Energy Transition: The Impact of Increasing Energy Production from Renewable Sources on the Commercial Optimization Process of Conventional Power Generation Assets

Lucian V. PAMFILE
Bucharest University of Economic Studies, Bucharest, Romania
pamfilelucian17@stud.ase.ro

Abstract. *Changing the way electricity is produced, as part of the energy transition process, brings new challenges to the energy industry and in particular to the power generation practices. The switch from energy systems based on fossil fuels to generation technologies based on renewable sources is proving to be much more complex than expected. Multiple recent studies have shown that the intermittency in renewable production processes is putting pressure on the system and increasing balancing and maintenance costs of the grid, calling for an efficient management of the electricity produced. Therefore, a complete phase-out of conventional power generation units (e.g. coal, gas and nuclear) is still difficult to imagine in practice, mainly because of their role in balancing the system during the hours when renewables are not available (e.g. no wind, no sun or reduced hydraulicity). From the perspective of technical and commercial management aspects, the operation of conventional assets involves the consideration of multiple constraints (such as a longer operating time before they are shut down, or a longer preparation time before they can be restarted) in order to avoid financial loss and further damages. Therefore, the aim of this is to: 1. study the impact brought by the large installed capacity of renewable assets on the energy system; 2. analyse the options for gradual phase-out of conventional assets, from the perspective of system stability; 3. draw conclusions on how the commercial optimization of the production assets should develop as the energy transition advances. The novelty of this paper lies in the fact that it makes a business study of this transition process, which does not really exist yet, and case and simulation studies, along with statistical and time series analysis were used as a methodological approach for the research.*

Keywords: energy transition, power generation, energy management, renewables, energy market, electricity.

Introduction

Today's energy sector is diverse and complex, and the need to manage the decline of fossil fuels as the world shifts towards a low-carbon energy transition brings new challenges to it. Although fossil fuels have enabled many nations to industrialise and enhance the quality of life for billions of people in the past century, the sector needs now to change and adapt to a new reality in which the greenhouse gas (GHG) emissions must be reduced, especially because fossil fuels are responsible for the majority of them. Among the solutions identified to this issue, the switch to energy production from renewable sources in the next decades seems among the most efficient at first glance, thus redirecting more funds to the renewables sector. A complete fossil fuel phase-out is also proposed as a goal and desired by 2050 and even earlier, in order to limit global warming and to stop the problems the climate change poses to the planet, something that is extremely important - not just as an arbitrary target, but as an absolute necessity for mankind. But this transition from fossil-fuels to renewable is much more complicated than it seems, precisely because of the complexity of the energy system.

While many solutions to increase clean energy generation have been identified in the past decade, fossil fuels continue to dominate the energy landscape, accounting for more than 80% of

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primary energy consumption today - 82% in 2022 (Energy Institute & KPMG, 2023), which was 4% lower than in 2015 and with just 5% less from that recorded in 2005. (Wood & Baker, 2020, 5) There are multiple reasons why the growth of renewable energy production is still slow, among them being the way the energy market works today, the difficulty of managing an incredibly large number of production units and the fact that they are unpredictable, in terms of production periods, and also less flexible than the conventional units (e.g. coal, gas and nuclear), from the production control point of view, in times of high demand and increased consumption or vice versa. Therefore, understanding how to manage the decline of fossil fuels is essential, but understanding the impact of increased renewable generation on energy markets, system stability and other types of energy generation assets is relevant as well and it needs to be extremely well calculated and assumed by the key actors (governments, investors, energy companies, academia and research and citizens as well).

The intricate challenge of climate change that humanity faces is inherently unknown, as this spectrum of change must also include the way in which we fundamentally produce, use and consume energy. As a result, climate change has been called a "Wicked Problem" as it is either impossible or very difficult to solve, according to studies. The most significant reasons are the number of people and opinions involved, the incomplete or contradictory knowledge, the large economic burden - still not fully known because of the wide-ranging impact in all sectors of activity - and the interdependence of the issues brought by the transition with other global problems. (Tsigaris & Wood, 2016) In terms of electricity generation, the switch from energy systems based on fossil fuels to generation technologies based on renewable sources is therefore proving to be much more complex than expected, which is why further research on the topic is needed.

Power (or electricity) is produced today from several types of sources, which are called conventional and renewable sources. The conventional power units include steam turbines (gas or oil), nuclear power plants, combined cycle gas turbines (CCGT) and biomass power plants. These units are based on traditional thermal power cycles and are commonly used in power systems for frequency stability studies. On the other hand, the renewable generation units are hydropower plants, wind power plants (onshore and offshore), photovoltaic (PV) installations and concentrated solar power (CSP) plants. These renewable energy sources are increasingly integrated into power systems and present unique challenges for frequency control and grid stability due to their intermittent nature and decoupled operation from the grid.

When it comes to the stability of electricity grids, intermittency is an important aspect to take into account, which makes the difference between stable and less stable generation units at times of specific system requirements (when maintaining high generation is required from producers to cover high consumption, or when generation units have to be withdrawn from grids to meet lower consumption), but not only. The system intermittency refers to the irregular and unpredictable nature of renewable energy sources, such as wind and solar power, in terms of their energy production. This intermittency arises from the variability of natural elements, such as wind speed and sunlight, which directly impact the generation of electricity from renewable sources. As a result, the output of renewable energy systems fluctuates over time, leading to challenges in maintaining grid stability and reliability. The intermittency of renewable energy systems is a key consideration in power system planning and operation, as it requires the development of strategies and technologies to mitigate the impact of these fluctuations on the overall stability of the power grid. (Blondeau & Mertens, 2019)

Multiple studies have shown that the intermittency in renewable production processes is putting pressure on the system and increasing balancing and maintenance costs of the grid and higher electricity costs to consumers, calling for an efficient management of the electricity produced. (Johnathon et al., 2023) On the one hand, renewable units have a great advantage, compared with the conventional ones, that the electricity produced by them is clean and thus the pressure on the exploitation of natural resources is heavily reduced (as is the case with coal, natural gas or uranium, for nuclear power plants). But, a complete phase-out of conventional power generation units is still difficult to imagine in practice, mainly because of their role in balancing the system during the hours when renewables are not available (e.g. no wind, no sun or reduced hydraulicity), but also because they can maintain a constant output of electricity produced and injected into the system, compared to the intermittency of renewables. So managing power grid complexity is challenging.

Apart from the stability of the energy system, another impact of renewable units is the economic impact from the perspective of managing the business of a power generation asset. While the commercial and technical management of a renewable unit involves, most of the time, having production forecasts as accurate as possible, in line with the unit's source (sun, wind) and asset's available capacity, the management of a conventional unit relies on precise planning of production times, which is much more accurate and creates less imbalances in the system. However, from the perspective of technical and commercial management aspects, the operation of conventional assets involves the consideration of multiple constraints (such as a longer operating time before they are shut down, or a longer preparation time before they can be restarted) in order to avoid financial loss and further damages.

There are also other things which should be taken into consideration commercially: most of the auxiliary reserve capacities that the power system operators require to be available for immediate dispatch are from conventional units, because of their stability (bringing revenue to these assets); conventional assets have more taxes to pay, compared with renewable ones, either for their production sources (like coal or gas) or on the emissions taxes they produce (e.g. in the European Union, adding costs during their operation time); renewable units are usually subsidised by the states to be able to increase their installed capacities (such as the green certificate system, bringing revenues to these assets). (Hove & Geres, 2021) All these aspects make electricity produced by conventional assets more expensive than renewable ones, although they bring more security for the system and they are more used by the system operators.

Therefore, a dilemma arises about what the energy sector should look like in the future, because at present it cannot function with just one type of generation, but needs both types - conventional and renewable together. A more stable approach for both the energy system and the generation assets is to have a diversified energy mix, but this could slow down the energy transition process. Also, several strategic and pragmatic challenges arise when managing, upgrading and maintaining a distributed portfolio of linear, vertical and portable assets (like owning both conventional and renewable power generation units) in an asset-intensive industry like the energy sector. (Wood & Baker, 2020, 139-178) A number of factors should be changed in the way that businesses manage their energy today and these changes should give producers more ways to control their assets and budgets. (Mojarad et al., 2018, 627)

A vital first step in maximising the value of an energy asset is power asset optimisation. (Merbach, 2023) These optimisations assume that a unit should only operate when the price of the power sold covers its production costs and also marks a profit margin. This activity is practised by all energy companies today and is an integrated part of the energy management activity. In the past decade, the growing number of installed capacity of renewable production has led to a new trend in the electricity markets, which has made the optimization process of conventional power generation assets increasingly difficult. The price is very low when there is a lot of power production of renewable assets, but it increases and reaches very high values when renewable sources are low or non-existent (e.g. there is no wind for wind turbines, or it is night and there is no sun radiation for PV panels). This phenomenon has made prices extremely volatile, even within a day, and has shown the direct link between the electricity price and renewable generation, but has also affected the production plans of conventional units and increased the imbalances in the system (due to the increased intermittency).

Taking into consideration all these aspects, this paper investigates further the impact brought by the large installed capacity of renewable assets on the energy system and also analyses the options for gradual phase-out of conventional assets, from the perspective of system stability. At the same time, it draws conclusions on how the commercial optimization of the production assets should develop as the energy transition advances, which have the role of guiding possible investors and public policies in a right direction for managing the energy market in the future.

Literature review

The hypothesis of this paper is that a large increase of renewable energy introduced in the energy system and grids can lead to an economic destabilisation of the rest of the electricity generation producers, especially conventional assets (based on gas, coal, oil, but also nuclear and hydro). Moreover, if not supported and controlled by effective energy policies, this new green energy capacity can have a negative economic impact on them too. The paper therefore investigated whether it is better for an energy mix to be based on multiple sources, with both renewable and conventional sources, or whether the whole system can be switched to renewable energy only.

In this regard, the energy transition has become increasingly discussed and researched in recent years, both by academia and the private sector. Studies so far have tried to better understand what is happening with this process, but have mostly focused on the beneficial side of renewable energy development, while the constraints and concerns have emerged more recently due to the multiple crises taking place globally (economic, health, political and geopolitical).

For the past few decades, official reports show that the primary cause of anthropogenic GHG emissions has been the use and combustion of fossil fuels, which account for around 78% of all GHG emissions worldwide. (Intergovernmental Panel on Climate Change, 2015) At the same time, in order to keep the average global temperature increase from pre-industrial levels to within the 2 degree, and ideally 1.5 degree, set as the goal under the Paris Climate Agreement (United Nations, 2015), a significant portion of the fossil fuel stocks currently available must be kept abandoned and remain unused - around 80% of global coal reserves, half of all natural gas reserves and a third of oil reserves. (Jakob & Hilaire, 2015)

By 2100, the current climate policies put the world towards 2.9 degrees of global warming (Climate Action Tracker, 2023), therefore a swift transition to an energy system based on low-carbon and renewable sources is required to prevent disastrous climate change. But in order to drastically decrease the use of fossil fuel, significant societal changes and a profound transformation of the way our economy works must take place, given that fossil fuels are so entrenched in the global economy and in our daily lives. (Wood & Baker, 2020, 139)

However, the use of energy is essential for economic growth, which might be affected by the negative externalities associated with the combustion of fossil fuels. Therefore, sustainability, energy efficiency and renewable energy sources are often mentioned as viable approaches to achieving energy security and climate goals and transition. (Tanțău & Șanta, 2019, 700) Although there is a chance that renewable energy sources will replace fossil fuels, there are still significant financial and technological barriers to their widespread use. (Verdolini & Galeotti, 2011)

In recent times, energy mix diversification has gained recognition as a viable strategy for developing nations, as it aims to achieve two critical goals by 2050: net zero carbon emissions and enhanced energy security. (Nibedita & Irfan, 2024) However, the pursuit of a diversified energy mix raises concerns about meeting carbon reduction targets and potentially hindering the energy transition process. In 2017, researchers Deng and Newton suggested that for obtaining substantial decarbonization, a multifaceted policy approach is essential, which includes: replacing conventional power plants with a blend of gas, wind farms and solar thermal plants; prioritising energy efficiency improvements across electrical products, housing, transportation and urban design; and promoting widespread energy conservation practices among the general public. (Deng & Newton, 2017) Moreover, the substantial welfare and government support provided to the fossil fuel industry present a paradox. Redirecting these subsidies toward climate actions could significantly bolster efforts to meet the more ambitious target of the Paris Climate Agreement. As a result, studies show that rather than perpetuating an industry that jeopardises human health, ecosystems and the climate, urgent action is needed, therefore a shift from fossil fuel welfare to a system that prioritises social well-being and ecological balance in our pursuit of a cleaner, more equitable future is needed. (Wood & Baker, 2020, 563)

Another effect of climate change could be directly related to energy generated from renewable sources, such as wind power. For example, according to analysts, European wind power is expected to fall up to 30% below expectations by the end of this decade as global warming brings more frequent periods of high pressure with calm weather. (Dalfest, 2024) Therefore, if action is not taken to reduce global warming, this could jeopardise plans now underway to develop wind energy in the future, underlining the need for urgent compliance with the Paris Agreement.

We can therefore say that renewable energy assets play a crucial role in reducing society's reliance on fossil-fuel-generated electricity and mitigating associated carbon emissions and environmental challenges, which many researchers have been saying for more than 10 years now. (Marszal et al., 2011, 971) However, there are concerns about potential adverse effects, as already mentioned. Energy companies must generate sufficient income to recover infrastructure investment costs and the transmission and distribution network must be developed in order to meet both a peak consumption demand and also a higher system flexibility. (Qiu et al., 2019) Beyond cost reduction and pressure relief on conventional generation units, the deployment of PV panel technology also holds significance for electrifying underserved rural areas, and so achieving decarbonization goals in the energy transition requires addressing both economic and equitable aspects. (Buragohain, 2012, 335)

However, the integration of intermittent sources (such as renewables) into the power grid significantly affects existing conventional power plants. This impact is compounded by a decline in demand over the past decade, leading to global network overcapacity. (European Commission, 2023) Consequently, thermal power plants experience reduced operating hours annually. These plants, prioritised in the market merit order, are the first to connect to the grid during peak demand. Interestingly, despite their higher conversion efficiencies, CCGT power plants, which utilise natural gas, start up after coal-fired power plants on the same network. CCGT plants are considered ideal for renewable energy backup due to their load flexibility, efficiency, and lower CO2 emissions. Some scenarios even propose them as a sustainable alternative during the energy transition, advocating for a coal phase-out for environmental reasons. (Bushnell & Novan, 2021)

The key challenges and risks in the power sector include ageing equipment, compliance with climate adaptation measures, and regulations related to decarbonization of the electricity and heat sector, including coal-phase out. As already mentioned, power production is a significant source of global GHG emissions, with fossil fuels still accounting for over 75% of global electricity production. The need to put a price on CO2 and other GHG emissions is emphasised, as it can significantly impact system dispatch over the short-term and generation investment decisions over the long-term. These challenges are particularly exigent for developing countries with limited resources to respond to these issues. (Kazagic et al., 2022)

There are also studies which offer a counterbalance to the notion that current markets are ineffective because the baseload generation sources face financial challenges, and renewable energy is mainly responsible for this situation. According to Bushnell & Novan (2021, 24) it's important to note that renewable investment is a consequence, rather than the cause, of these challenges. Furthermore, state policies regarding the promotion of renewable energy strongly influence these dynamics, the researchers said. On another note, although an increase in specific emissions from conventional power plants operated as backup units was anticipated (Lecomte et al., 2017) and has been predicted (Katzenstein & Apt, 2009), there is not enough evidence in the literature yet.

As a result, there is a gap between the extant literature and the new perspective presented in the paper, therefore it contributes to reducing it.

Methodology

Case study, simulation study, statistical, indicators and time series analysis were used as a methodological approach for the paper. First, applied research and case study methods were used, as the analysis focuses on applying scientific knowledge to solve practical problems, while also studying and deepening a certain very complex subject: what impact a large renewable energy capacity creates for the energy system and how it affects other electricity generation units or the energy system.

In terms of qualitative and quantitative methods, statistical analysis and time series analysis were used as they involve analysing numerical data using statistical methods to identify patterns or relationships. By using time series analysis, hourly power prices were analysed over a nine-year period. This method is efficient when it comes to finding underlying links and to forecast future values, as it involves examining patterns, trends and behaviours in consecutive data points. Also, applications for time series analysis may be found in many fields, such as economics, engineering, finance and social sciences, where the ability to comprehend and predict temporal patterns is crucial for planning and making decisions.

In addition to time series analysis, indicator-based analysis was used in the paper as a method to analyse, from a technical point of view, the electricity market values and hourly price curve patterns that can be used to define future values. The data used were provided as a result of collaboration between researchers and industry, government or other organisations that are interested in reporting global and local data on the energy system and its status.

The analysis was carried out taking into account realised spot prices over the last nine years, from 2015, and it took into account prices at hourly level (with 24 intervals per day) - as it is the reference time in the Day-Ahead Market in all the European Union (EU) area, as well as in many other countries worldwide. The nine-year time period was chosen because the oldest data available in the ENTSO-E Transparency Platform for all the countries which were analysed in this paper is from 2015. In addition, in the analysis, based on the fact that countries usually have different energy systems and different realised prices, from one country to another, it was necessary to cancel out the different year-to-year level at which prices have been recorded throughout this period by creating a standard price curve (a profile), on which statistical analysis was applied. The standard price curve consisted of calculating the annual average price (using the arithmetic mean) at hourly level and then dividing each hourly average price by the daily average price. This method, of taking the arithmetic mean between all the hourly prices, is also how the energy exchanges calculate the daily price. The result of this calculation was a coefficient, which indicates how close the hourly price is to the average daily price and which can easily give the hourly price, just based on the daily price. Thus, regardless of price differences between countries, the price curve remains the same, whether the price is 1 euro per MWh or 1000 euro per MWh. This calculation has been applied to all the analysed years in order to highlight the impact of renewable energy, which is continuously increasing, on the price curve.

In order to process statistical data, Microsoft Office Excel was used as a software program and part of the conclusions are the result of the analysis done with it. Some of the results are presented in the tables annexed to this paper and represents simulations to create a standard price profile based on historical prices. To calculate the average hourly price, average daily price, and hourly price curve using mathematical notation, the following mathematical notations were used:

1. Average Hourly Price ($P_{average}$):
$$P_{average} = \frac{1}{8760}\sum_{t=1}^{8760} P_{hourly}(t)$$
Where $P_{hourly}(t)$ represents the price at hour *(t)* over the course of a year and 8760 the total number of hours during a year.

2. The Average Daily Price (P_{daily}):
$$P_{daily} = \frac{1}{24}\sum_{h=1}^{24} P_{average}(h)$$
Where $P_{average}(h)$ represents the average hourly price calculated for each hour *(h)* during each 24 hours in a day and over the course of a year, using the formula:
$$P_{average}(h) = \frac{1}{365}\sum_{d=1}^{365} P_{hourly}(h + 24 \times (d-1))$$

3. Hourly Price Curve ($C(t)$):
$$C(t) = \frac{P_{average}(t)}{P_{daily}}$$

Another relevant aspect in this analysis was the difference between peak and off-peak consumption hours, which usually lead to different energy prices. According to Europe's largest energy exchange, the European Energy Exchange (EEX), peak consumption hours are between 08:00 and 20:00 (for 12 hours), while the remaining hours during the night are the off-peak hours (12 hours, from 20:00 to 08:00). On the electricity exchanges around the world, these are the exact correspondents of these time periods, i.e. Peak (daylight hours), Off-peak (night hours) and Baseload (entire day). These time intervals are relevant also because it is more accurate to separate the time of day when solar producers inject their electricity into the grids, which happens only during the day (when solar radiation can be perceived by PV panels).

Moreover, the paper analysed the impact of the growth of renewable energy sources on the electricity price curve also by separating the calendar year into two parts, the summer and the winter period. This separation was done because PVs record the highest production during summer, their impact is significant and this needs to be highlighted separately. To be noted that this separation is also used by various companies in the energy sector, such as electricity distribution operators, according to which the winter period (or cold season) is considered during the months of October-March, while the summer period (or warm season) is considered during the months of April-September. For energy distributors, defining these seasons is useful in creating specific consumption profiles (also called virtual profiles) that they use to exchange information with energy suppliers when consumers do not have a smart-metering system - thus distributors allocate a virtual profile based on the consumer's activity and total monthly consumption. (DEER, 2020)

Figure 1 presents a plot of the hourly spot market price characteristics from January 1, 2015 (first hour), to December 31, 2023 (the last hour). In total, 236,691 numerical indicators were analysed, representing the hours for each day, each month and each year of the nine-year time series analysis period. As the figure shows, some negative prices were recorded among the spot market prices during the study period and this mainly occurs because of system inflexibilities that can lead to periods with excess power, especially during the summer. These inflexibilities include renewable generation systems dealing with priority dispatch and production support mechanisms, conventional generation systems facing techno-economic limitations in their output variations, and the must-run conditions of certain power plants for system security reasons (Keeley et al., 2020). In the figure can also be seen the beginning of the energy crisis, started in 2021, marked by the return of the economy after COVID-19 pandemic restrictions. At the same time,the historical peak reached by electricity prices can also be seen in 2022, the main cause being the outbreak of war in Ukraine and the beginning of the armed conflict of Ukraine with Russia. Prices in the meantime, in 2023, have calmed down, according to analysts, but they remained at a high level compared to the ones realised before 2021.

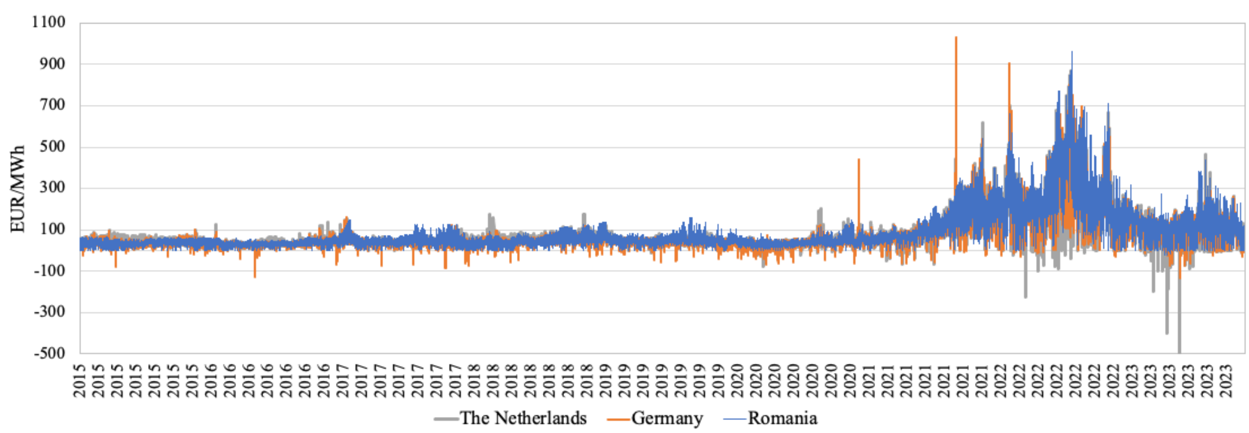

Figure 1. Time series of spot prices from 01.01.2015 to 31.12.2023 in Romania, Germany and the Netherlands

Source: ENTSO-E Transparency Platform.

Data on installed power capacities by type of generation were also analysed in the paper and the official figures were provided by ENTSO-E Transparency Platform. The analysis period was the same, nine years (2015-2023), and the share of energy types, trends in recent years in each country and then a correlation was made with the price curve and the impact of changes in the energy mix on the electricity price curve.

Therefore, a Pearson correlation was performed to determine if there was a correlation between the evolution of several types of power generation installed capacities (called variables), for each country over the last nine years, and on the basis of this it was possible to define whether a coherent policy of a gradual phase-out of conventional assets was in place in the three countries analysed in this paper. This type of correlation was chosen because it provides information about the link between two variables by summarising how closely they move together in a linear way. Thus, the correlation analyses were presented in tables that showed two sets of values: r (correlation coefficient) and p (p-value), for the relationship between the variables. According to DATAtab (DATAtab, 2024) the p-value tests the hypothesis that the correlation is significantly different from zero in the data. In most research, a p-value less than 0.05 is considered statistically significant. At the same time, in the context of Pearson correlation, the degree of linear relationship between two variables is referred to as the correlation strength. This link is quantified by the Pearson correlation coefficient, which should be read as follows: the r value ranges between –1 and 1; a positive correlation (when one variable increases, the other tends to increase) has an r value between 0 and 1; a negative correlation (when one variable increases, the other tends to decrease) has an r value between –1 and 0; an r value of 0 indicates no linear correlation between the variables; and the magnitude of r indicates the strength (greater than 0.5 is strong positive correlation is greater than 0.5, moderate positive correlation is between 0.3 and 0.5, weak correlation is 0-0.3, moderate negative correlation is between -0.3 and -0.5, and a strong negative correlation is less than -0.5).

In addition, based on the analysed data, the paper also tried to simulate how a conventional power production unit operating schedule looks like today and compared to 2015, considering the impact that renewable energy has brought to the energy system.

This study thus shows an inductive approach, which is a method of data collection and idea construction based on observations made from the data. It is commonly used in exploratory research when there is limited prior information about the problem being studied. When analysing the spot market hourly price curve evolution and changes in each country's energy mix, there were multiple steps taken to apply the inductive research method such as collecting data, identifying patterns, developing theories, testing those theories and refining them based on the results of testing. In theory, this approach can help to uncover new insights into the ways that renewable assets are impacting the power market and may inform future policy decisions or investment strategies.

Results and discussions

Large installed capacity of renewable assets impact

Electricity produced from renewable energy sources (RES) has started to have a significant impact on power systems due to its utilisation of natural, free energy and its sustainable nature. (REN21, 2020) Furthermore, the decreasing investment costs also contribute to its growing importance. RES generation includes both dispatchable resources like hydroelectric power, as well as non-dispatchable sources known as variable renewable energy (VRE), such as solar and wind power. VRE represents a significant percentage of RES goals in various countries, especially in Europe. (IRENA, 2023)

In conventional generation-based systems, electrical system planners[1] have always faced some degree of variability and uncertainty, both technically and economically. However, the integration of variable renewable energy (VRE) presents unique challenges that have a significant impact on overall system costs (including electricity generation and transmission) and revenue from electricity generation. These total system costs are ultimately passed on to customers, while generation revenue is crucial for attracting investment. Therefore, it is essential for forward-thinking system planners and policymakers to confront these challenges in order to minimise costs for customers with their VRE plans and policies. In addition, they must also properly assess the effects on all electricity producers to establish consistent policies.

The impacts of RES integration have already been confirmed in numerous research. According to them, the expenses associated with the electricity production process encompass capital costs (CCs) for generation and transmission infrastructure, fuel expenses and operational costs. Additionally, the integration of any generation type into electrical grids results in supplementary expenses which are called integration costs. (Milligan et al., 2011) These costs appear due to the interactions between the integrated generation units and the existing electrical frameworks, comprising technical considerations such as adhering to system constraints and economic factors like alterations in electricity market dynamics. Nevertheless, integrating VRE producers imposes notably higher integration costs compared to conventional generators, and these costs escalate with increasing VRE penetration for various reasons.

Therefore, two categories and multiple types of costs have been identified that can be associated with the integration of large installed capacity of renewable assets, respectively direct and indirect costs. (Imcharoenkul & Chaitusaney, 2022) Direct integration costs result from electricity generation and transmission processes - i.e. balancing costs, grid costs and profile costs from flexibility effects - while indirect integration costs come from reduced revenues from electricity generation - translated into the profile costs from the effects of use (also called utilisation costs).

Balancing costs: representing raising operational expenses due to the differences between power production forecasts and the realised production injected into the grid. The unpredictability of VRE leads to stability concerns within the system and when there are forecast inaccuracies or unforeseen circumstances, traditional generators are required to offer balancing services like frequency regulation to uphold system stability, thereby raising the balancing costs. It's important to note that if VRE forecasts were accurate, balancing costs would be nonexistent or close to zero. (EWEA, 2016)

Grid costs: are expenses which include various factors such as voltage stability costs, transmission congestion, transmission line losses and the need for transmission expansion. VRE generation might take place at considerable distances from load centres, requiring suitable transmission systems and operational measures. (Hirth et al., 2015)

Profile costs generated by "flexibility effects": incurred from the need to have a flexible electricity system which can support large RES capacities. Conventional producers must operate at suboptimal levels to provide this flexibility, often requiring frequent startups and shutdowns to

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[1] System planning is the process of developing plans systems and its elements. In the current context, an electrical system planner is a professional who is part of a continuous process, typically within a composite department that includes technical, economic and managerial specialists, statisticians and weather forecasters. Their main focus is to expand and operate power systems effectively, from the creation of the feasibility study to the production and maintenance forecast of the production units.

compensate for fluctuations in VRE generation. However, profile costs only include planned operations, while any unscheduled operations resulting from forecast errors are categorised as balancing costs.

Profile costs generated by "utilization effects": which cover the demand of reliable capacity available for the grid in order to sustain the variability of VRE. This costs incurred because VRE leads to inefficient utilisation of both conventional and renewable generation. Also, in addition, VRE introduces unique market dynamics not observed in conventional systems due to various reasons. (NEA, 2019)

The "Duck Curve" concept is one example of the impact of renewable energy sources, particularly solar power, which underscores the necessity for market design to adapt accordingly. This concept, initially referred to by the California Independent System Operator (CAISO), visualises the daily patterns of electricity demand and supply and how rooftop PVs and solar assets are re-shaping the electricity price during the day, thus becoming a growing concern for industry, regulators and academia. (Wilkinson et al., 2021; Azemena et al., 2022) Depicted in the shape of a duck, with its head and neck representing the daily net load, or the disparity between power consumption and generation, it serves as a significant indicator of how RES can lead to an excess of electricity and to the need for change of the electricity system. This phenomenon creates a dilemma since it might result in an excess of power during the day and a rapid spike in demand as nightfall approaches. Therefore, for an energy system to be dependable and stable, but also for price stability, this imbalance must be addressed.

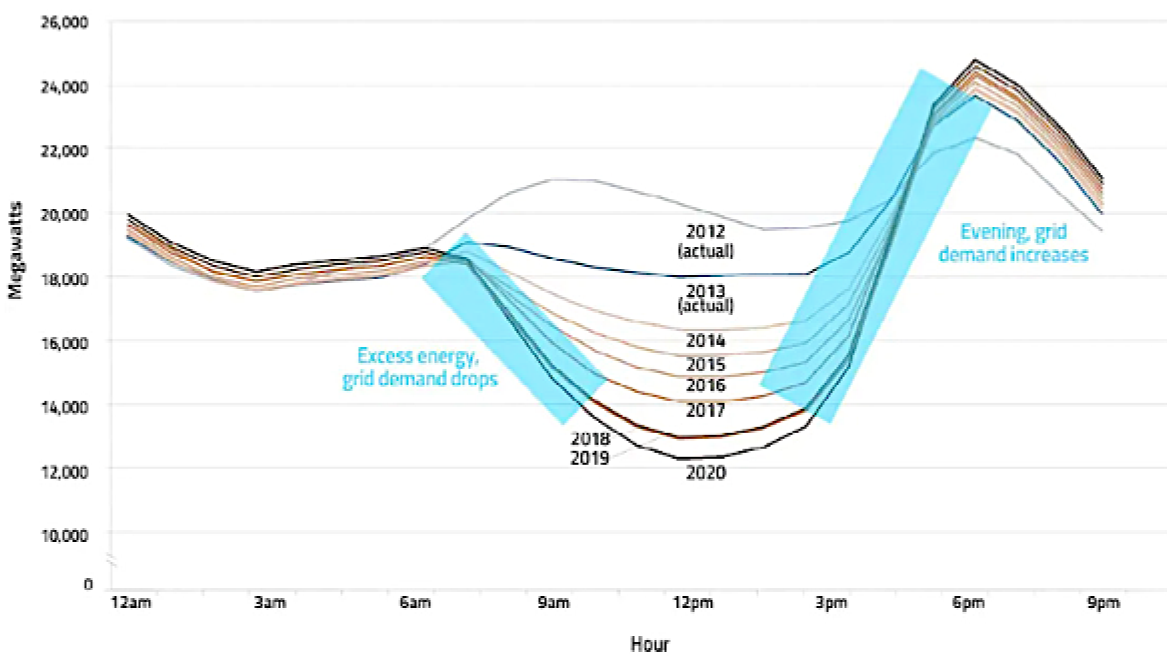


Figure 2. Presentation of the Duck Curve problem

Source: California ISO, 2016.

As a result, understanding how the rapidly increasing development of RES affects market prices has become an important component of economic research on RES and electricity markets, and it may be useful in both RES policy making and planning, as well as in the design of electricity markets. One of the effects of these green electricity producers is that while solar energy reduces the need for other energy sources during the day, it also directly reduces the electricity demand of consumers (domestic and industrial) which have PV panels on their roofs. With these two impacts, both energy demand and supply are reduced, making electricity prices much lower in the middle of the day. And the more solar radiation there is, the more significant the impact (especially during summer), leading to negative energy prices. This phenomenon is visible in all areas of the world where VRE, respectively RES units have been installed. However, over time, with the increase in installed renewable energy capacity, the Duck Curve phenomenon is even more visible, making energy prices extremely volatile and the effects diverse.

To gain a better understanding of the price variation effect of renewables on market prices, this paper examines the influence of wind and solar power on the spot market price, i.e. the day-ahead market, of three EU countries by using time series and statistical analysis. These countries are Romania, Germany and the Netherlands, which were chosen because they have both common and different features in terms of the energy system and structure, each of them having individual specificities, but at the same time are part of the European Energy Community and they are also coupled. Romania is a country known for its extremely balanced energy mix, including after the introduction of RES. Germany is the largest market in Europe with high renewable energy penetration, especially wind, but which had relied heavily on fossil fuels before. While the Netherlands is a country with a mixed energy system that has benefited tremendously from the growth of green energy from the sun.

According to the results of the analysis of this paper, price curves in all countries were impacted by the significant increase in renewable energy generation, as can be seen in the figures below. As an overall impact on the three countries compared, the high daytime electricity generation from PV assets has changed the price curve the most, while the injection from wind farms is less visible because, on an annual basis, the injection values are netting out and becoming almost equal on an hourly basis. Therefore, looking at the three countries, it can be seen that the high solar generation has decreased the peak day value (Peak profile, 08:00-20:00) by 11%-12%, but has equally increased the prices in the remaining hours (Off-peak profile, 20:00-08:00). This means that electricity, regardless of its annual, quarterly, monthly or daily value, is on a downward trend during the day and an upward trend during the night, especially during the evening peak consumption. However, the most significant impact is the increase in price volatility and the variation from one hour to the next, as shown in the figures below.

Typically, Peak prices have always been higher than Off-peak ones, reflecting higher energy demand during the day and lower demand at night. However, with the increasing penetration of solar energy, this ratio has started to change. Thus, although the annual average still indicated a higher price during the day than at night in 2023, this has not been consistently the case and there have even been days with a higher price during the peak hours of the day compared to the night. This is abnormal because the highest energy consumption occurs during the day when industries are running, putting pressure on energy offer (generation side), instead there have started to be times when prices are more expensive at night instead.

Table 2 of the Appendix to this paper contains the average hourly prices calculated on an annual basis for the reference years 2015 and 2023 in Romania, and the price curve profile calculated as coefficients using the average hourly price divided by the average daily price during a year. As already mentioned, 2015 is the historical year to which the year 2023 has been compared to reflect the impact on the price curve of increasing renewable energy injected into the grid, in a nine-year period. The mathematical formulas used to calculate each value in the table are mentioned in the methodology chapter of this paper.

In Romania, at the daytime period level (Peak and Off-peak), in the case of the annual analysis, the increase in renewable energy capacity and solar power generation brought an impact of 10.7% on average compared to the Peak and Off-peak prices in 2015, i.e. the price value decreased in the daytime hours and increased in the same proportion in the nighttime hours. At the hourly level, the differences are even greater, so that the most impacted hourly interval in Peak is 1pm (12:00-13:00), where a -31% price impact was seen compared to the same hourly interval in 2015, as well as in 8pm (19:00-20:00 interval) in Off-peak, where a +23% price impact was seen. This made the price volatility (difference between the lowest and highest price) 54%, which meant that the difference between the hour with the lowest price (i.e. the cheapest MWh) and the hour with the highest price (i.e. the most expensive MWh) was only seven hours.

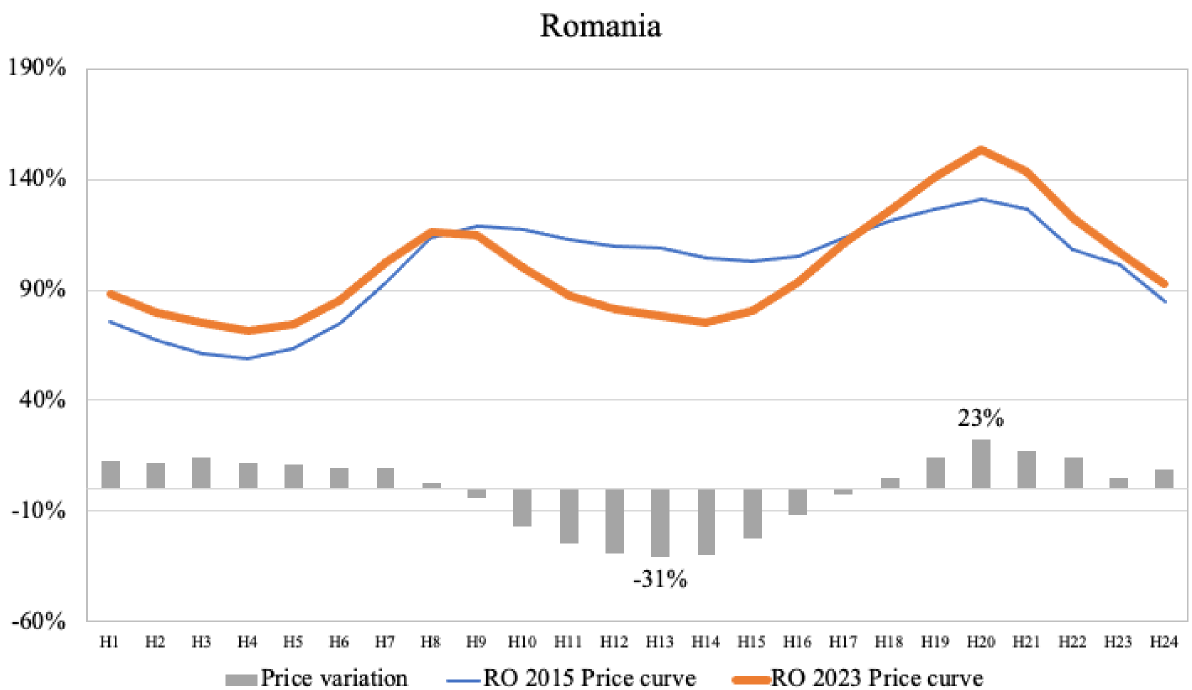


Figure 3. Full-year analysis on spot market price curves in Romania during an average day in 2015 and 2023 and price variation between years

Source: Authors' own research.

In contrast, price volatility was even higher in the summer, while the winter was more like the historical price curve, because less renewable energy was in the system (generally due to unfavourable weather). As a note, all the results analysed at seasonal level were based on a table with the same format as Table 2, but only the prices for the months of each season (summer and winter) were used.

At the warm season level and time of day (Peak and Off-peak), the impact of renewable generation was +/-17%, and the most extreme price changes were observed in the same hourly intervals: 1pm and 8pm. During the warm season, the mid-day price decreased by 42% on average, and in the evening it increased by 40%. This resulted in a price volatility of 80% between the lowest and highest daytime price, with the price going from the cheapest to the most expensive time slot in just seven hours.

During winter, however, the lowest price volatility could be observed, 28% between the cheapest and most expensive time of day, with 1pm being 21% lower and 8pm 7% higher, compared to hourly prices in 2015. The average recorded price variation between Peak and Off-peak was +/-6%.

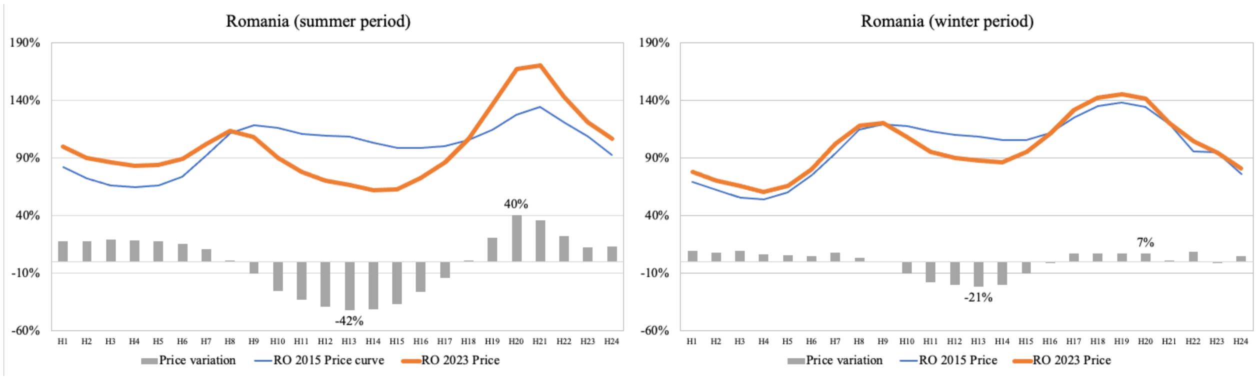


Figure 4. Warm and cold seasons analysis on spot market price curves in Romania during an average day in 2015 and 2023 and price variation between years

Source: Authors' own research.

The resulting data looks similar in Germany. Table 3 (available in the Appendix) contains the average hourly prices calculated on an annual basis for the reference years 2015 and 2023, and the price curve profile calculated as coefficients using the average hourly price divided by the average daily price during a year. The mathematical formulas used to calculate each value in the table are mentioned in the methodology chapter of this paper and they were applied to the prices of this country.

In Germany, at the daytime period level (Peak and Off-peak), in the case of the annual analysis, the increase in renewable energy capacity and solar power generation brought an impact of 10.6% on average compared to the Peak and Off-peak prices in 2015, i.e. the price value decreased in the daytime hours and increased in the same proportion in the nighttime hours. At the hourly level, the differences are even greater, so that the most impacted hourly interval in Peak is 2pm (13:00-14:00), where a -21% price impact was seen compared to the same hourly interval in 2015, as well as in 9pm (20:00-21:00 interval) in Off-peak, where a +13% price impact was seen. This made the price volatility (difference between the lowest and highest price) 34%, lower than in Romania (54%), but maintaining the difference between the hour with the lowest price (i.e. the cheapest MWh) and the hour with the highest price (i.e. the most expensive MWh) the same of only seven hours.

One explanation why this difference was smaller in Germany than in Romania is that Germany has an extremely large wind power capacity and because of this the energy produced is better fed into the system. By comparison, even though the ratio of wind to solar is similar in Romania, solar has a greater impact, including from a geographical perspective (more efficient geographical location and better weather conditions). At the same time, Germany is the largest economy in the EU, and another reason could be that industry has absorbed the surplus solar production in the peak of the day, compared to Romania, where industry and its consumption have not grown in recent years.

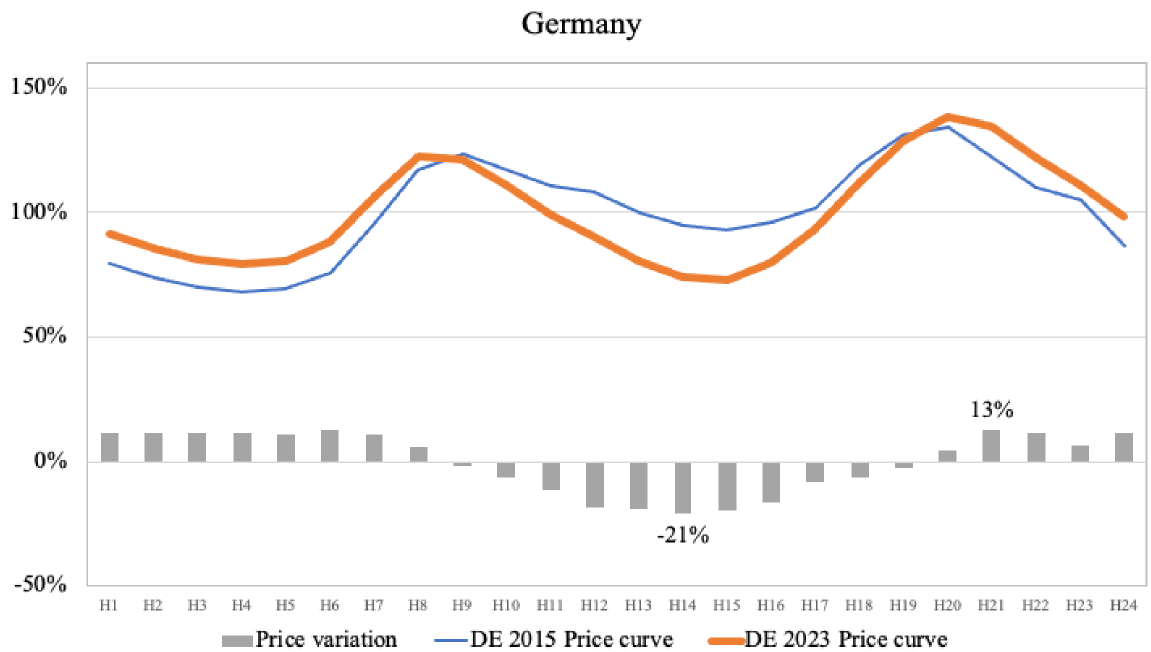


Figure 5. Full-year analysis on spot market price curves in Germany during an average day in 2015 and 2023 and price variation between years

Source: Authors' own research.

However, price volatility was higher in the summer, while the winter was more like the historical price curve - similar to the situation in Romania. At the warm season level and time of day (Peak and Off-peak), the impact of renewable generation was +/-16%, and the most extreme price changes were observed in the same hourly intervals: 2pm and 9pm. During the warm season, the mid-day price decreased by 32% on average, and in the evening it increased by 21%. This resulted in a price volatility of 53% between the lowest and highest daytime price, with the price going from the cheapest to the most expensive time slot in just seven hours (vs. 80% in Romania).

During winter, however, the lowest price volatility could be observed, 16% between the cheapest and most expensive time of day (vs. 28% in Romania), with 2pm being 11% lower and 9pm 5% higher, compared to hourly prices in 2015. And the average recorded price variation between Peak and Off-peak was the same as in Romania: +/-6%.

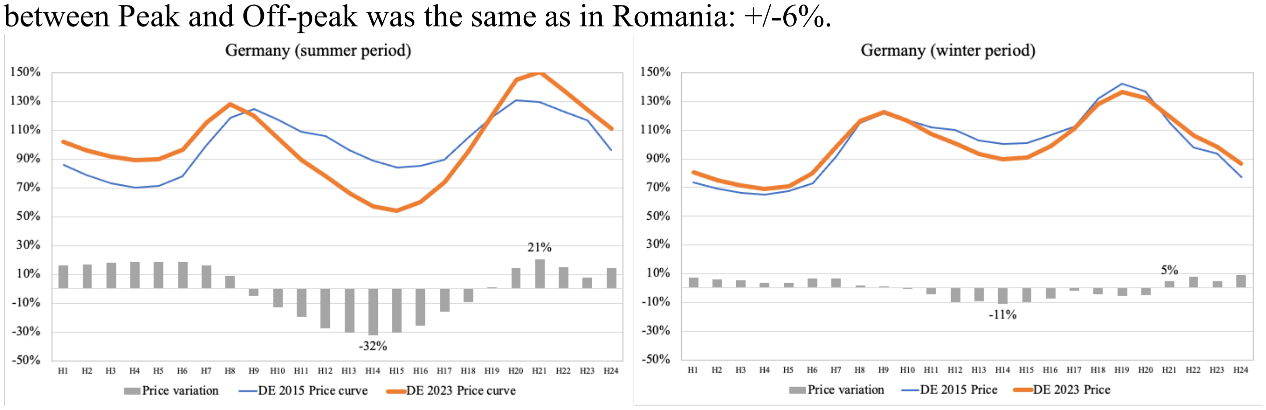


Figure 6. Warm and cold seasons analysis on spot market price curves in Germany during an average day in 2015 and 2023 and price variation between years

Source: Authors' own research.

The Netherlands is in a more extreme direction than the other two countries, the main reason being that solar energy production here is the most consistent in the energy mix (almost half of the energy mix contains only solar) and the PV installed capacity has increased considerably in the past nine years compared to other energy sources. In comparison, only about a quarter of the energy mix in Germany contains solar, while the energy mix in Romania contains about one fifth of the total. This was relevant for the impact that solar production has had on the price curve, especially between the warm and cold seasons. Table 4 (available in the Appendix) contains the average hourly prices calculated on an annual basis for the reference years 2015 and 2023, and the price curve profile calculated as coefficients using the average hourly price divided by the average daily price during a year. The mathematical formulas used to calculate each value in the table are mentioned in the methodology chapter of this paper and they were applied to the prices of this country.

As a result, in the Netherlands, at the daytime period level (Peak and Off-peak) and in the full-year analysis case, the increase in renewable energy capacity and solar power generation brought an impact of 12.4% on average compared to the Peak and Off-peak prices in 2015, i.e. the price value decreased in the daytime hours and increased in the same proportion in the nighttime hours. At the hourly level, the differences are even greater, so that the most impacted hourly interval in Peak is 2pm (13:00-14:00), where a -41% price impact was seen compared to the same hourly interval in 2015, as well as in 9pm (20:00-21:00 interval) in Off-peak, where a +26% price impact was seen (double that of Germany in both cases). This made the price volatility (difference between the lowest and highest price) 67%, by 13% higher than in Romania (54%) and by 33% higher than in Germany (34%), but maintaining the difference between the hour with the lowest price (i.e. the cheapest MWh) and the hour with the highest price (i.e. the most expensive MWh) the same of only seven hours.

The Netherlands is thus the perfect example where the Duck Curve problem is present. It is important to note that this phenomenon occurred on the basis of hourly data analysed over the whole year. The situation at season level is much more significant, and the problem was worse during the summer, when there was a lot of sun radiation and led to a high solar energy generation.

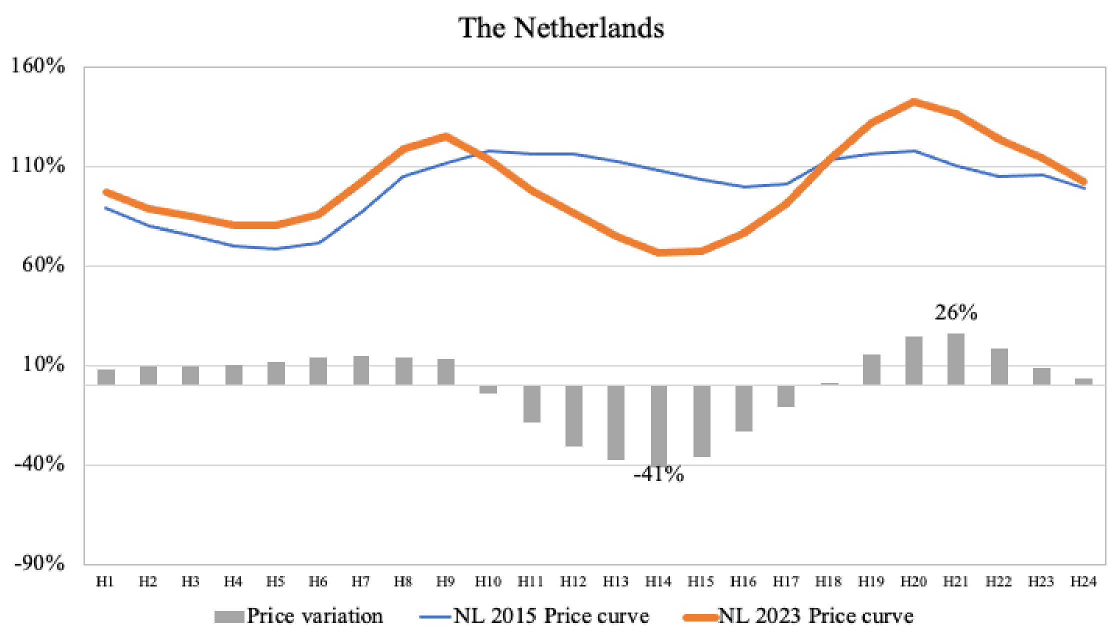


Figure 7. Full-year analysis on spot market price curves in the Netherlands during an average day in 2015 and 2023 and price variation between years

Source: Authors' own research.

The same as in Romania and in Germany and as already mentioned, price volatility was higher in the summer, while the winter was more like the historical price curve. This indicates that the major impact was given by photovoltaics. At the warm season level and time of day (Peak and Off-peak), the impact of renewable generation was +/-25%, and the most extreme price changes were observed in the same hourly intervals: 2pm and 9pm. During the warm season, the mid-day price decreased by 68% on average, and in the evening it increased by 44%. This resulted in a price volatility of 112% between the lowest and highest daytime price, which is very high, with the price going from the cheapest to the most expensive time slot in just seven hours (vs. 53% in Germany and 80% in Romania).

During winter, the mid-day price decreased by 17% on average, and in the evening it increased by 11%, marking just +/-2% price variation between Peak and Off-peak. In total, the price volatility was 28% between the cheapest and most expensive time of day (vs. 16% in Germany and the same as in Romania, 28%, but with different distribution of price impact between Peak and Off-peak: +/-2% in the Netherlands vs. +/-6% in Romania), compared to hourly prices in 2015.

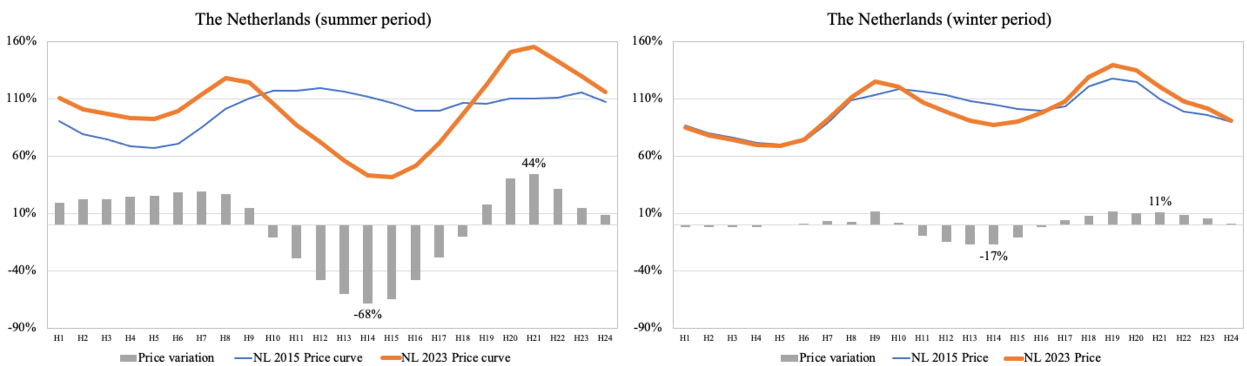


Figure 8. Warm and cold seasons analysis on spot market price curves in the Netherlands during an average day in 2015 and 2023 and price variation between years

Source: Authors' own research.

The same impact coming from large installed capacity of renewable assets was also analysed and confirmed in Thailand by the Department of Electrical Engineering from Chulalongkorn University, in Bangkok. In a study published in 2022 by Veeraya Imcharoenkul and Surachai Chaitusaney (Imcharoenkul & Chaitusaney, 2022, 12), the two researchers showed the relations between the average hourly marginal prices among multiple study cases and VRE penetration (Figure 9) and demonstrated that marginal prices can be very low in windy or sunny hours. According to them, prices are considerably lowered when VRE penetration exceeds 40% - a situation that is present and can also be seen in the analysis of Dutch prices, in the Netherlands, for example. During the day, when solar and wind energy accounted for the majority of the electricity demand, costs were largely lowered. According to a simulation made by the two authors in Thailand, CCGT generators had the greatest marginal cost in the system, therefore the marginal prices when little energy was supplied by VRE were equal to the marginal cost of the CCGTs - which was approximately 53 USD/MWh in their simulation. However, the price curve would fluctuate more and the prices would be more volatile and would be high during peak load and low VRE time if gas turbines or other generators, like coal, with market costs greater than CCGTs were included in the energy market. This shows how much pressure the power transmission systems have to withstand to cope with these power fluctuations and keep the system safe.

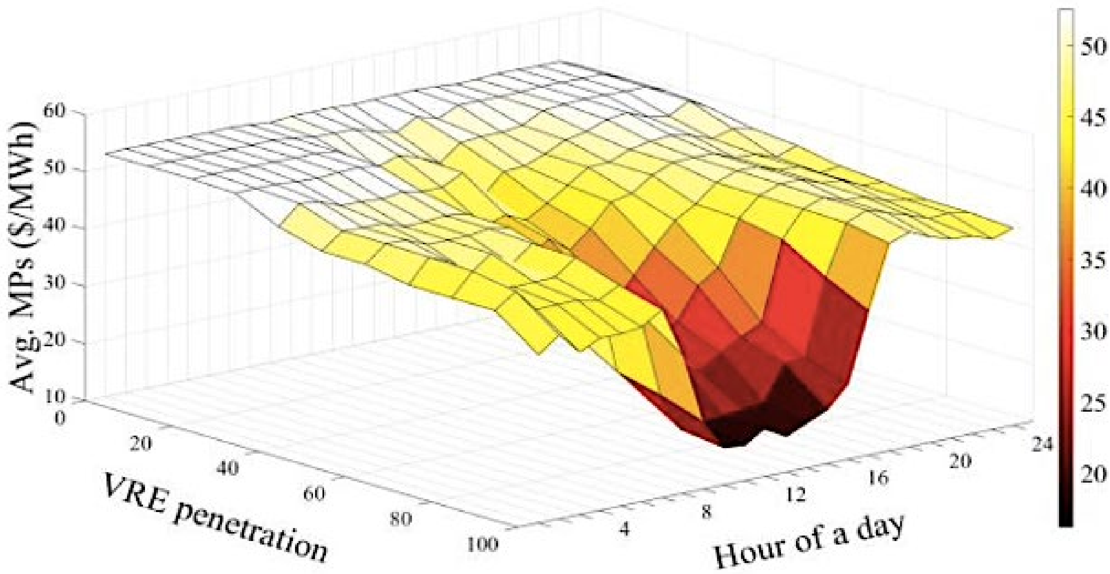


Figure 9. Relations between the average hourly marginal prices (MPs) and VRE penetration
Source: Imcharoenkul & Chaitusaney, 2022.

It should be noted that other analyses on this topic have been carried out in recent years, one of them being a study which analysed the impact of renewable energy generation on the spot market price in Germany, published in "The Energy Journal" of the International Association for Energy Economics in 2020 (Keeley et al., 2020). The results support and confirm the same impact in lowering Day-Ahead Market prices on peak consumption due to the intermittency of renewables.

We can expect this impact of price volatility to increase further in the coming years, given the plans to increase global renewable energy capacity. (IEA, 2023) At the same time, as a result, we can also expect and anticipate that if the EU's renewable energy goals are mirrored worldwide, power prices will be notably impacted.

Options for gradual phase-out of conventional assets

There are several options to an energy system free of fossil fuels, but these options also have obstacles or not all are feasible. Nuclear power, for instance, is a low-carbon energy source, but it also carries a significant risk of accident - as evidenced by the disasters at Fukushima, Chernobyl and Three Mile Island, which have left a lasting impression on society. Furthermore, many nations still lack nuclear storage facilities that are suitable for the future since the problems surrounding the storage of radioactive waste are sensitive political issues. (Carrington, 2018) RES are predicted to play a transformative role in displacing the use of fossil fuels, even even though the same sources (like solar, wind, hydro and marine power) have questioned the role that renewables can play in meeting the overall energy requirements, partly because of their intermittency and partly because of the size of investment required, these sources are predicted to play a transformative role in dispelling the use of fossil fuels. (MacKay, 2008) Thus, increased energy efficiency is expected to lower the amount of fossil fuels used, as seen by the adoption of low-power lighting and better white goods regulations, i.e. adopted by the EU. (European Commission, 2023)

According to the Energy Transitions Commission (ETC), a global coalition of leaders from across the energy landscape committed to achieving net-zero emissions by mid-century, any realistic plans to keep global warming to 1.5°C or far below 2°C will need to drastically cut back on the use of fossil fuels because recent developments in the energy sector and attempts to reduce emissions have not had the expected result. Also, according to the same source, 67% of coal and 46% of gas are used in the production of electricity, which is responsible for most of the global GHG. Furthermore, there will be a rise in the demand for electricity as a result of the decarbonisation of the energy-using sectors, such as through electrifying industrial processes. The first step towards creating a net-zero emissions economy is decarbonising the world's electricity networks and generation and in this respect there is a growing demand for a gradual phase-out of conventional assets. (The Energy Transitions Commission, 2022)

Recent studies show that electricity generation can now be decarbonised faster and cheaper than it was expected ten years ago, and this could be possible because of two factors: the decreasing cost of producing green energy and development of electricity transmission networks to support increased intermittency. During the past years, there have been significant drops in the cost of producing wind and solar power, making renewable electricity economically competitive with fossil fuel generation in the majority of places. At the same time, there is an increasing realisation that balancing the power grids and the demand in the system with significantly higher proportions of intermittent generation is more achievable now than 10-15 years ago - as much as 75 to 90%. This is a reflection of the falling costs of batteries and the impending reductions in the cost of producing green hydrogen, as well as the growing comprehension of the capacity to balance systems with thermal dispatchable plants operating for a certain number of hours annually. (Pamfile, 2023; Ocenic & Tanțău, 2023)

In a paper published by Julien Blondeau and Jan Mertens in 2019, the authors noted that renewable energy sources, such as wind and solar power, are intermittent due to the variability of natural elements that drive their energy production. This means that wind speed and sunlight are not constant and can fluctuate throughout the day and across different seasons and, as a result, the output of renewable energy systems is not consistent and can experience sudden changes, leading to intermittency in energy generation. This variability poses challenges for integrating renewable energy into power systems, as it requires additional measures to ensure grid stability and reliability during periods of fluctuating energy production. However, on the other hand, "the growing share of intermittent renewable energy sources in electricity production allows for a significant reduction of the emissions of CO2 and other pollutants from conventional, thermal power plants." (Blondeau & Mertens, 2019)

About 55% of the world's current electricity generation is produced in China, the United States and the EU. But other significant developing nations, like Indonesia and India, are expected to play an increasingly significant role in the near future as the demand for electricity will rise in tandem with their economic growth. (Bloomberg Finance L.P., 2024) Consequently, these large nations' transitions to net-zero energy industry will take significantly different forms. For example, the US and the EU are already committed to achieving almost zero emission power systems by 2035 and have made significant progress in lowering their usage of coal. They are also in a good position to do it. At the same time, although China is a leader in the installation of renewable energy sources, it uses a lot of coal and gas to produce its electricity. In a report published in 2022 by ETC, scenarios for this country point to a much slower reduction in emissions and polluting sources: only a 17% decrease in thermal coal power generation by 2030. (The Energy Transitions Commission, 2022)

On a different note, projections of the overall scale of carbon capture in power systems have been drastically reduced, even if carbon capture systems (CCS) applied to flexible thermal plants may still play a considerable role in power systems. Additionally, the most recent analysis predicts a modest role for baseload thermal generation plus CCS (as can be seen in the forecast data in Figure 10). The goal of decarbonisation is therefore becoming more and more evident throughout the majority of the world, with wind and solar playing a prominent role, along with hydro where resources allow, nuclear power potentially playing a role, and some type of thermal dispatchable plant that uses CCS to burn gas or hydrogen, ETC noted.

Figure 10 shows a forecast of the sources of electricity produced up to 2050, i.e. what the generation energy mix will look like in 2030, 2040 and 2050, in terms of power generation expressed in TWh. These forecasts are also presented from two scenarios: ACF (Ambitious but Clearly Feasible scenario) and PBS (Possible but Stretching scenario). The ACF scenario is economically and technically possible, but it will need stronger policy support than what is already in place in some areas. Also, it would be largely compatible with keeping global warming below 2°C if significant carbon reductions were also implemented, but it would not result in a 1.5°C limit. In parallel, the PBS scenario is technically and financially possible, but it would require a major reinforcement of present commitments and policies. When coupled with substantial carbon reduction technologies, this scenario would almost guarantee a 50% success rate of keeping global warming to 1.5°C by the year 2100. As a short note, in the figure below it can be seen that energy produced from gas and coal will not be able to be reduced to zero, for multiple reasons, but will still be able to exist in combination with various emission reduction methods, such as CCS.

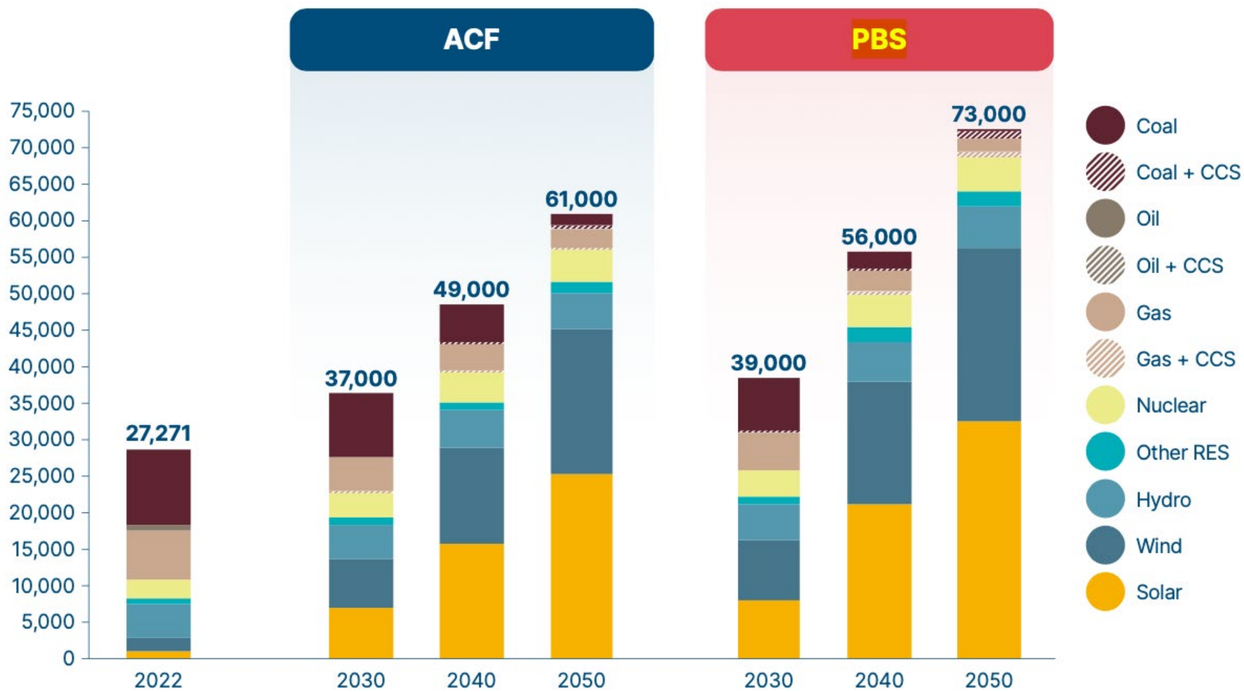


Figure 10. Global power generation by source in ACF and PBS scenarios

Source: The Energy Transitions Commission, 2022.

The most common question in most of the studies and research is how quickly the target of reducing fossil energy production and switching to renewables can be achieved. Given the differences in the rate of growth in the demand for electricity, the installed generation capacity, the availability and speed of wind, solar radiation and hydro resources, and the willingness and ability of each country to absorb additional costs during the early phases of renewable deployment, this will differ significantly across countries. Because of this, this question still remains a dilemma or without a definite answer. In addition, the last few years have brought multiple global crises to the forefront, diverting or even forcing people's attention towards other crises. In the case of the energy sector, there are many aspects that are linked to each other when it comes to a gradual phase-out of conventional assets and which, unfortunately, still cannot be treated individually, but as a whole.

Apart from the impact of VRE generation plants on the electricity price curve, there are also issues that relate to the physical side of the electrical system, as renewable units also impact the operation of the transmission and distribution grids. From this point of view, it is hard to believe, even among specialists in the field, that an energy system without conventional production units could exist, at least based on existing technology. The main reason is a practical one, the main argument being that the energy system must have a safety net when renewable energy sources do not exist in nature. In order to continue to meet the consumption needs of the population and industry, especially at peak consumption, there must be conventional units to provide electricity generation when there is no wind, no sun or not enough water in rivers or reservoirs for hydro plants. Thus, the most commonly mentioned types of units are nuclear and gas-fired, but for economic, social and political reasons coal-fired plants as well (at least for another 10-15 years).

As an option to support a gradual phase-out of conventional assets, power systems are becoming more and more interested in using new energy storage technologies, in addition to the simple idea of moving away from fossil fuels. The main reason is because of their inflexibilities, solar, wind, marine and hydropower asset's production is dependent on weather patterns. According to existing research, it is highly improbable that the power produced by solar panels would match the final energy needs as the electricity is directly correlated with the temperature and irradiance of the solar panels or other similar collectors. For instance, a passive cloud may instantly cut a huge solar plant's production by more than 90%. Additionally, solar energy output is impacted by days of continuous bad weather, which happens all around the world. Similar vulnerabilities affect wind farms, which frequently see rapid increases in output during storms, followed by drops in output during the alleged "calm after the storm." (Wood & Baker, 2020, 569-570) Therefore, energy storage is important in systems where RES are the dominant energy source since it helps maintain power during blackouts and reduces abrupt output swings during storms, passing clouds, or other events unfavourable to green energy generation. (Pamfile, 2023, 42)

If we look at the evolution of the energy mix in the three European countries analysed in this paper, Romania, Germany and the Netherlands, it can be seen that the installed electricity generation capacity has changed significantly over the last nine years (over the same analysed period, 2015-2023). A first trend that can be seen is that renewable energy capacities increased in all countries - something that happened all over the EU. (Eurostat, 2024) It is important to mention that in the data analysis, only solar and wind generation capacities were taken into account and other VRE sources such as hydro or biomass were excluded. Among the reasons for their exclusion is the fact that these energy sources do not show a high intermittency like wind and solar units, thus not changing the electricity price curve, but only its value (which is normal, since each generation unit has a certain production and sales cost and the spot market works on the basis of the marginal price). They are also easier for dispatchers to control and so do not show as much instability in the transmission system or grids as solar and wind generation units. Moreover, because power generation units like hydro ones are much more difficult to install and build, the largest increases in new capacity installed in recent decades have been PV and wind units.

In Figure 11, according to official data, Romania had a total installed wind and solar capacity of 5,642 MW at the end of 2023 (34% of total national installed capacity), which was 41%

higher than its 2015 capacity of 3,997 MW. This capacity was made up of 2,957 MW wind and 2,685 MW solar - 1,185 MW PV parks and 1,500 MW PV panels installed by prosumers on rooftops nationwide. (ENTSO-E, 2024; ANRE, 2023; Petrescu, 2023) The significant aspect is that all the increase in renewable capacity is due to photovoltaics, as wind power was only 2% higher in 2023 compared to 2015 (onshore only).

As far as prosumers are concerned, Romania is a country with a more special situation, because this trend where ordinary consumers have started to install photovoltaic panels is a recent one. Until 2021 there was no monitoring of them because their number and installed power was insignificant. However, there was a significant rise in PV panels installed on roofs starting in 2022 and the primary drivers were the high cost of electricity, introducing state subsidies to promote this, and the desire of consumers to reduce their energy bills and to increase their energy efficiency. As an indirect side-effect, this has also triggered an accelerated process of energy transition in the country, according to studies. (Pamfile & Proșcanu, 2024) The number of prosumers increased from 13,109 at the end of 2021, with an installed capacity of 84 MW, to an estimated 110,000 prosumers and 1,500 MW of capacity by the end of 2023 (similar to nuclear power in terms of capacity, but with an operating efficiency of about 20% compared to 90% for reactors). From an operational efficiency point of view, this greatly destabilised the electricity transmission networks and has led to increasing balancing prices and imbalances in the national power system over the last two years.

On the other hand, fossil coal and gas-based energy fell by 57% over the same nine-year period: from 10,733 MW in 2015 to just 4,661 MW in 2023. This was due to several factors: the ageing of conventional generation units and their decommissioning, the correction of the total installed capacity by the regulatory authority after it was found that in reality there was no longer so much available, and the last reason was also due to policies to close down fossil-fuel power generation units (although public policy was not necessarily very clear on this).

As the note, nuclear generation capacity was included in the graphic because it is seen as a source of energy transition but also because it helps maintain the stability of the transmission system - delivering almost all the time Baseload power into the system. Also, at the same time, a relevant aspect in the case of Romania is the fact that although consumption has remained similar throughout this period, renewable energy capacity increased less than conventional energy capacity decrease. This shows that at the national level there has not been a policy of replacing polluting energy sources, but rather a result of the passage of time, without much state involvement (therefore not due to a clear desire to accelerate the energy transition process). Thus, in addition to increasing imbalances in the system, this has also contributed to the shift in the electricity price curve in the spot market, as demonstrated in the analysis in this paper. It can thus be said that there is not necessarily a clear policy for gradual phase-out of conventional assets in Romania which can lead to an even greater impact of renewables in the market and for other conventional power generation units, which represent a significant percentage of total national capacity (59%).

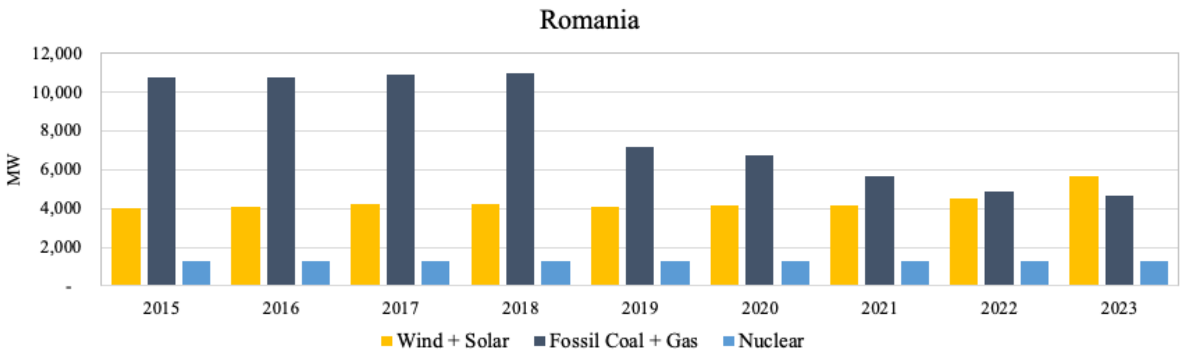


Figure 11. Installed generation capacity aggregated per production type in Romania between 2015 and 2023

Source: ENTSO-E Transparency Platform and authors' own research.

In the case of Germany, the official data are a bit different. Figure 12 shows that Germany had a total installed wind and solar capacity of 129,237 MW at the end of 2023, which was 64% higher than its 2015 capacity of 78,794 MW. RES energy covers 55% of the energy mix, which is significant. This capacity was made up of 65,871 MW wind and 63,366 MW PV parks. The impact of prosumers is also high in Germany, but there are no differentiated reports, so it is understandable that they are included in the total solar capacity.

Compared to Romania, both wind and solar energy sources have increased substantially in Germany: +67% solar energy in 2023 vs. 2015 and +61% wind energy in 2023 vs. 2015 (+45% onshore wind and +719% offshore wind). On the other hand, fossil coal and gas-based energy fell by 20% over the same nine-year period and nuclear energy by 66% for the past nine years.

In Germany, it can be observed that the percentages of increasing renewables and decreasing conventional sources were more balanced, which indicates a clear strategy on gradual phase-out of the conventional power assets, but while ensuring energy supply and system safety. However, as the price curve analysis shows, the impact of increasing renewable capacity is also significant in Germany - which has been noted more and more often in recent years by the German authorities, in various academic studies or industry research. This is because even though capacity from fossil sources was replaced (including nuclear power, recognised for its safety, including by other European countries) with similar or even greater capacity from renewables, RES intermittency made the system more unstable, bringing new challenges to all actors in the energy sector.

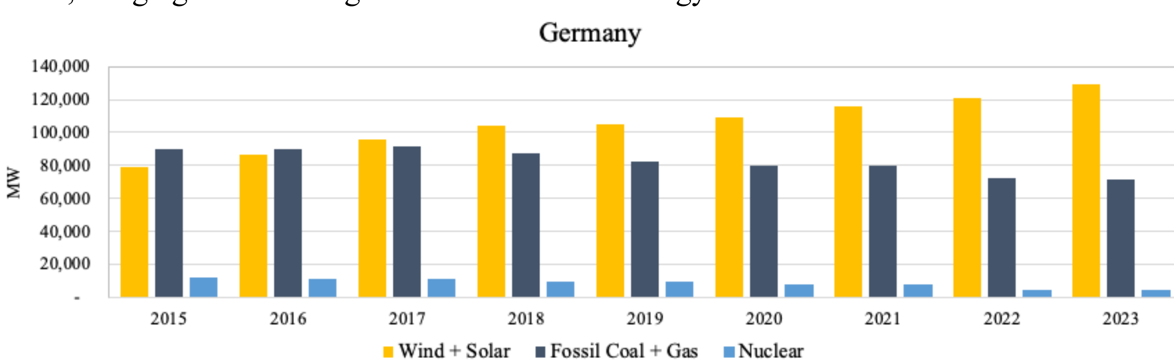


Figure 12. Installed generation capacity aggregated per production type in Germany between 2015 and 2023

Source: ENTSO-E Transparency Platform and authors' own research.

But one of the most spectacular changes in the energy mix and one of the biggest increases in renewable capacity could be seen in the Netherlands. Figure 13 shows how much solar and wind energy was added to the system in the last nine years, bringing many challenges. According to official data from ENTSO-E, the Netherlands had a total installed wind and solar capacity of 32,000 MW at the end of 2023, which was 726% higher than its 2015 capacity of 3,874 MW. RES energy covers 57% of the energy mix today, which is 45% higher compared to 2015 (when solar and wind power was only 12%). This capacity is made up of 9,410 MW wind and 22,590 MW PV parks - of which around 9,500 MW is installed capacity of prosumers, according to the National Bureau of Statistics. (CBS, 2023) The Netherlands thus has the largest installed solar power capacity in the whole EU area, which makes the country significant for the analysis in this paper.

Compared to Romania, both wind and solar energy sources have increased substantially in the Netherlands, however, the share of installed wind and solar capacity is huge compared to even Germany: +2,159% solar energy in 2023 vs. 2015 and +227% wind energy in 2023 vs. 2015 (+134% onshore wind and +1,312% offshore wind). In parallel, fossil coal and gas-based energy fell just by 17% over the same nine-year period, while nuclear energy almost stayed the same, constant (only 1% decrease).

It can thus be seen that Dutch policies have mainly promoted solar energy compared to other sources in the past years. At the same time, there was also a policy of phasing out conventional generation units, but these were turned back in 2021 with the onset of the energy crisis - and maintained consistently ever since in order to maintain stability in the energy system, heavily impacted by the increased intermittency of renewables. As mentioned, renewable energy in the Netherlands provides today the largest percentage of electricity demand. On the one hand, this is highly appreciated in terms of meeting the energy transition targets, but on the other hand, this has led to a high instability of the electricity transmission system, as well as to the existence of very high volatility of energy prices - including the existence of many hours when the price is negative, greatly destabilising the income of energy producers.

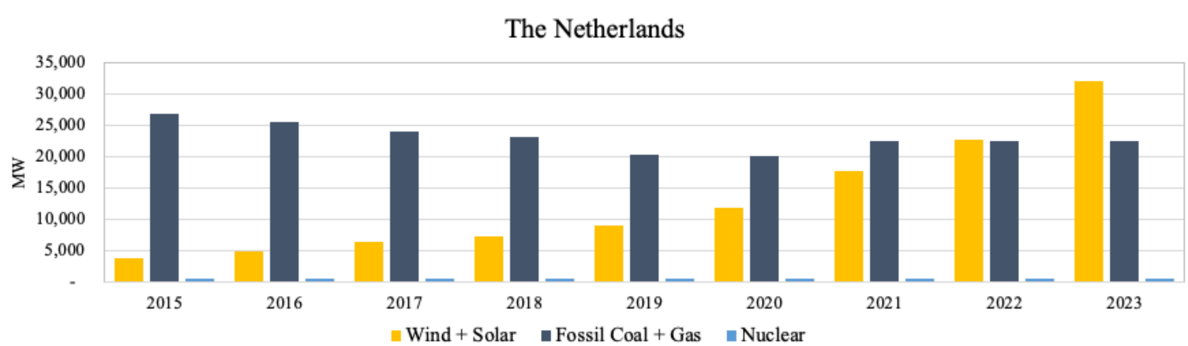


Figure 13. Installed generation capacity aggregated per production type in the Netherlands between 2015 and 2023

Source: ENTSO-E Transparency Platform and authors' own research.

In order to verify whether a coherent policy of a gradual phase-out of conventional assets was in place in the three countries analysed in this paper, the simplest method identified was to calculate that the evolution of installed capacity of renewable energy (wind and solar) has occurred in tandem with the decrease of installed capacity of conventional energy (such as coal, gas and nuclear), especially the polluting ones. Only these types of energy were chosen because they represent the largest part of the energy mix and are the most significant (all data are presented in tables 5, 6 and 7 in the Appendix of this paper).

In this regard, a Pearson correlation was performed to determine if there was a correlation between the variables, for each country (mentioned in the analysis with short names: RO - Romania, DE - Germany and NL - the Netherlands) over the last 9 years (number which was the valid cases in the correlation). The main variables taken into account were *Wind + Solar installed capacity*, *Fossil coal + Gas installed capacity* and *Nuclear installed capacity*. The correlation coefficient (r) and p-value (p) resulted from the correlation analysis showing whether there was a link between variables. In the analyses, the null hypothesis was that there was no correlation between the two variables (e.g. between the evolution of installed wind and solar capacities and fossil coal and gas capacities), while the alternative hypothesis was that there was a correlation between the variables.

Table 1. Pearson correlation analysis results

Variables	r	p
RO Wind + Solar installed capacity and RO Fossil coal + Gas installed capacity	-0.59	.094
RO Wind + Solar installed capacity and RO Nuclear installed capacity	0.34	.378
RO Fossil coal + Gas installed capacity and RO Nuclear installed capacity	-0.56	.12
DE Wind + Solar installed capacity and DE Fossil coal + Gas installed capacity	-0.91	.001
DE Wind + Solar installed capacity and DE Nuclear installed capacity	-0.93	<.001
DE Fossil coal + Gas installed capacity and DE Nuclear installed capacity	0.96	<.001
NL Wind + Solar installed capacity and NL Fossil coal + Gas installed capacity	-0.4	.291
NL Wind + Solar installed capacity and NL Nuclear installed capacity	-0.36	.346
NL Fossil coal + Gas installed capacity and NL Nuclear installed capacity	0.7	.035

Source: aDATAtab, 2024.

According to Pearson correlations conducted, only in Germany there is a coherent policy of a gradual phase-out of conventional assets in place, as the results showed that there is a significant correlation between the renewable installed capacity (*DE Wind + Solar installed capacity*) and conventional installed capacity: $p = .001$, $r = -0.91$ in case of *DE Fossil coal + Gas installed capacity* and $r = -0.93$ in case of *DE Nuclear installed capacity*. The coefficients -0.91 and -0.93 suggests a very high, negative correlation. This means that, generally, as *DE Wind + Solar installed capacity* increases, *DE Fossil coal + Gas installed capacity* and *DE Nuclear installed capacity* tends to decrease. Also, the p-value of <.001 is less than 0.05, which suggests that the correlations observed (*r*) are unlikely to be due to chance. Therefore, there is definitely a statistically significant relationship between the growth of renewables and the phase-out of conventional units. In addition, the coefficient 0.96 suggests a very high, positive correlation that, generally, as *DE Fossil coal + Gas installed capacity* decreases, *DE Nuclear installed capacity* also tends to decrease, and this pattern is unlikely to be a result of random chance, confirming once again that energy policies in Germany are interrelated.

On the other hand, although there was an increase in installed renewable energy capacity in Romania and the Netherlands, the policy of phasing out conventional assets seems to have either not been very well planned or the growth of renewables has gotten out of control, penetrating too much the market. The result of the Pearson correlation showed that there was no significant correlation between the renewable installed capacity (*Wind + Solar installed capacity*) and conventional installed capacity in both Romania and the Netherlands. However, this may also mean that the data analysed were not sufficient and a more detailed analysis is needed.

For Romania, r = -0.59 and p = .094 in the case of *RO Fossil coal + Gas installed capacity* and r = 0.34 and p = .378 in case of *RO Nuclear installed capacity*. While nuclear capacity remained constant over the years, there is no statistically significant relationship between *RO Wind + Solar installed capacity* and *RO Fossil coal + Gas installed capacity* either. The p-value of .094, which is greater than 0.05, suggests that the correlation observed (r = -0.59) is likely to be due to chance. But the only link between variables may be that the value of the correlation coefficient (-0.59), which indicates the strength and direction of the linear relationship between *RO Wind + Solar installed capacity* and *RO Fossil coal + Gas installed capacity*, suggests a high, negative correlation. This means that, generally, as *RO Wind + Solar installed capacity* increases, *RO Fossil coal + Gas installed capacity* tends to decrease.

For the Netherlands, r = -0.4 and p = .291 in the case of *NL Fossil coal + Gas installed capacity* and r = -0.36 and p = .346 in case of *NL Nuclear installed capacity*. Nuclear capacity remained constant over the years as well and there is no statistically significant relationship between *NL Wind + Solar installed capacity* and *NL Fossil coal + Gas installed capacity* either. The p-value of .291, which is greater than 0.05, suggests that the correlation observed (r = -0.4) is likely to be due to chance. However, the value of the correlation coefficient (-0.4), which indicates the strength and direction of the linear relationship between *NL Wind + Solar installed capacity* and *NL Fossil coal + Gas installed capacity*, suggests a moderate, negative correlation, which is better than in Romania, meaning that, generally, as *NL Wind + Solar installed capacity* increases, *NL Fossil coal + Gas installed capacity* tends to decrease.

In other words, the conclusion drawn earlier in this paper underlines the fact that in Romania there was no feasible policy, but changes in the energy system happened out of inertia without much state intervention - which is also confirmed in this correlation. At the same time, in the case of the Netherlands, there was more a policy of massively increasing solar energy capacity and less a policy of phasing out conventional assets. But because changes were not done in parallel or at a similar pace, the impact of RES assets was reflected in the market price curves anyway.

Development of commercial optimisation of production assets

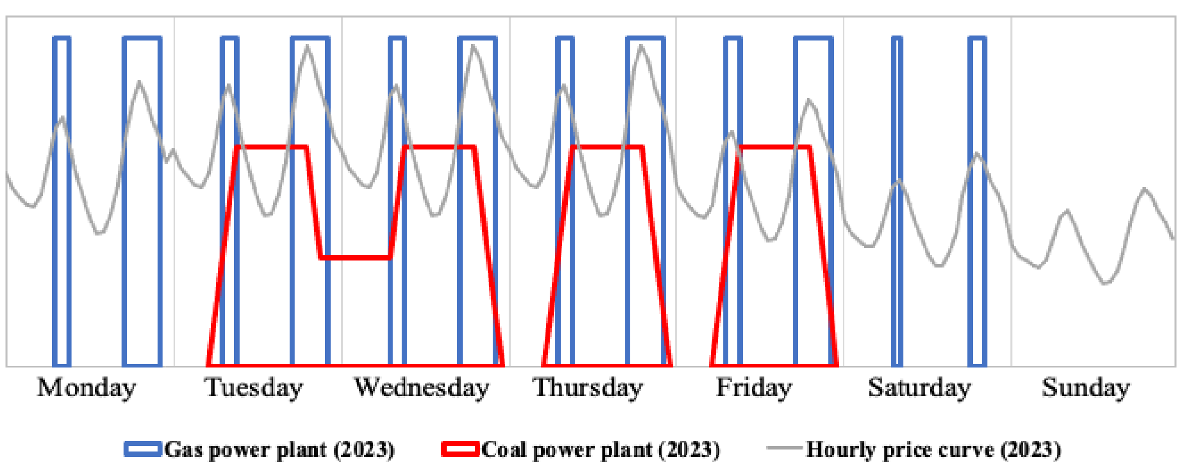
In this new context of the energy system, running a conventional asset has become increasingly complicated and the revenues are increasingly affected. Managing this type of asset usually involves supervising and maximising the performance of conventional thermal power plants, such those powered by coal, natural gas and oil, and this includes taking care of constraints like respecting minimum and maximum generation levels, following specific ramp-up and ramp-down production profiles and different start-up times, in addition to guaranteeing the effective and dependable generation of power. Furthermore, managing conventional assets can entail setting control mechanisms in place to maintain frequency control and grid stability, particularly in light of the growing integration of RES. An effective energy management of conventional assets is essential for maintaining supply and demand balance and tackling the difficulties presented by intermittent renewable energy production. (Blondeau & Mertens, 2019)

But the timeframe in which they can operate became shorter, to keep them in the money. (EEX) As a side effect of including more renewable energy capacity in the system, conventional power plants must deal with a discernible increase in the number of start-ups and rapid load restarts in order to ensure a backup for the system. During such periods, the units' performance in terms of thermal efficiency and pollutant emissions declines, which might lead to a loss in the as-yet-unquantified environmental advantages of renewable energy sources, according to specialists. Therefore, not only do the transmission system and grids need to be more flexible and efficient to cope with the intermittency of renewables, but also conventional units are becoming more strained and have to cope with more frequent and shorter start-ups, thus emitting more GHG emissions than if they were kept on for a longer period of time. In addition, because conventional thermal plants operate less yet produce higher specific emissions, it is thus not possible to compute the emissions reductions brought by the intermittent RES as a straightforward linear function of their market penetration factor.

During the previous decade, many gas-fired CCGTs in Europe were converted into peak units due to their low merit order and great load flexibility, despite their initial design for base load operation. (Van Nuffel et al., 2017) As a result, their annual running hours were drastically reduced, while the number of start-ups, shut-downs and fast load transients increased significantly. While fewer operational hours obviously result in lower pollutant emissions, the greater incidence of transient phases may offset this benefit by raising the specific emissions of these plants, i.e. the emissions per unit of energy produced. During start-ups, shut-downs and fast transients, the performance of gas and coal units in terms of pollutant emissions and efficiency is reduced.

Considering the above mentioned information, as well as the analysis of the impact of renewables on the price curve and the phasing out of conventional units from the system, conventional units end up running less time and having higher costs, thus affecting their commercial optimisation. In addition, these units have to pay extra costs because they emit carbon emissions, which add to the already high cost of the resource they need to operate (gas, coal). Therefore, today, on days when spot market prices are high enough to cover the costs of these conventional power plants, a simulated production profile would look like Figure 14 below (*Hourly price curve*).

According to the price analysis over the last nine years, the highest prices occur in the mornings and evenings, while prices tend to be lower in the middle of the day (due to the intermittency of renewables), night hours and weekends - when electricity demand is lower and generation must follow the falling demand.



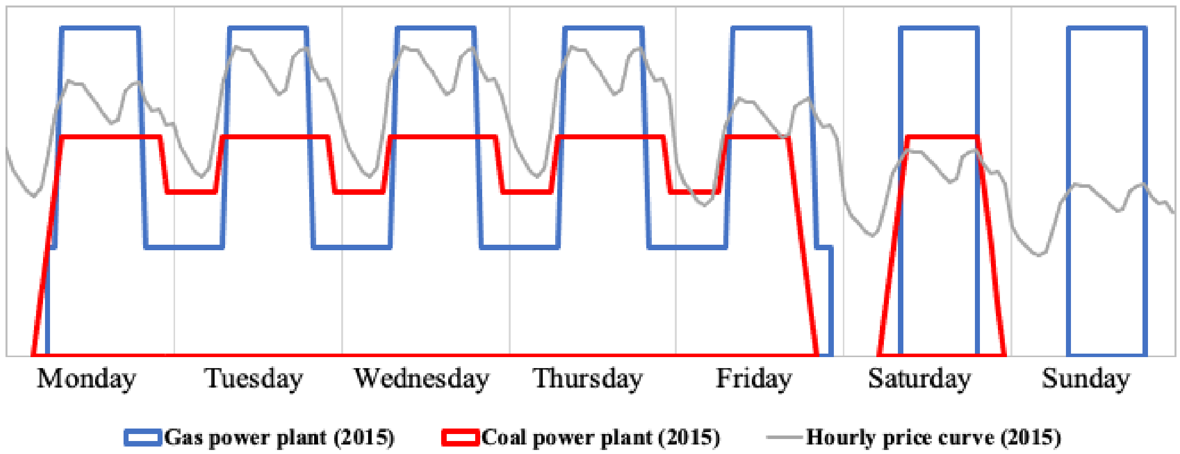


Figure 13. Simulation of the runtime of conventional gas and coal power plants in an average week of 2023 compared to 2015

Source: Authors' own research.

In the simulation, the price curve calculation was described in the methodology chapter and in the sub-chapter "Large installed capacity of renewable assets impact", in the full-year analysis of the Netherlands. As it was calculated on the basis of average prices, in reality, the situation for conventional generation units could be much different, as there are both days when renewable resources (wind and sun) are scarce or almost non-existent, but also days when RES energy is very high and prices fall extremely. Thus, while in 2015 there were even periods of uninterrupted operation for conventional units, today they have to cope with extreme volatility and stop and start again much more frequently than in the past. (Blondeau & Mertens, 2019)

As a note, although nuclear power plants are also part of the category of conventional power generation units, they have been excluded from this study because they still do not show a change in system uptime. Because their technical operation involves greater complexity and risks, they are still considered a priority in the system and are not affected by the intermittency of renewables, remaining constantly on. Also, in times where very low prices are recorded in the market, they are commercially optimised by reducing the power delivered to the grid.

For the rest of the conventional power plants, mostly gas and coal, one solution that would help them remain profitable would be for them to be offered as auxiliary reserve or to be used for system backup units by the transmission system operators. This would mean that the units would have to supply and produce baseload power - a profile for which they work very well - for the whole period of a day, for example, helping both the power system and the investors and owners of these units. However, this would still require the price offered by the transmission operator to be high enough to cover the cost of the assets. If not, the situation would be exactly the same as in the spot market. And one problem for these conventional assets, which has emerged in recent years, is that large renewable energy units have also begun to enter this part of the energy market and offer these services, making conventional units uncompetitive for this activity as well.

As a result, concerns about the commercial viability of more flexible generation technologies in systems with a high level of renewable energy have increasingly appeared in the industry and academia. There are concerns about the fate of baseload generation, particularly regarding reliability risks posed by conventional plant phase-out, extend beyond private interests, especially in regions where nuclear capacity retirements have occurred and it is planned that they will be replaced by VRE power plants. (Bushnell & Novan, 2021, 24)

So the main concern also comes when we talk about the safety of the energy system, as already mentioned in this paper. The output of renewable units is unpredictable and to cope with a high demand for energy, the electricity system and the grids need as many flexible units as possible. Some gas fired thermal units could cope, but this would still forge them over time more quickly. And hence the need, in recent years, for energy storage units to operate in tandem with renewable and conventional units and keep the system running smoothly. However, these storage systems are still expensive and still in a development phase, research and studies are still being done to find the most viable solution to be integrated into the system, and investors have not yet shown much interest in them. (Pamfile, 2023)

In another note, another concern is regarding the wholesale power markets, for which it is not yet certain how it will accommodate large volumes of renewable capacity and adequately reward energy sources that provide essential services for maintaining reliable operations. Over the last few decades, various optimisation techniques have been used for demand management, power loss minimization and optimal economic dispatch of energy loads. They could be adjusted to work with multiple types of assets at the same time, thus maintaining stability both for the system and commercially for the assets. The influence of integrating VRE sources with energy storage devices in Micro-grid operations under the deregulated electricity market is becoming a hot topic these days. (Chakraborty et al., 2023) Due to the intermittent nature of renewables, accurate load forecasting in the spot/day-ahead energy market is difficult. Moreover, energy demand has recently taken on an exponential shape over the world, and this trend is projected to continue. (IEA, 2023) In this regard, studies show that the introduction of a microgrid powered by renewable energy sources will play a significant role in satisfying rising demand, but they can also help conventional asset management. Microgrids may deliver both controllable and uncontrollable loads in remote places (particularly for small or medium-sized distribution networks) and their operation can improve reliability, ancillary services, power quality, as well as reduce environmental emission loss and operating costs. (Gomes et al., 2021)

Another commercial optimization process of production assets could be done through an innovative solution to address the weather-driven intermittency of VRE assets, proposed in a recent study by Johnathon C., Agalgaonkar A. P., Planiden C. and Kennedy J. (2023). In their study, the researchers introduce financial instruments in the form of hedge contracts in order to create a hedge market alongside the day-ahead energy market. By settling the hedge contracts before participating in the day-ahead market, VRE operators gain increased confidence in their bids. Simulation studies corroborated the theoretical findings, revealing enhanced profits for both VRE operators and flexible conventional generators (like CCGTs and hydro power producers). These positive results serve as investment signals for renewable and flexible generation technologies and they can also support the activity of the conventional units.

Conclusion

Given all the developments that have taken place over the last decade in the energy sector, it is very important to always keep track of all the consequences as well, bundled with all the benefits which are already being discussed in the public and academic space. In addition to the many opportunities widely researched and known regarding RES integration in the electricity grid, it is also relevant to mention that, in the opposite direction, a too high renewables penetration can discourage investments in the power generation side, while leading to a substantial increase in energy costs.

In the analyses made in this paper of the impact of significant investments in renewable energy technology on electricity prices, several key points were addressed. Traditional power advocates argue that policies favouring renewable energy have distorted their industry, while there are also recent studies suggesting that declines in natural resources prices (like coal and gas), rather than renewables, are primarily responsible for decreased power prices. However, this study, conducted on three European countries (Romania, Germany and the Netherlands, all with both similarities and differences in their energy mix) indicates that renewable investment has indeed significantly affected power prices and it appears to have driven the majority of mid-day hourly prices declines over the past nine years, putting pressure on the morning and evening peaks and leading to much higher price volatility. As a forecast for the coming years, if ambitious renewable energy goals are mirrored worldwide, hourly prices will be notably impacted, and with this change will also be affected the commercial operation of conventional power plants.

This paper, along with many other existing studies, confirm that baseload power is being penalised by renewable expansion, which supports the argument that this market does not require baseload generation. In contrast, the market requires flexible generation and market responses indicate that this value is, at least substantially, if not entirely, represented in prices. (California ISO, 2016) And so another perspective concerns the capability of current wholesale power markets to accommodate large volumes of renewable capacity and adequately reward energy sources that provide essential services for maintaining reliable operations. Concerns about the fate of baseload generation, particularly regarding reliability risks posed by conventional power plant phase-out, extend beyond private interests, especially in regions where nuclear capacity retirements have occurred. There are apprehensions about the commercial viability of more flexible generation technologies in high-renewable systems.

The findings of this paper thus offers another perspective on the energy transition. While it's true that conventional power generation assets produce GHG emissions that are harmful to the environment, they are still needed to exist in the system for technical, rather than commercial, reasons, but more state support will be needed to ensure this. Commercially speaking, they face financial challenges, and renewable energy may contribute to this situation, however it's important to note that renewable investment is a consequence, rather than the cause, of these challenges. Furthermore, state and federal policies regarding the promotion of renewable energy strongly influence these dynamics. (Bushnell & Novan, 2021, 24)

Also, given the results of this paper, market operators' needs for risk management are evolving as a result of the energy mix's quick change and the rise of RES power plants. Moreover, this energy revolution is affecting market liquidity and impeding investments in environmentally friendly companies, because even if RES producers inject green energy into the system, they end up selling it at negative prices and although they make a sale, they actually pay a cost. Paradoxically, the reason why this happens is because of them, also mentioned in this paper. Therefore, the need for risk management tools available to green energy market participants has grown increasingly, according to studies, and the lack of them could prevent investment in green projects in the future. (Johnathon et al., 2023, 8)

The RES integration increased by RES penetration can thus become an economic barrier to develop other generation power plants in the future. Gas, coal and even other conventional assets (nuclear or hydro generators) cannot recover their costs due to this penetration. According to Imcharoenkul & Chaitusaney (2022), wind generators become unprofitable if they account for more than 60% of the total, while solar generators are profitable at all VRE penetration levels, however the profit declines when there is no efficient energy policy behind it whereby conventional units are phased out.

Therefore, support schemes for all types of power plants may be required, taking into account and prioritising the severity of indirect integration costs for each technology as renewables adoption increases. However, because the cost of support schemes is ultimately borne by customers, policymakers should strike a balance between the cost of support schemes and the value given by RES assets to the system in order to avoid passing on needless burdens to final customers. Furthermore, system designers and policymakers should think about ways to reduce the impact of VRE integration on overall system costs and energy generation revenue.

A limitation of this research is that only the impact on the price curve was addressed and not the price of electricity itself. This would require much more statistical analysis and in this sense this paper can be a starting point for more detailed research on price evolution. Also, the analysis was only done on three EU countries (Romania, Germany and the Netherlands), but perhaps a deeper analysis of other countries or even of other regions in the world would bring a better visibility on the impact of increased renewable capacities in the system, or of the phasing out of conventional power generation assets.

Another limitation is the fact that there has also been little mention of the impact on the energy market as well as the system and grids. There are many other aspects, especially technical ones, that have not been addressed and would help to better understand the subject addressed by this paper. In terms of energy production resources or even resources to build production units, another relevant aspect is where they come from and what the prices are. This is relevant because the power demand is forecasted to increase in the future, as well as the solar and wind power production to cover the new demand, but most of the resources needed for PV panels and other rare materials come from China, which is risky, warned IEA. (IEA, 2023) This is of particular interest from a geopolitical and strategic point of view, given the current tense political and economic situation globally.

Last but not least, another limitation of this research is the fact that it discusses the optimization of conventional energy production assets only from a business, commercial point of view, but it could have gone into more detail to address the technical side and could have proposed more strategies that can be applied to the energy management of these producers. Also, it did not address at all other units such as nuclear or hydro, also considered conventional. In addition, more simulation studies could be done to investigate the uptime of the various production units in order to find better strategies to keep them running. So this paper can also represent a basis for other academic and industrial research that could be started in this direction.

Managing power grid complexity is therefore challenging and this will become even more difficult in the future. The entire energy system costs, taking into account the different features of generators and determining the lowest-cost generation mix of available resources, is ultimately becoming the responsibility of the society. It is still debatable whether it is better for an energy mix to be based on renewable energy only or whether the whole system is better to be based on multiple sources, with both renewable and conventional sources. Thus, further research in this direction needs to be done.

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Appendix

Table 2. Full-year analysis on average hourly spot market prices in Romania in 2015 and 2023, price coefficients and variations between the two years

Hour type	Hour	Average prices in 2015	RO 2015 Price curve (coefficient)	Average prices in 2023	RO 2023 Price curve (coefficient)	Price variation (2023 vs. 2015)
Off-peak	H1	27.42	0.753743	91.70	0.883959	13%
Off-peak	H2	24.54	0.674675	82.59	0.796115	12%
Off-peak	H3	22.23	0.610969	77.89	0.750855	14%
Off-peak	H4	21.57	0.592917	73.85	0.711856	12%
Off-peak	H5	22.96	0.631030	77.04	0.742572	11%
Off-peak	H6	27.27	0.749626	87.95	0.847782	10%
Off-peak	H7	33.93	0.932858	106.42	1.025774	9%
Off-peak	H8	41.27	1.134589	120.41	1.160648	3%
Peak	H9	43.27	1.189546	118.93	1.146409	-4%
Peak	H10	42.59	1.170690	103.61	0.998696	-17%
Peak	H11	40.89	1.124135	90.99	0.877045	-25%
Peak	H12	39.93	1.097552	83.98	0.809482	-29%
Peak	H13	39.57	1.087861	81.06	0.781371	-31%
Peak	H14	38.07	1.046404	78.03	0.752155	-29%
Peak	H15	37.33	1.026261	83.30	0.802999	-22%
Peak	H16	38.35	1.054274	97.14	0.936367	-12%
Peak	H17	41.19	1.132385	115.23	1.110752	-2%
Peak	H18	43.96	1.208428	130.94	1.262190	5%
Peak	H19	46.09	1.267129	146.38	1.411030	14%
Peak	H20	47.59	1.308227	159.29	1.535465	23%
Off-peak	H21	46.01	1.264687	148.83	1.434638	17%
Off-peak	H22	39.34	1.081533	126.95	1.223736	14%
Off-peak	H23	36.98	1.016678	110.82	1.068214	5%
Off-peak	H24	30.70	0.843803	96.47	0.929891	9%
Baseload		*36.38*	***1***	*103.74*	***1***	***0%***
Peak		*41.57*	***1.143***	*107.41*	***1.035***	***-10.7%***
Off-peak		*31.18*	***0.857***	*100.08*	***0.965***	***+10.7%***

Source: Authors' own research.

Table 3. Full-year analysis on average hourly spot market prices in Germany in 2015 and 2023, price coefficients and variations between the two years

Hour type	Hour	Average prices in 2015	DE 2015 Price curve (coefficient)	Average prices in 2023	DE 2023 Price curve (coefficient)	Price variation (2023 vs. 2015)
Off-peak	H1	25.39	0.797495	86.62	0.911465	11%
Off-peak	H2	23.53	0.739271	81.00	0.852331	11%
Off-peak	H3	22.21	0.697696	77.29	0.813274	12%
Off-peak	H4	21.57	0.677485	74.99	0.789082	11%
Off-peak	H5	22.03	0.691924	76.16	0.801448	11%
Off-peak	H6	24.07	0.756029	83.80	0.881764	13%
Off-peak	H7	30.41	0.955300	101.30	1.065982	11%
Off-peak	H8	37.18	1.167982	116.23	1.223057	6%
Peak	H9	39.18	1.230790	115.30	1.213247	-2%
Peak	H10	37.26	1.170383	105.18	1.106798	-6%
Peak	H11	35.16	1.104384	93.80	0.986990	-12%
Peak	H12	34.40	1.080755	85.26	0.897178	-18%
Peak	H13	31.75	0.997430	76.44	0.804382	-19%
Peak	H14	30.26	0.950676	70.25	0.739211	-21%
Peak	H15	29.54	0.927883	69.49	0.731262	-20%
Peak	H16	30.64	0.962598	76.06	0.800345	-16%
Peak	H17	32.33	1.015435	88.55	0.931821	-8%
Peak	H18	37.81	1.187876	106.54	1.121137	-7%
Peak	H19	41.70	1.309784	122.27	1.286663	-2%
Peak	H20	42.67	1.340392	131.57	1.384471	4%
Off-peak	H21	38.89	1.221510	128.04	1.347385	13%
Off-peak	H22	35.08	1.102008	115.47	1.215074	11%
Off-peak	H23	33.38	1.048666	105.72	1.112475	6%
Off-peak	H24	27.58	0.866248	93.43	0.983159	12%
Baseload		*31.83*	***1***	*95.03*	***1***	***0%***
Peak		*35.23*	***1.107***	*95.06*	***1.000***	***-10.6%***
Off-peak		*28.44*	***0.893***	*95.00*	***1.000***	***+10.6%***

Source: Authors' own research.

Table 4. Full-year analysis on average hourly spot market prices in the Netherlands in 2015 and 2023, price coefficients and variations between the two years

Hour type	Hour	Average prices in 2015	NL 2015 Price curve (coefficient)	Average prices in 2023	NL 2023 Price curve (coefficient)	Price variation (2023 vs. 2015)
Off-peak	H1	35.54	0.887137	92.50	0.965372	8%
Off-peak	H2	31.88	0.795823	84.96	0.886659	9%
Off-peak	H3	30.18	0.753255	81.00	0.845335	9%
Off-peak	H4	28.17	0.703148	77.19	0.805556	10%
Off-peak	H5	27.44	0.684883	76.64	0.799830	11%
Off-peak	H6	28.80	0.718988	82.21	0.857947	14%
Off-peak	H7	34.83	0.869423	97.73	1.019867	15%
Off-peak	H8	42.00	1.048403	114.11	1.190864	14%
Peak	H9	44.77	1.117506	119.58	1.247931	13%
Peak	H10	47.24	1.179138	109.04	1.137959	-4%
Peak	H11	46.62	1.163750	93.69	0.977772	-19%
Peak	H12	46.67	1.164984	82.38	0.859727	-31%
Peak	H13	44.90	1.120850	71.49	0.746112	-37%
Peak	H14	43.34	1.081913	64.11	0.669094	-41%
Peak	H15	41.52	1.036406	64.91	0.677376	-36%
Peak	H16	39.97	0.997590	73.12	0.763053	-23%
Peak	H17	40.57	1.012767	86.75	0.905347	-11%
Peak	H18	45.48	1.135273	109.03	1.137874	0%
Peak	H19	46.68	1.165072	126.16	1.316631	15%
Peak	H20	47.05	1.174362	136.22	1.421554	25%
Off-peak	H21	44.03	1.099070	130.67	1.363650	26%
Off-peak	H22	42.00	1.048294	118.47	1.236363	19%
Off-peak	H23	42.25	1.054476	109.71	1.144947	9%
Off-peak	H24	39.56	0.987488	98.04	1.023180	4%
Baseload		*40.06*	***1***	*95.82*	***1***	***0%***
Peak		*44.57*	***1.112***	*94.71*	***0.988***	***-12.4%***
Off-peak		*35.56*	***0.888***	*96.94*	***1.012***	***+12.4%***

Source: Authors' own research

Table 5. Main power generation installed capacities and assessment of Peak and Off-peak prices in Romania in the period 2015-2023

Year	RO Price Peak valuation	RO Price Off-peak valuation	RO Solar installed capacity	RO Prosumers installed capacity	RO Wind + Solar installed capacity	RO Fossil coal + Gas installed capacity	RO Nuclear installed capacity
2015	1.14	0.86	1101	0	3997	10733	1298
2016	1.12	0.88	1152	0	4090	10773	1298
2017	1.19	0.81	1210	0	4195	10874	1300
2018	1.15	0.85	1211	0	4198	10947	1300
2019	1.14	0.86	1150	0	4118	7161	1300
2020	1.12	0.88	1163	0	4135	6769	1300
2021	1.12	0.88	1145	85	4187	5653	1300
2022	1.07	0.93	1160	417	4534	4891	1300
2023	1.04	0.96	1185	1500	5642	4661	1300

Source: ENTSO-E Transparency Platform and authors' own research.

Table 6. Main power generation installed capacities and assessment of Peak and Off-peak prices in Germany in the period 2015-2023

Year	DE Price Peak valuation	DE Price Off-peak valuation	DE Solar installed capacity	DE Wind + Solar installed capacity	DE Fossil coal + Gas installed capacity	DE Nuclear installed capacity
2015	1.11	0.89	37859	78794	89539	12068
2016	1.10	0.90	39410	86482	89812	10793
2017	1.11	0.89	41866	95859	91263	10793
2018	1.08	0.92	43998	103723	87267	9516
2019	1.07	0.93	45435	104774	82599	9516
2020	1.08	0.92	48376	109218	79691	8114
2021	1.08	0.92	53538	115978	80208	8114
2022	1.02	0.98	58002	121245	71989	4056
2023	1.00	1.00	63366	129237	71780	4056

Source: ENTSO-E Transparency Platform and authors' own research.

Table 7. Main power generation installed capacities and assessment of Peak and Off-peak prices in the Netherlands in the period 2015-2023

Year	NL Price Peak valuation	NL Price Off-peak valuation	NL Solar installed capacity	NL Prosumers installed capacity	NL Wind + Solar installed capacity	NL Fossil coal + Gas installed capacity	NL Nuclear installed capacity
2015	1.11	0.89	1000	972	3874	26860	492
2016	1.13	0.87	1526	1261	4917	25572	486
2017	1.11	0.89	2135	1682	6392	23905	486
2018	1.09	0.91	2584	2329	7216	23064	486
2019	1.07	0.93	4608	3326	9001	20201	486
2020	1.08	0.92	7226	4488	11710	20158	485
2021	1.07	0.93	11108	5843	17756	22512	485
2022	1.00	1.00	14911	8028	22681	22536	486
2023	0.99	1.01	22590	9516	32000	22357	486

Source: ENTSO-E Transparency Platform and authors' own research.