small share results, among other things, from the distorted structure of the electricity market where the actual costs of energy generation are increasingly transferred to various support systems. Exclusion of a part of the production capacity from the energy market, by granting subsidies, has led to an extreme situation in which market price mechanisms are insufficient to stimulate new investments. This has resulted in the emergence of further support schemes, such as capacity mechanisms, PPA (Power Purchase Agreement) or CfD (Contract for Difference), which are designed to stimulate the creation of necessary dispatchable outputs by guaranteeing revenue stability. The outcome of such actions is the transfer of the real burden of cost resulting from the implementation of national energy strategies onto retail end users, i.e. households and small and medium-sized enterprises. A high degree of diversity between wholesale and retail prices is clearly visible in highly developed countries, which decided much earlier to dynamically develop renewable sources. For example, wholesale prices in countries such as Germany (44.5 EUR/MWh[5]) or Denmark (45.1 EUR/MWh) are significantly lower than the EU average (50.4 EUR/MWh). However, when looking at the retail market and costs borne by households, both countries show prices over 30% higher than the EU average. On the other hand, in countries such as Poland or Hungary wholesale prices are higher than the EU average — prices in Poland are 52.6 EUR/MWh and Hungary 51.0 EUR/MWh respectively. However, the much later development of renewable sources now in both cases contributes to retail prices sustaining a level lower than the EU average (199.5 EUR/MWh) — 139 EUR/MWh in Poland and 110.5 EUR/MWh in Hungary respectively.

The above referred comparison of wholesale prices, taking into account only partial costs of energy generation in the system and retail prices, covering all market and regulatory components of energy costs, is presented to show the actual price differences occurring in the European market. This is particularly important because of the aforementioned differences in the operating parameters of the generation technologies applied in the system, which are also reflected in end energy prices.

In order to show the relation between energy prices and system costs one should look at all factors that shape retail prices. According to the EU Regulation [19] on statistics on natural gas and electricity prices, these factors are:

- **Energy and supply** — including generation, aggregation, balancing energy, supplied energy costs, customer services, after-sales management, and other supply costs
- **Network** — including transmission and distribution tariffs, transmission and distribution losses, network costs, after-sale service costs, system service costs, and meter rental and metering costs
- **Taxes, fees, levies and charges** — including VAT, any support schemes and environmental charges

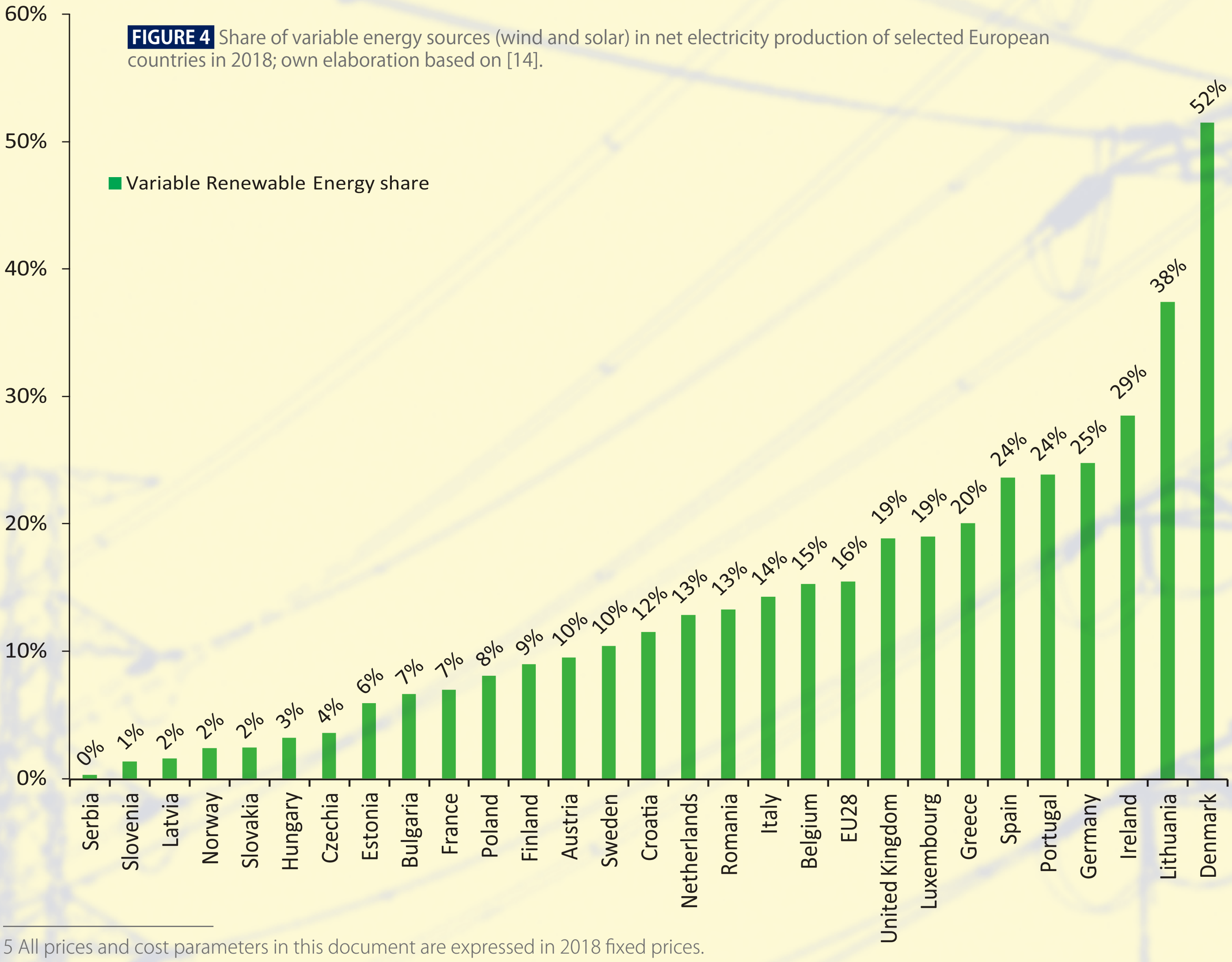

FIGURE 4 Share of variable energy sources (wind and solar) in net electricity production of selected European countries in 2018; own elaboration based on [14].

5 All prices and cost parameters in this document are expressed in 2018 fixed prices.

Based on ENTSOE data [14], we have also conducted an analysis of the electricity generation structures of individual European countries in order to distinguish variable RES share in net electricity generation. After determining the degree of penetration of these technologies in national power systems, we were able to assess the impact of variable sources on electricity retail prices, as well as on components of these prices. The countries were arranged in ascending order of the share of VRES (total wind and solar electricity production) in the case of both power generation structure and retail prices

The data presented (Figure 5) indicates correlations between variable RES share and retail prices. In most of the analyzed European countries, high electricity retail prices are observed where there is a large amount of energy generated from VRES. This is caused by significant subsidizing of RES development through support schemes, financed with additional charges imposed on households. A particularly generous support scheme (over 30 EUR/MWh of additional charge) is in place in Germany (66.9 EUR/MWh), Portugal (56.5 EUR/MWh), Italy (46.0 EUR/MWh), Belgium (34.2 EUR/MWh), and Spain (33.5 EUR/MWh). It is worth noting that in the case of Denmark, which currently has the largest share of VRES in net electricity production, in addition to extra charges for support schemes (21.0 EUR/MWh), a large part of the energy bill is covered by environmental charges (122.5 EUR/MWh). This indirectly supports the development of renewable sources (funds raised this way are used to support activities to protect the environment and promote clean energy).

A less obvious and usually disregarded reason for higher retail electricity prices is the system costs discussed earlier. In Eurostat's retail price decomposition, system costs are included in energy and supply and network cost categories. In order to examine the relation between these costs and the share of variable RES, these categories have been analyzed separately (Figure 6). The countries with the highest share of VRES were also excluded from the analysis. Lithuania (38%) was excluded due to excessive imports distorting the results of comparison with net domestic production. Denmark (52%) was excluded because of the extremely high share of VRES (20 percent higher than the next country). Due to the reliability of the analysis results,

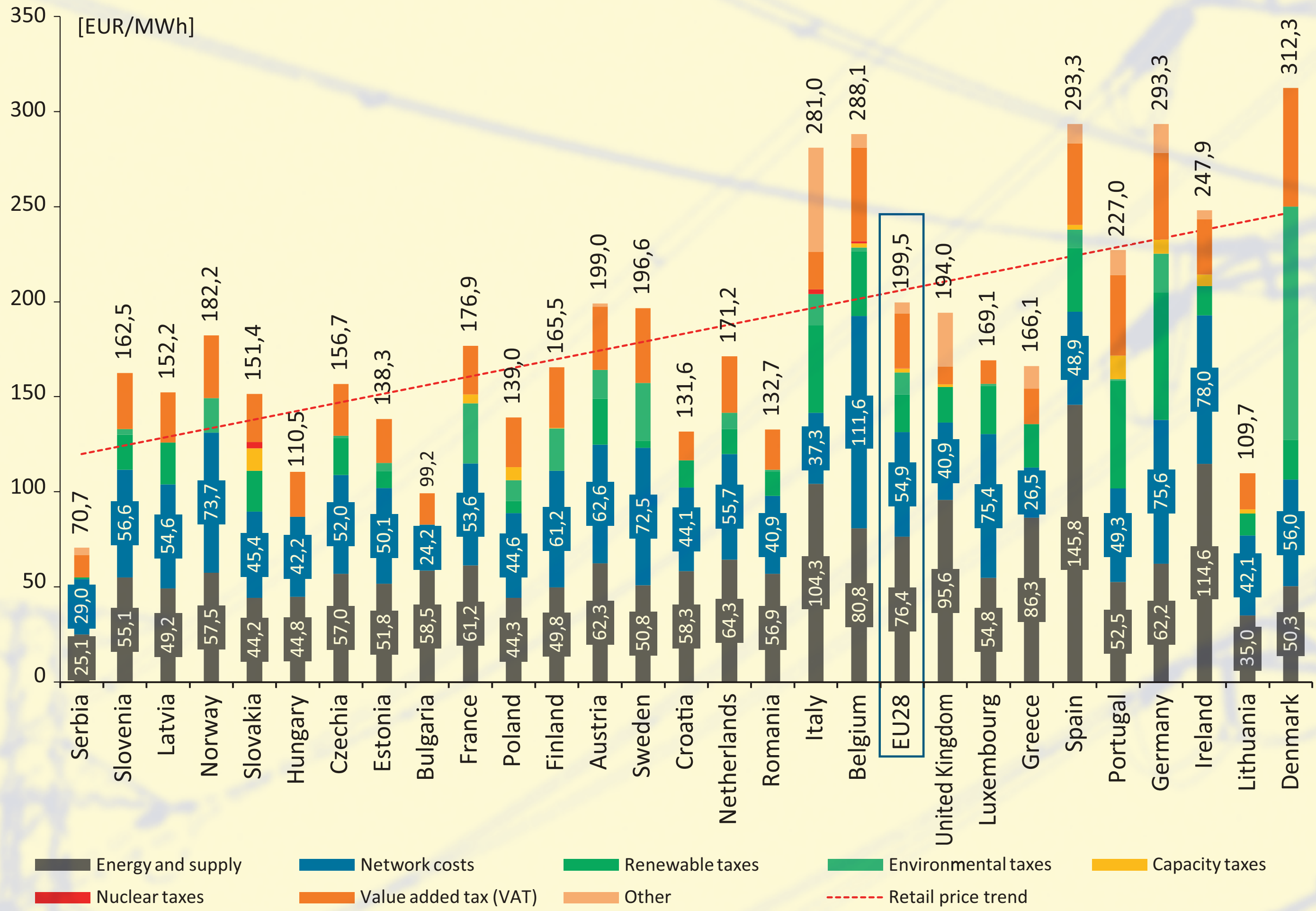

FIGURE 5 Full decomposition of retail electricity prices in selected European countries in 2018 — average households with energy consumption of 2500 – 5000 kWh/year; countries listed in ascending order regarding VRES share in net electricity production according to (Figure 4); own elaboration based on [11][14]

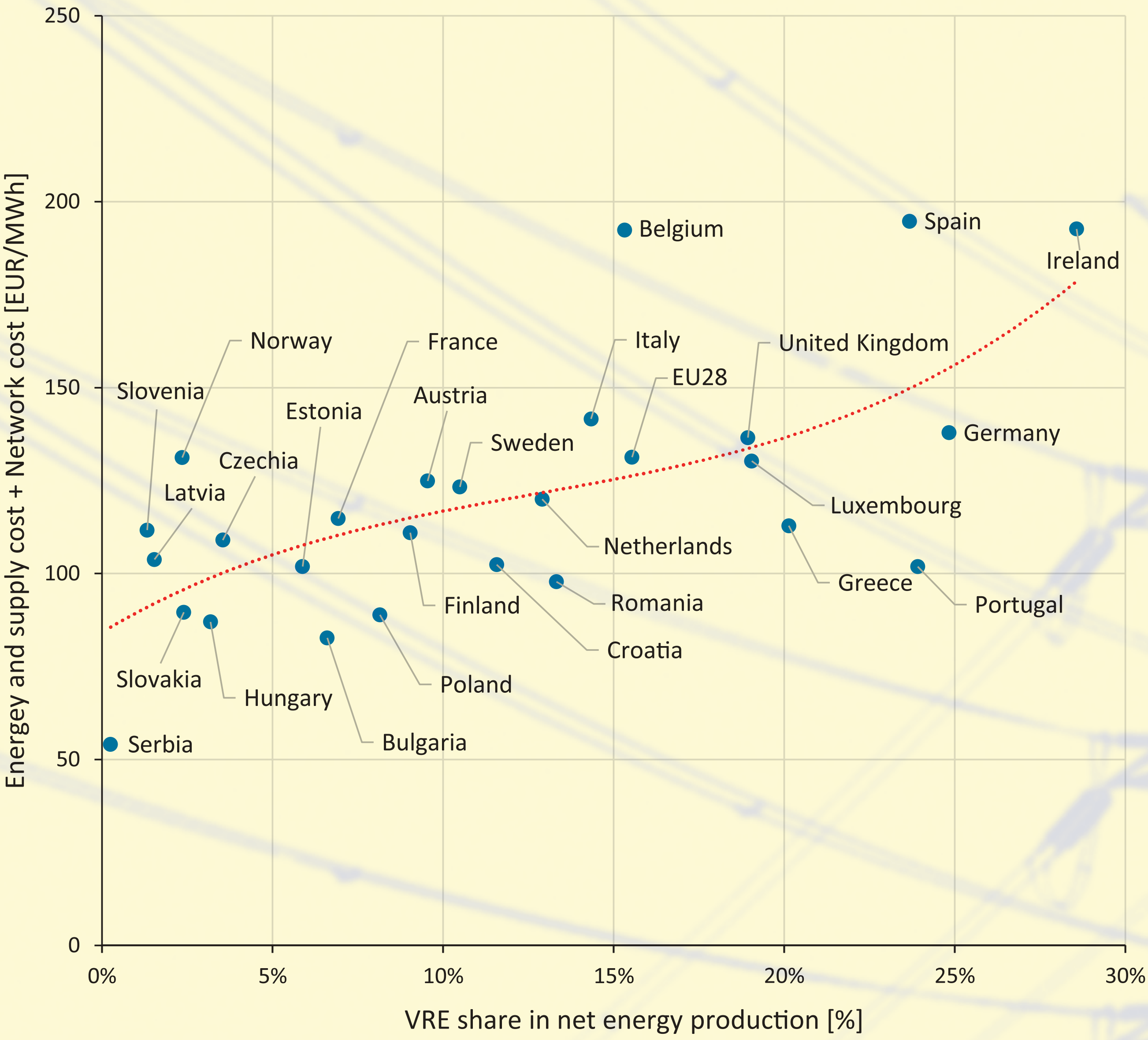

FIGURE 6 Relation between energy, supply and network maintenance costs and the share of variable RES in net electricity production in selected European countries in 2018 — average households with energy consumption of 2500 – 5000 kWh/year, own elaboration based on [11] [14] [20]

a single point in this curve's section should not be used for making conclusions about the course of the whole curve. The large dispersion of cost values between the countries in both analyses (Figure 5 and Figure 6) is caused by the specificity of individual power systems [21]. The condition and age of a country's network infrastructure, the number of cross-border connections, the shape of the daily power demand curve, the energy mix applied, and the balancing conditions of neighboring systems all largely differentiate the systems under analysis, making it difficult to determine and directly compare system costs [17].

Despite these inconveniences, the sample analyzed (Figure 6) shows a non-linear correlation between the increase in variable RES share in net electricity production and the increase in energy, supply and network maintenance costs. The slope of the European system cost curve is steeper with first investments in variable sources (up to 5-7.5%); then its course becomes almost linear with about 20% VRES penetration. Exceeding the threshold of 20% share of variable RES in electricity production significantly increases the growth dynamics of total energy and supply and network costs. Based on the analysis carried out (Figure 6), it is safe to conclude that the cost impact of variable RES on the power system intensifies as the share of these technologies in the mix increases, causing an increase in the overall cost of system operation.

A similar, non-linear relation is shown by much more comprehensive studies carried out with joint efforts of the Potsdam Institute for Climate Impact Research (PIK), the Faculty of Economics of Climate Change at the Technical University of Berlin, the Mercator Research Institute on Global Commons and Climate Change in Berlin and Vattenfall GmbH [43]. The "System LCOE" is defined by the researchers as the total amount of electricity generation costs using variable RES (private power plants owners' costs) and the costs of integrating these installations with the power system (system costs). The results of this research are presented as marginal costs — an incremental unit of the analyzed technology and is fully burdened with additional investment, operational and integration costs resulting from its appearance in the system. The analysis of the presented results shows a similarity between the shapes of the profile cost curves shown in Figures 6 and 7 and the European system cost components curve developed based on energy market data (Figure 4). The convergence of academic research with market

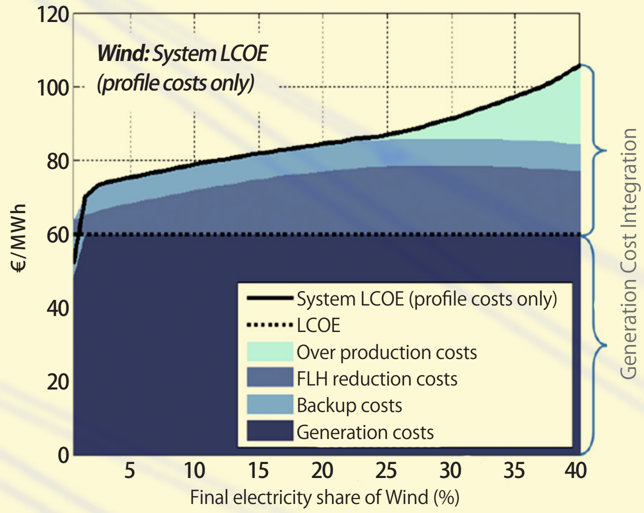

FIGURE 7 Relation between profile costs and the share of wind energy in electricity production; source [9]

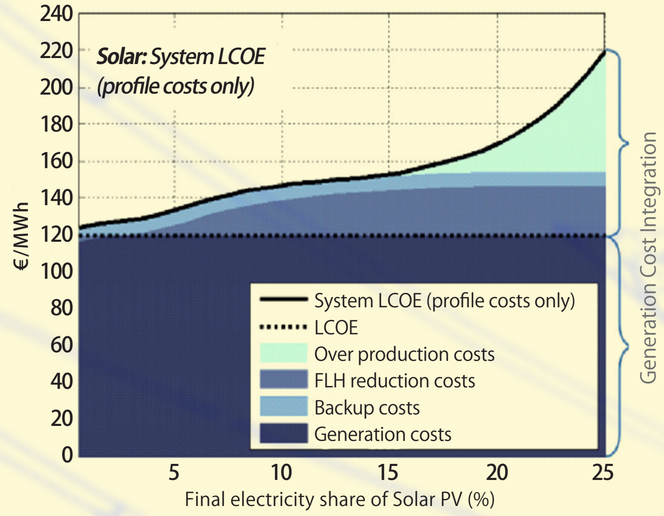

FIGURE 8 Relation between profile costs and the share of solar energy in electricity production; source [9]

data proves the real impact of profile costs on the increase in energy generation costs in the European system and the resulting increase in retail prices.

Another important factor influencing the costs of VRES integration is the level of preparation of individual countries' power networks for the development of unstable sources, as well as the dynamics of investments carried out in this respect. In the long-term, power systems are gradually adapted to new market conditions, thereby lowering the operation costs through gradual change of generation structure and network development. On the other hand, when dealing with rapid changes – resulting from individual Member States' ambitious objectives concerning dynamic development of RES – transformation costs are significantly higher due to the necessity to intensify adaptation works in the power system and the inadequacy of current network development.

To present these relations, we have carried out a comparative analysis of network costs variability in Germany and Poland between 2008 and 2017 (Figure 9). The objective of the analysis was to examine the impact of RES development rate on aggregated network costs. The analysis was based on Eurostat data on the share of all RES in gross electricity production. From this data, we have separated those based on energy generated with weather-dependent sources (wind and solar). The column diagram in Figure 9 shows the network costs in Poland and Germany; the trends these costs are subject to are marked with dotted lines, and the percentage share of variable sources in gross electricity production are marked with continuous lines. In 2008 both countries showed similar network costs, while differing in terms of share of variable RES in gross energy consumption: 0.6% in Poland and 7.2% in Germany respectively. Subsequent years of Energiewende implementation have led to a significant expansion of solar and wind sources in Germany. In 2017, the share of variable RES in the German system's net installed capacity was 46.6%, which translates to a share of 22.5% in gross electricity production. At the same time, development of RES in Poland for a long time was based solely on onshore wind farms, in 2017 amounting to a share of 15.1% in installed capacity and about 8% of gross electricity production.

This analysis confirms a correlation between system costs and the share of variable energy sources, in this case specifically

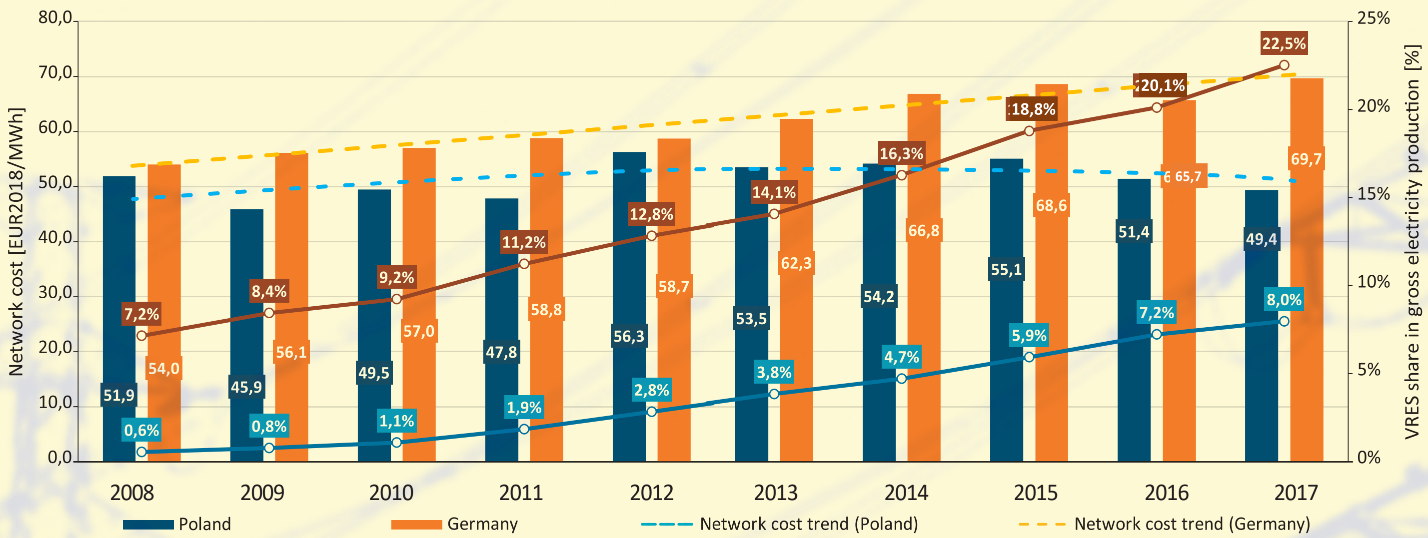

FIGURE 9 Network costs for households between 2008 and 2017 relating (to) the share of all RES in gross electricity production; own elaboration based on [11][12]

at the level of network costs. The hypothesis of higher dynamics of network costs growth along with accelerated development of variable sources in the system is also confirmed. Over the past decade, gross consumption of energy generated with weather-dependent sources in Germany has increased from about 7% to 23% of the total electricity production. This is almost twice as much as in Poland, where production of energy generated with weather-dependent sources has increased by nearly 8 percent in the same period (vs. 16 percent in Germany). Following the growing share of wind and solar power sources, over the years 2009-2017 network costs increased — in Germany by approx. 26 EUR/MWh (56%) and in Poland by approx. 6 EUR/MWh (11%) respectively.

Obviously, the increase in network costs presented was not only related to the growing penetration of variable RES. Progressive electrification and increase in energy demand both determine the need for new network investments, which are then depreciated over transmission and distribution fees. The essence of the matter is that for the development of unstable and dispersed energy sources the required network investment amount is significantly higher than in the case of the development of dispatchable sources. It should also be noted that the analyzed network costs cover only costs related to network infrastructure maintenance and development, transmission losses, metering and network management by both transmission and distribution network operators. Should costs related to intensification of transmission system operators' efforts for intra-zonal and inter-zonal system balancing be considered, as well as profile costs disregarded in general economic and decision-making calculations, the total difference in system costs values between Poland and Germany could be even higher.

Conclusions and Recommendations

Despite the EU's resilient efforts to minimize environmental and climate costs, the issue of system costs – an uncontrolled growth of which adversely impacts social well-being — is very rarely mentioned in the public debate. The climate policy promoted by the EU assumes reduction of greenhouse gas emissions mainly by increasing production of energy with the use of weather-dependent renewable energy sources. In recent years, there have been more and more public statements signaling a move away from not only fossil fuel-based energy, but also from nuclear energy. Such messages sent to the sector deteriorate investment risk assessment, creating difficulties in obtaining the necessary financing. Progressive deterioration of conditions of investment in dispatchable energy sources makes it increasingly difficult to achieve generation substitution, while also making it more and more difficult for system operators to maintain the necessary level of supply security, increasing the costs of operating the system as a whole.

Having taken into account the system costs in economic calculation, it turns out that without commercially mature energy storage facilities that would allow for a secure supply in case of several days of absence of wind and sun, a hasty alteration of energy mix to a VRES-based one will entail a significant additional strain on the economy. This is mainly due to an uneven electricity generation profile, leading to a reduction in the average annual operating time of dispatchable power plants and consequently an increase in the cost of their financing, construction and operation. Moreover, significant dispersion of small generation capacities in a system based mostly on the production of electricity through weather-dependent sources requires proportionally larger investments in the extension of distribution networks in the case of solar panels, and transmission networks in the case of onshore wind farms. Offshore wind farms are distinguished by the highest costs of connection to national power systems. This is an important argument, given that in an increasing number of countries (currently Germany, Denmark and the Netherlands), in order to improve the economic viability of these investments, the costs of connection construction are borne by the TSO [32]. A large amount of unpredictable generation in the system also translates into a growing need for balancing and flexibility. Moreover, the additional cost generated by uncontrollable sources, after reaching system flexibility limits, starts to grow exponentially due to increasing difficulties in maintaining energy supply stability.

The development of renewable energy sources is indeed needed, both for climatic reasons and for building long-term energy independence of the EU and its Member States. However, when making strategic decisions, it must be remembered that the size of VRES penetration determines additional costs of system maintenance. Building variable power capacity shifts hidden green energy supply costs to all electricity market participants and end users. In order to avoid additional economic burdens during the recovery from the COVID-19 crisis, long-term energy strategies must take into account all costs related to electricity generation. Comprehensive cost optimization of the sector's operations must consider private, system, environmental, and climate costs, as well as macroeconomic and geopolitical impacts. Neglecting one of these categories will result in the adoption of solutions that are suboptimal in terms of social and cost-related issues, which may eventually disturb economic and social development.

Annex 1 – System Costs Parametrization

The above reasoning and evidence presented confirms that ignoring system costs when optimizing the energy mix leads to an increase in energy generation cost in a given power system. System costs become particularly important when the threshold of 20-30% of electricity production from variable sources is exceeded — when the dynamics of system costs increase significantly. Depending on the specificity of a given system, its size, network age and condition, average customers' demand profile, as well as on the type of dispatchable and variable technologies used (electricity mix), system costs curves and the critical point of cost increase will be different for each EU country. However, for the purposes of discussion on the need to take into account system costs when determining the directions of the sector's development, it is necessary to ensure methodically uniform, approximate indicators.

To do this, averaged system cost curves of leading variable sources were developed based on an overview of studies (see Annex 2 below), together with equations that describe them. The curves are provided for illustrative purposes, showing averaged values of European studies, together with the necessary approximation. These curves are static, and therefore they do not reflect cost variability resulting from alterations to the generation structure on the side of dispatchable energy sources. Moreover, the curves for offshore wind farms — due to difficulties in finding reliable studies on this technology — were developed based on research conducted for onshore wind farms. We assumed that the characteristics of offshore wind production are similar to those of onshore wind production, and that the lower system costs of offshore wind farms result from their natural higher capacity utilization factor compared to onshore.

Due to significant differences between the results of studies, average values have been applied in several places, as described below. In case of discontinuity of cost characteristics (refer to indications in the literature), necessary approximations and interpolations were made, depending on the case. The shape of the characteristics and type of equation result from source data used to parametrize each technology. The increase of balancing and network costs was approximated with linear curves. While linear approximation for balancing costs seems reasonable, it can be expected that network costs, after exceeding a certain critical point, start to grow non-linearly at a higher rate, as some studies indicate [4]. However, large discrepancies between estimates of various scientific centers spoke in favor of applying linear averaging. Non-linearity of profile cost curves, confirmed by the majority of analyzed studies, [3][6][9][29][31], as well as this publication, is particularly important for estimating system costs.

All values were discounted to 2018 fixed prices by indexing base year fixed prices with inflation appropriate for the currency and economic area (USD — CPI World Bank, EUR — HICP Eurostat). Conversion into EUR was made using average exchange rate of 2018 in EUR/USD relation, provided by the National Bank of Poland (NBP).

General equations of system cost curves applicable to all analyzed technologies are presented below:

$$\textit{profile cost}\left[\frac{EUR}{MWh}\right] = A * SP[\%]^3 + B * SP[\%]^2 + C * SP[\%] + D$$

$$\textit{T\&D grid cost}\left[\frac{EUR}{MWh}\right] = A * SP[\%] + B$$

$$\textit{balancing cost}\left[\frac{EUR}{MWh}\right] = A * SP[\%] + B$$

Where:

- **SP** – source penetration in net electricity production, given in %
- **A,B,C,D** — equation coefficients

Despite the simplifications applied, the equations presented can be used as the first source of assumptions in the absence of detailed studies and national models, allowing for a real assessment of the magnitude of system costs under different scenarios of extension of power generation structure. The advantage of approximate indicators is that they provide the possibility of developing a necessary intuition with regard to the variability of optimization results for the production sector, with valuation of negative effects of implementation of variable sources taken into account. However, the target solution recommended is to develop dedicated system cost curves prepared in accordance with the characteristics of power systems of individual countries.

Onshore Wind Farms

Profile cost curves for onshore wind farms were obtained by translating marginal profile costs from the study by Ueckerdt et al. (2013) [9] into averaged values by applying curve integration. These values reflect profile costs calculated for the German system, which at that time was based largely on centrally controlled thermal power generation (coal and lignite and gas) and nuclear power, providing a total of 72% of gross electricity production around 2013. The benchmarking system used in the study was determined by way of economic optimization with the application of gas, coal and nuclear technologies, and the resulting profile cost reflects the scale of challenges and additional costs that await countries that rely on large system sources when developing variable technologies. The balancing costs were assumed based on the linear curve of average balancing costs from about 30 international studies, developed in the report by Hirth et al. (2015) [6]. The transmission and distribution network development costs curve reflects the linear interpolation of results presented in the OECD-NEA report (2012) [1].

TABLE 1 System cost curve coefficients – onshore wind farms

Curves coefficients	A	B	C	D
profile cost	550.941285	-437.426	141.8224	4.29113
T&D grid cost	17.67698211	0.56294877	-	-
balancing cost	6.775747978	1.700199	-	-

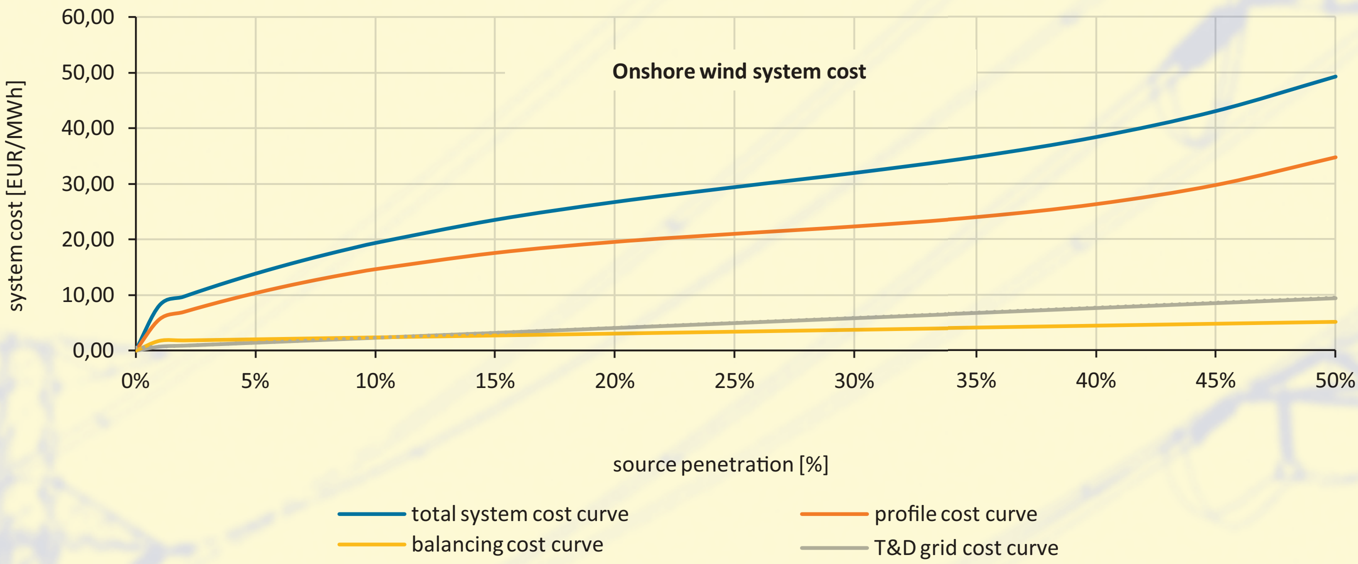

FIGURE 10 Relation between system costs and source penetration in energy production – onshore wind farms

Offshore Wind Farms

System cost curves for offshore wind farms, due to difficulties in finding reliable studies on the issue in question regarding this technology, were developed based on studies and onshore wind farms curves. The network costs were assumed to be at the same level as onshore technologies. In terms of profile costs and balancing costs, due to similar characteristics of offshore and onshore wind farm operation, the reduction of system costs of offshore technologies was assumed to be proportional to the difference in capacity utilization coefficients of both wind technologies. The proportion was expertly determined at the level of power utilization coefficients from the upper limits of both technologies CFoffshore = 50% and CFonshore = 30%. The conversion was made using the following formulas:

$$\textit{profile cost}_{offshore}\left[\frac{EUR}{MWh}\right] = \textit{profile cost}_{onshore}\left[\frac{EUR}{MWh}\right] \times \frac{CF_{onshore}}{CF_{offshore}}$$

$$\textit{balancing cost}_{offshore}\left[\frac{EUR}{MWh}\right] = \textit{balancing cost}_{onshore}\left[\frac{EUR}{MWh}\right] \times \frac{CF_{onshore}}{CF_{offshore}}$$

TABLE 2 System cost curve coefficients – offshore wind farms

Curves coefficients	A	B	C	D
profile cost	330.564771	-262.4556359	85.09345768	2.574678213
T&D grid cost	18.03443578	0.466287245	-	-
balancing cost	4.065448787	1.020119326	-	-

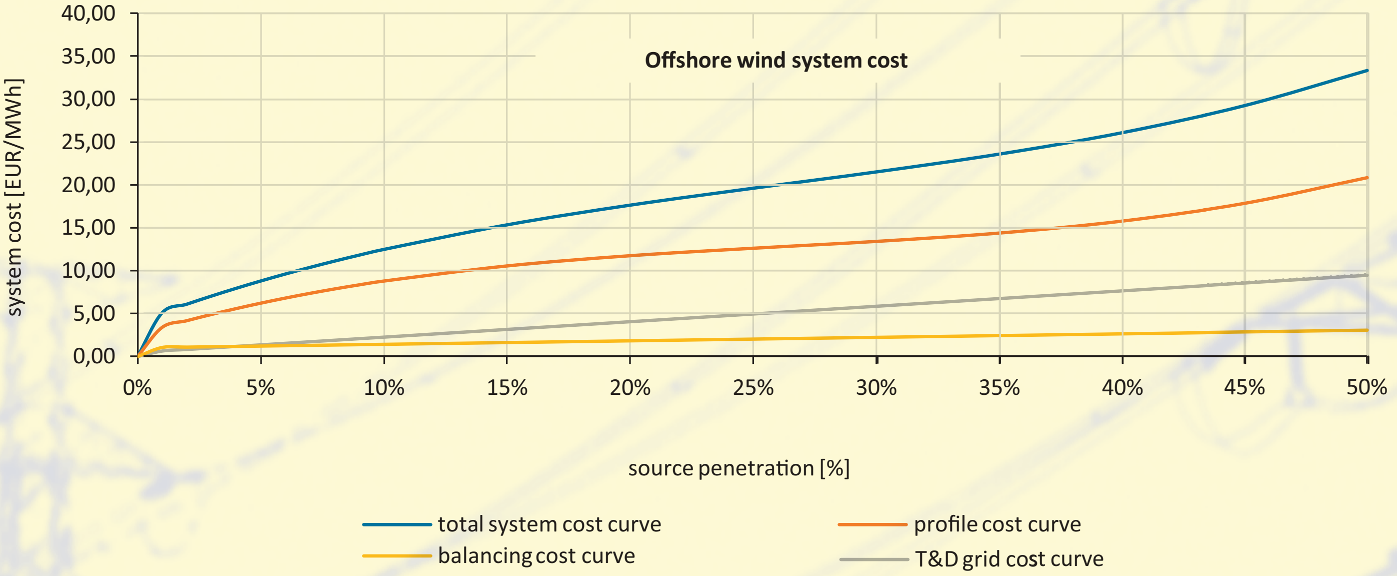

FIGURE 11 Relation between system costs and source penetration in energy production – offshore wind farms

Photovoltaics

Profile cost curves for photovoltaics, similarly to onshore wind farms, were determined by translating marginal profile costs from the study by Ueckerdt et al. (2013) [9] into averaged values by applying curve integration. The balancing costs curve was determined by linear interpolation between two given points taken from the study Pudjianto et al. (2013) [4]. The network costs curve was developed by linear approximation of results contained in Pudjianto et. al. (2013) [4] and OECD-NEA (2012) [1].

TABLE 3 System cost curve coefficients – photovoltaics

Curves coefficients	A	B	C	D
profile cost	3590.495591	-1329.56851	251.2505382	1.518455719
T&D grid cost	33.07588802	0.768946026	-	-
balancing cost	4.66807505	0.139608541	-	-

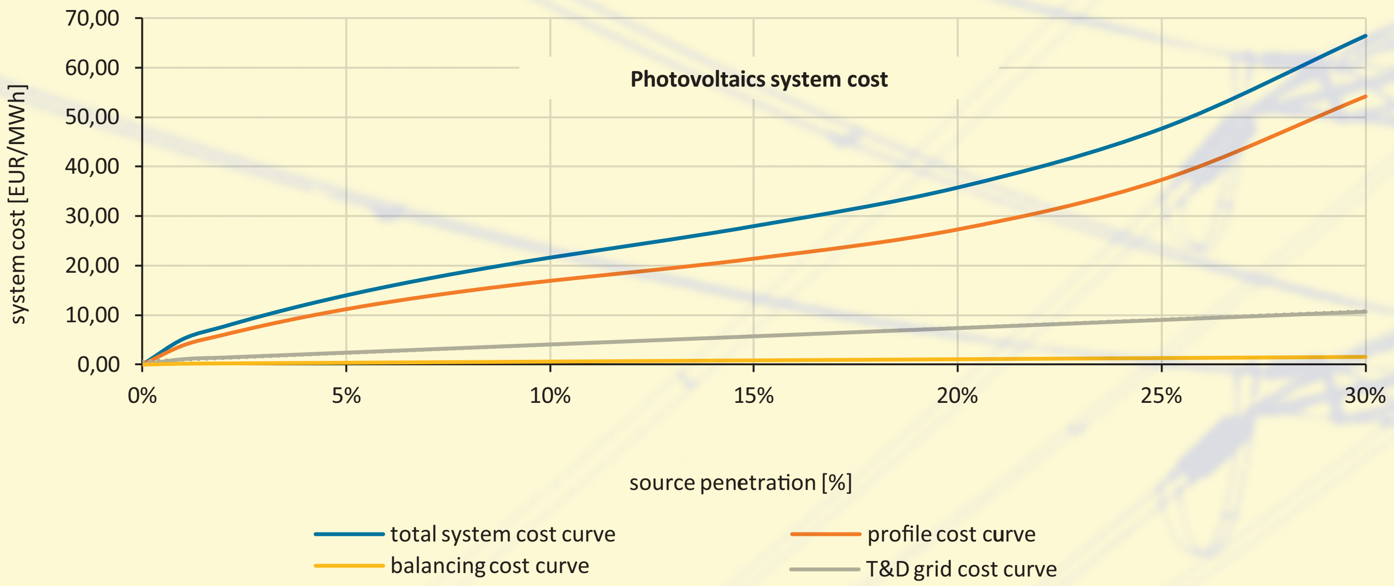

FIGURE 12 Relation between system costs and source penetration in energy production – photovoltaics

Annex 2 – Studies Overview

TABLE 4 Overview of studies on profile costs estimation; costs discounted to EUR 2018: USD inflation – CPI World Bank, EUR inflation – HICP Eurostat, NBP currency data, own elaboration based on [1][2][3][4][6] [9][10]

Profile costs

Study	Topic analyzed	Technology	VRES Penetration Level	Original Currency	Min	Max	Mean
					[EUR2018/MWh]		
IEA (2014) [10]	Europe based on Germany (2011 data)	Wind energy	10% 30%	USD 2013	- -	- -	4.28 10.1
		Solar energy	10% 30%	USD 2013	- -	- -	2.8 14.8
NEA (2012) [1]	6 selected OECD countries (FI, FR, DE, UK, US, KR)	Onshore Wind Power (OnWP)	10% 30%	USD 2012	2.2 3.7	7.5 9.0	5.6 6.8
		Offshore Wind Power (OffWP)	10% 30%	USD 2012	1.9 3.7	8.9 9.9	5.3 7.1
		Solar energy	10% 30%	USD 2012	0.0 8.7	24.1 24.8	12.0 24.0
		Coal energy	10% 30%	USD 2012	0.0 0.0	0.1 0.1	0.0 0.0
Ueckerdt et al. (2013) [9]	Systems relying on thermal energy – based on Germany Costs reduced from marginal values to averaged values	Wind energy	10% 20% 30% 40%	EUR 2013	- - - -	- - - -	14.7 19.6 22.3 26.3
		Solar energy	10% 15% 20% 25%	EUR 2013	- - - -	- - - -	16.9 21.4 27.3 37.3
Hirth et. al. (2015) [6]	30 different studies from Europe and the world	Wind energy	10% 20% 30% 40%	EUR 2015	1.0 4.1 14.5 17.6	12.4 17.6 24.9 22.8	7.8 12.9 18.1 22.8
Catholic University of Leuven (2016) [2]	Europe – CWE (BE,FR,DE,LU,NL+UK)	Wind and solar power	19% 26%	EUR 2016	- -	- -	6.7 13.0
	Belgium	Wind and solar power	19% 26%	EUR 2016	- -	- -	3.4 8.7
AGORA (2015) [3]	Germany (system based on coal power plants)	Wind and solar power	10% 20% 30% 40% 50%	EUR 2015	- - - - -	- - - - -	20.4 24.9 26.3 27.1 27.5
	Germany (system based on carbon-gas mix)	Wind and solar power	10% 20% 30% 40% 50%	EUR 2015	- - - - -	- - - - -	3.5 5.0 7.9 10.8 12.9
PV Parity (2013) [4]	Europe (AT, BE, CZ, FR, DE, GR, IT, NL, PT, ES UK) Fixed value at section	Solar energy	2-18%	EUR 2013	-	-	15.1

TABLE 5 Overview of studies on balancing costs estimation; costs discounted to EUR 2018: USD inflation – CPI World Bank, EUR inflation – HICP Eurostat, NBP currency data, own elaboration based on [1][2][3][8]

Balancing costs

Study	Topic analyzed	Technology	VRES Penetration Level	Original Currency	Min	Max	Mean
					[EUR2018/MWh]		
Hirth et. al. (2015) [6]	30 different studies from Europe and the world	Wind energy	10% 20% 30% 40%	EUR 2015	0.2 0.5 1.1 3.8	5.9 6.2 6.1 3.8	2.5 3.1 3.7 4.3
Holttinen at. al. (2013) [7]	Selected European countries (UK, SE, NO, DK, FI, DE) and US regions (Colorado, Minnesota, California)	Wind energy	10% 20% 30%	USD 2013	0.5 0.3 6.7	4.3 5.5 6.7	2.6 2.9 3.3
AGORA (2015) [3]	Austria	Wind energy	?	EUR 2015	-	-	11.4
	Europe (PV Parity) (AT, BE, CZ, FR, DE, GR, IT, NL, PT, ES, UK)	Solar energy	6.5% 18%	EUR 2015	- -	- -	0.5 1.0
NREL US (2013) [8]	USA (13 selected states)	Wind and solar power	33%	USD 2013	0.1	0.6	0.4
NEA (2012) [1]	6 selected OECD countries (FI, FR, DE, UK, US, KR)	Nuclear energy	10% 30%	USD 2012	0.1 0.1	0.8 0.5	0.5 0.3
		Onshore Wind Power (OnWP)	10% 30%	USD 2012	4.6 1.8	6.8 13.1	3.9 7.7
		Offshore Wind Power (OffWP)	10% 30%	USD 2012	4.6 1.8	6.8 13.1	3.9 7.7
		Solar energy	10% 30%	USD 2012	4.6 1.8	6.8 13.1	3.9 7.7
Catholic University of Leuven (2016) [2]	Europe – CWE (BE, FR, DE, LU, NL, UK)	Wind and solar power	19% 26%	EUR 2016	- -	- -	1.4 3.7
	Belgium	Wind and solar power	19% 26%	EUR 2016	- -	- -	2.8 4.9
PV Parity (2013) [4]	Europe (AT, BE, CZ, FR, DE, GR, IT, NL, PT, ES UK)	Solar energy	6.5% 18%	EUR 2013	- -	- -	0.5 1.0

TABLE 6 Overview of studies concerning estimation of network costs with a division into costs of development of transmission and distribution networks and connection costs; costs discounted to EUR 2018: USD inflation – CPI World Bank, EUR inflation – HICP Eurostat, NBP currency data, own elaboration based on [1][2][3][4][5][7][8]

Network Costs

	Study	Topic analyzed	Technology	VRES Penetration Level	Original Currency	Min	Max	Mean
						[EUR2018/MWh]		
Transmission and distribution network extension costs	IEA (2011)	Ireland	Wind and solar power	16% [5]	USD 2011	- -	- -	2.1 9.1
	AGORA (2015) [3] also includes grid connection costs	Germany	Offshore Wind Power (OffWP)	28-42%	EUR 2015	6.2	14.5	36.2
		min-max - of optimized and unoptimized distribution (min value for Germany) average value includes transmission	Onshore Wind Power (OnWP)	28-42%	EUR 2015	6.2	14.5	11.4
			Solar energy	28-42%	EUR 2015	6.2	14.5	7.8
	Catholic University of Leuven (2016) [2]	Europe – CWE (BE, FR, DE, LU, NL+UK)	Wind and solar power	19%	EUR 2016	-	-	2.6
				26%		-	-	9.3
	NEA (2012) [1]	Average of 6 selected OECD countries (FI, FR, DE, UK, US, KR)	Onshore Wind Power (OnWP)	10% 30%	USD 2012	0.2 1.6	3.2 20.6	2.2 5.8
			Offshore Wind Power (OffWP)	10% 30%	USD 2012	0.1 1.0	2.4 11.0	1.4 3.5
			Solar energy	10% 30%	USD 2012	0.5 2.6	8.0 43.8	4.1 12.5
	PV Parity (2013) [4]	Europe (AT, BE, CZ, FR, DE, GR, IT, NL, PT, ES UK)	Solar energy	18%	EUR 2013	-	-	12.5
Connection Costs	NREL US (2013) [8]	USA (13 selected states)	Wind and solar power	30%	USD 2013	1.8	8.2	-
	Holttinen et al. (2011) [7]	Europe	Wind energy	<40%	EUR 2011	2.2	7.5	-
	NEA (2012) [1]	Average of 6 selected OECD countries (FI, FR, DE, UK, US, KR)	Gas energy	10%-30%	USD 2012	0.3	0.5	0.5
			Coal energy	10%-30%	USD 2012	0.4	1.2	0.9
			Nuclear energy	10%-30%	USD 2012	0.8	2.1	1.6
			Onshore Wind Power (OnWP)	10%-30%	USD 2012	3.7	6.4	5.8
			Offshore Wind Power (OffWP)	10%-30%	USD 2012	14.1	22.0	17.3
			Solar energy	10%-30%	USD 2012	8.5	20.4	12.7
	Catholic University of Leuven (2016) [2]	Europe CWE (BE, FR, DE, LU, NL, UK)	Wind and solar power	19%	EUR 2016	-	-	2.7
				26%		-	-	3.2

List of abbreviations and acronyms:

EC – European Commission / EU – European Union
RES – Renewable Energy Sources
VRES – Variable Renewable Energy Sources
GDP – Gross Domestic Product
LCOE – Levelized Cost of Electricity production
T-LCOE – Total Levelized Cost of Electricity production
NPP PWR III+ – Nuclear Power Plant with Pressurized Water Reactor of generation III+
OCGT – Open Cycle Gas Turbine
CCGT – Combined Cycle Gas Turbine
CCS – Carbon Capture and Storage
ASC PC – Advanced Super Critical parameters Pulverized Coal power Plant
ASC PC + CCS – Advanced Super Critical parameters Pulverized Coal power Plant with Carbon Capture and Storage
IGCC – Integrated Gasification Combustion Cycle
PPA – Power Purchase Agreement
CfD – Contract for Difference

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