Powering Europe:

Energy costs and analysis of the electricity market among EU member states.

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Contents

Wholesale Electricity Market Dynamics in the European Union

Since the 1990s, the European Union (EU) has been putting efforts to move toward a pan-European energy market. The path was shaped through various legislations and "energy packages" that were heavily influenced by the transition toward utilization of Renewable Energy Sources (RES). Primary goal of this action is achieving price convergence, improve supply security, and foster healthy competition across the participants. Liberalizing the Power Exchange (PX) also meant promoting cross-border electricity trading, this would enable the efficient flow of clean energy and thus the maximization of renewable energy utilization.

To achieve these goals, a unaccent framework began to establish across all participating. To accomplish this goal the Target Model was introduced. The Target Model is a complex framework designed to unify the wholesale electricity markets of the EU member states, while achieving through an intricate mechanism the lowest electricity prices for the buyer side, and the highest payback for the seller side. However, to fully couple two regions with a separate PX, as the past has revealed comes with challenges, as each region has unique market dynamics.

This report will further examine regional dynamics with center of attention being the Greek profile, cross-border electricity flows and how existing and planned infrastructure will affect these dynamics. Alongside these dynamics in the spotlight will be different prices of conventional energy sources and their effect on wholesale electricity prices in Greece. Lastly, conclusions and lessons learned will be drawn from the analysis

Wholesale Market Structure – The European Target Model

The Target Model was formulated with the vision of a more efficient, sustainable, robust and competitive PX structure in the EU energy markets.

The Target Model can be broken down into four distinct divisions:

The Forward Market. In this division long-term contracts with physical delivery obligations take place. These contracts are called Over -The-Counter (OTC) trades and only the traded quantities should be disclosed to the Day-Ahead Market.

The Day-Ahead Market (DAM). In this section, most of the quantities traded in the wholesale electricity market take place. The transactions that occur take place one day before the delivery date obligation, thus the name of the division.

The Intraday Markets (IDMs).These auctions follow the DAM, allowing the participants (both buyers and sellers) to correct their positions as the time of physical delivery approaches. These markets are especially useful for the RES aggregators, as they can predict more accurately the production of non-dispatchable RES (wind turbines and solar PVs) more accurately. The intraday markets are split into IDA1, IDA2, IDA3, and the latest addition of XBID.

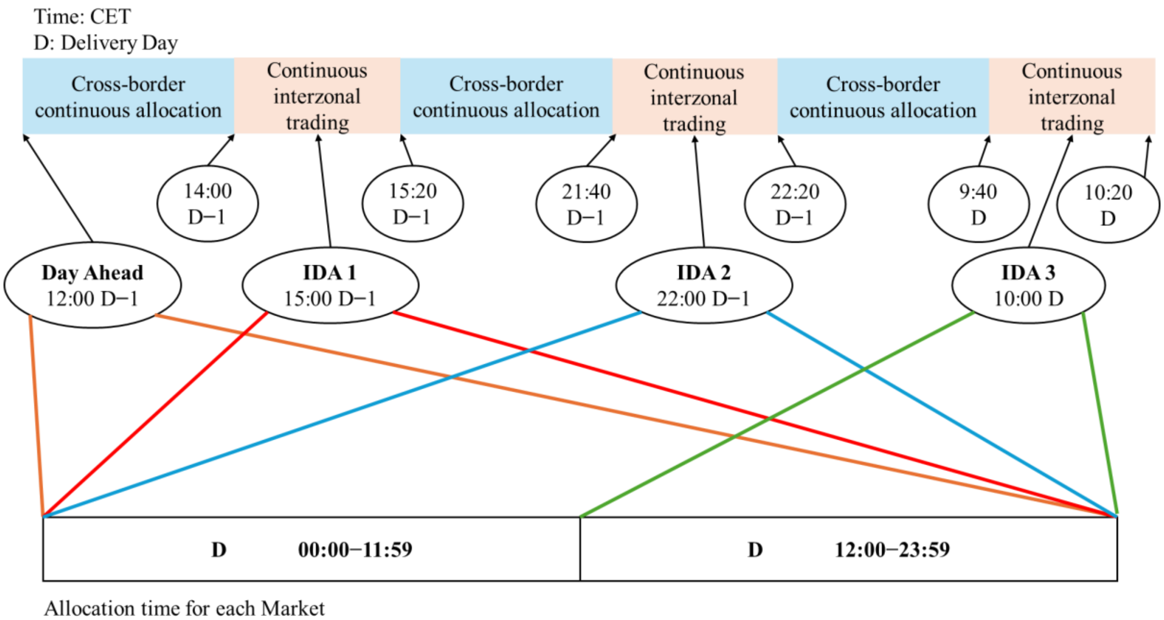

Figure 1 Trading periods in different market divisions of the Target Model

The Balancing Market. This division is regulated by the Distribution System Operator (DSO) and ensures that the System remains in balance. The regulation occurs in real-time. For the parties that did not correct their position in DAM and IDAs they are called to pay a fine for bringing the system out of balance, called the imbalance settlement.

As for the case of Greece the selling parties are obligated to pay apart from the imbalance settlement the non-compliance settlement again for bringing the System out of balance, this time in a cumulative manner during a specific month. In Figure 2 the structure of the Target Model in Greece is presented.

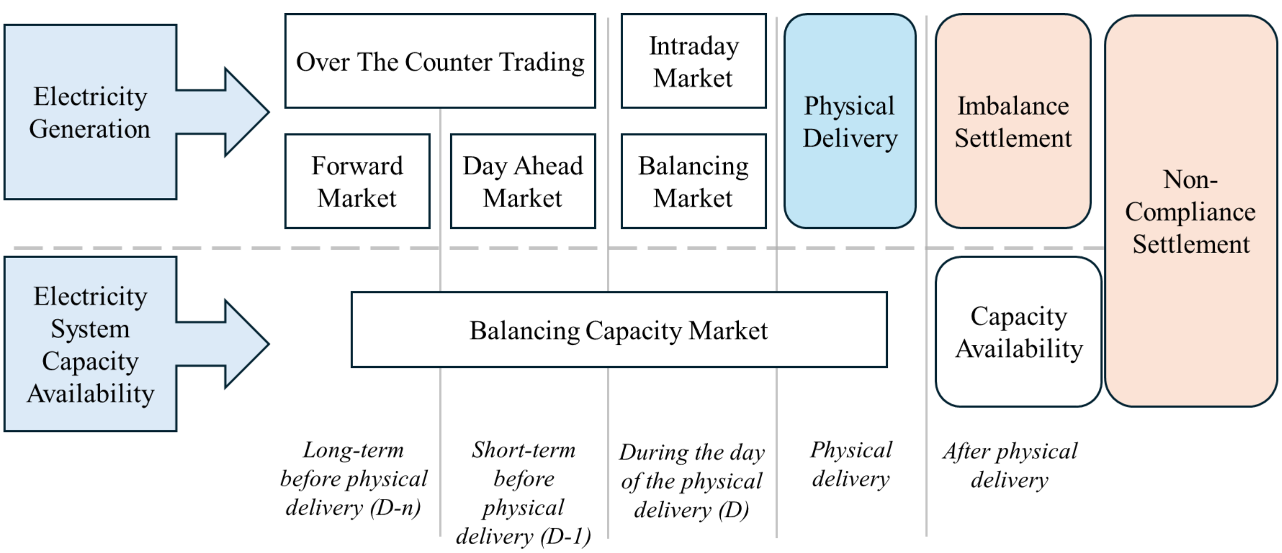

Figure 2 Target Model Structure in Greece

Market Coupling

Market Coupling (MC) is a core objective of the Target Model, as through this mechanism, the smooth transaction of electricity occurs. Unrealized electricity quantities are no longer wasted domestically but are exported to the coupled region. At the same time, the coupled region can allocate these quantities and can harvest the economic benefits of lower electricity prices (than producing more expensive electricity domestically).

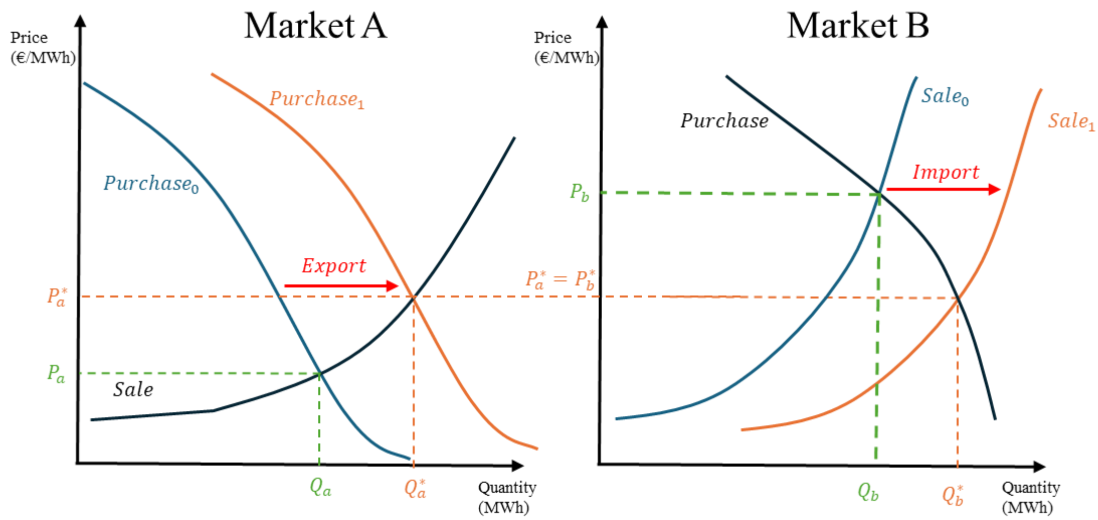

Figure 3 Market Coupling Mechanism

In the same manner as the domestic flows of energy, the MC is split into Day-Ahead and Intraday divisions.

Single Day-Ahead Coupling (SDAC)

The member states that have adopted the Target Model, automatically have the SDAC mode. The introduction of the Target Model came in six separate waves, as depicted in Figure 3Figure 4, starting in 2014.

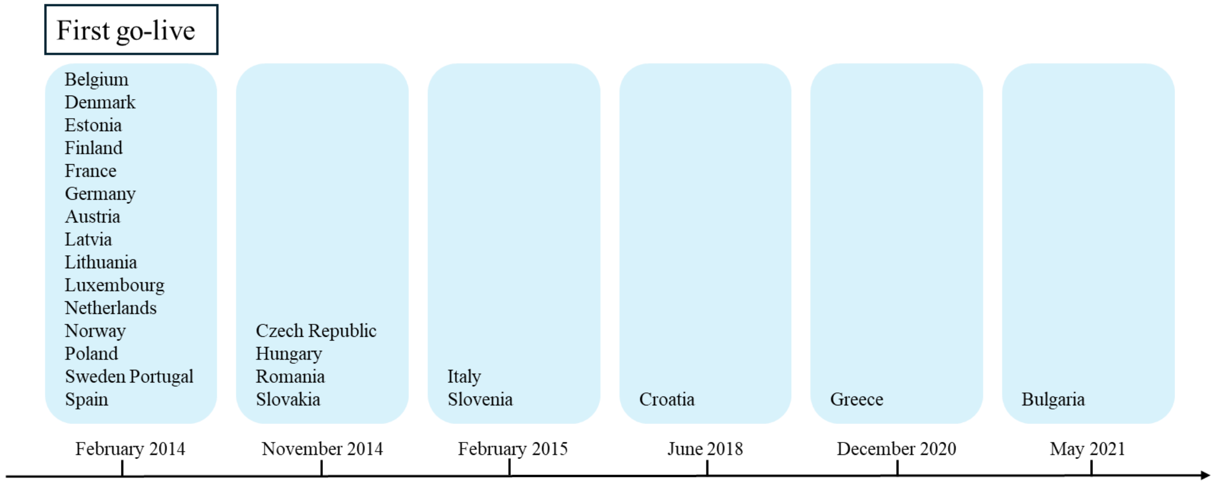

Figure 4 Target Model "Go-Live" waves

Single Intraday Coupling (SIDC)

The SIDC is a different case from the SDAC as not all member states adopting the Target Model had the advantage of continuous intraday coupling this is also known as the XBID project. The XBID aimed to create a continuous pan-European intraday market, allowing participants to trade electricity continuously, given the available capacities and their orders matched with the coupled regions. XBID is aimed at increasing liquidity and helps participants manage their positions closer to the delivery time.

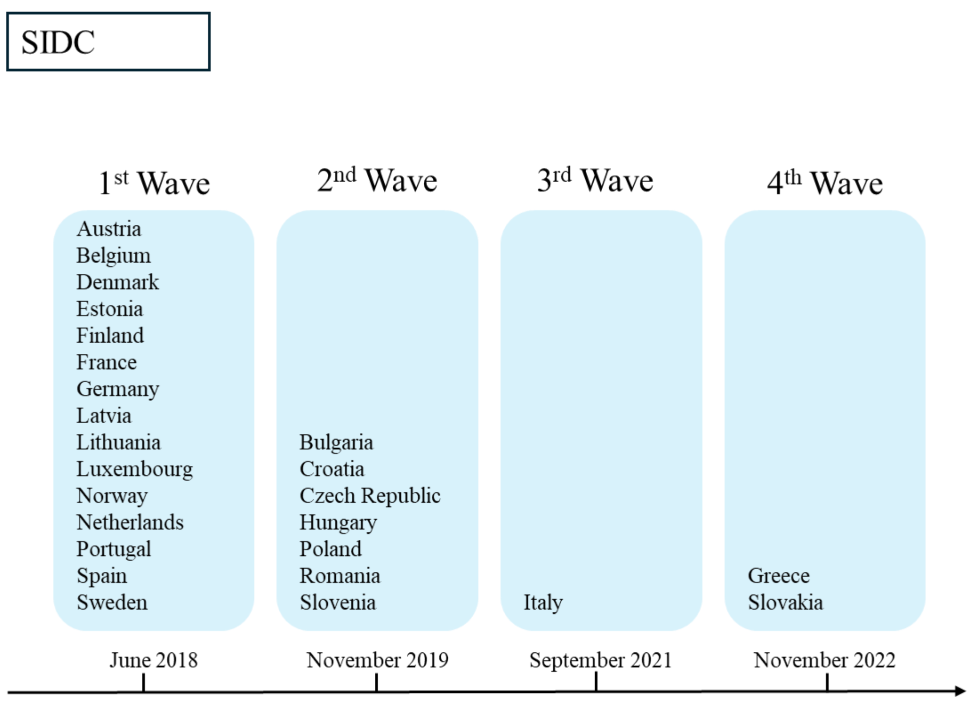

Figure 5 SIDC country introduction

Greece and Slovakia were the last countries to couple in intraday terms. At the moment, 25 out of 27 member states are coupled.

The Greek Wholesale Market: A Deep Dive and Regional Comparison

In 2018, the Target Model was introduced to Greece, but not in full force. A key milestone for the country was late November, when the Target Model was introduced in full force. The new framework served as a replacement for the Mandatory Pool.

Up to date, the structure of the Greek Electricity System was to accommodate conventional energy sources; thus, the massive penetration of Renewable Energy Sources (RES), more specifically solar PVs, signified the need for changes in the structure of the electricity system.

The over-penetration of RES indicated the need for storage technologies and modernization of the current grid infrastructure - both domestic and interconnections with the neighboring countries. These needs became prominent with the ever-growing amounts of curtailed energy, which, up to January 1st, 2025, could only be roughly estimated. For the domestically interconnected mainland System, these curtailments mainly came from solar PVs and from the Wind turbines in the non-interconnected Greek islands.

The anticipated benefits of the introduction of the Target Model – lower electricity prices- have yet to become prominent in the long run in Greece. Since the Mandatory Pool where prices averaged at 50€/MWh, today we see extreme lows and highs (varying from negative prices to 471.56€/MWh in 2025 alone).

The key players of the Wholesale Electricity Market.

The Hellenic Energy Exchange (HEnEx) oversees the wholesale electricity market and price formation. The Independent Power Transmission Operator (IPTO) - the DSO - is responsible for electricity transmission. The Clearing House (EnExClear) acts as the central clearing house for the DAM and IDM, managing financial settlements and transactions to reduce credit risk for the market. And finally, the Regulatory Authority for Energy, Waste and Water (RAEWW) supervises the daily function of the markets.

Price Trends in Greece

The introduction of the Target Model in Greece in November 2020 marked a significant shift from the previous Mandatory Pool system. The new framework aimed at integrating the Greek market into the envisioned pan-European energy market, promising greater efficiency and lower prices. Though, the reality of the price trends since this transition has been complex. As stated by the creators of the Target Model, this configuration at the introduction would bring higher electricity prices but as the market matured they would drop. This unfortunately was not the case, the market revealed high sensitivity to a number of domestic and international factors.

Initially, prices started soaring as a direct consequence of the new market model. The European energy crisis, sparked by a sharp increase in NG prices, had a profound impact. Given that Greece's electricity generation heavily relied on imported NG, the wholesale electricity prices in the DAM during Q2 and Q3 of 2022 mirrored these soaring fuel costs. As depicted in Figure 6 and Figure 8, average daily prices in the DAM skyrocketed, reaching unprecedented highs. The same period underscored the dependence of domestic electricity generation on external goods, making the Greek energy system extremely vulnerable and volatile on external factors, such as conventional fuel prices.

In a contradictory but predictable trend, the rapid increase in RES capacities has introduced a countervailing force. During the last years, Greece has become a regional leader in solar PV deployment, and this has created a noticeable merit-order effect. During periods of high solar irradiation, particularly midday, the massive influx of zero-marginal-cost for solar power displaces the expensive thermal generators out of the market equation. Combined with the low electricity demand during the same hours, this dynamic has frequently driven wholesale electricity prices in the DAM from near-zero to even negative values. This phenomenon is a clear indicator of the oversaturation of intermittent renewables during peak production hours. This challenge is becoming increasingly common in European electricity markets with high-RES penetration, especially in the Mediterranean region.

This dynamic has led to extreme price volatility. As portrayed in Figure 7 and Figure 8, the difference between daily peak and off-peak prices has grown significantly. During the day, prices crash as solar generation peaks, but then a sharp spike can be observed during the evening when solar output drops while demand rises. This creates the phenomenon "duck curve", but with each passing year this phenomenon resembles more a “canyon curve”-where the volatility is more extreme, where the System load forms a steep ramp. As initially the electricity system was created as to accommodate dispatchable and stable conventional energy sources, the created volatility poses as a significant challenge for grid operators and underscores the need for flexible generation and energy storage solutions in order to keep following the EU targets toward a net-zero future by 2050.

The price trends in Greece since the Target Model's full implementation demonstrate that the wholesale market is no longer a simple equation of supply and demand based on a fixed conventional energy production, as RES integration is greater with each passing year and conventional (specifically Lignite) energy-plants phase out. It has become a highly complex interplay between global commodity prices (especially NG prices, which acts as the marginal price setter), domestic RES growth and future plans-the increasing capacity of solar PVs and wind turbines, which displaces fossil fuels and drives down prices during high-production hours, and the grid's reliance on dispatchable conventional sources to balance the intermittency of renewables.

While the Target Model's introduction did not immediately result in consistently low prices, it has created a more transparent and competitive market. The extreme price signals—both highs and lows—now provide powerful incentives for market participants to invest in a new energy generation profile, such as short- and medium-term storage and peaking gas plants that provide immediate response and thus flexibility, these technologies can help balance and stabilize the grid and arbitrage these price differences. In the long run, these actions will bring price stability and convergence with the broader EU market.

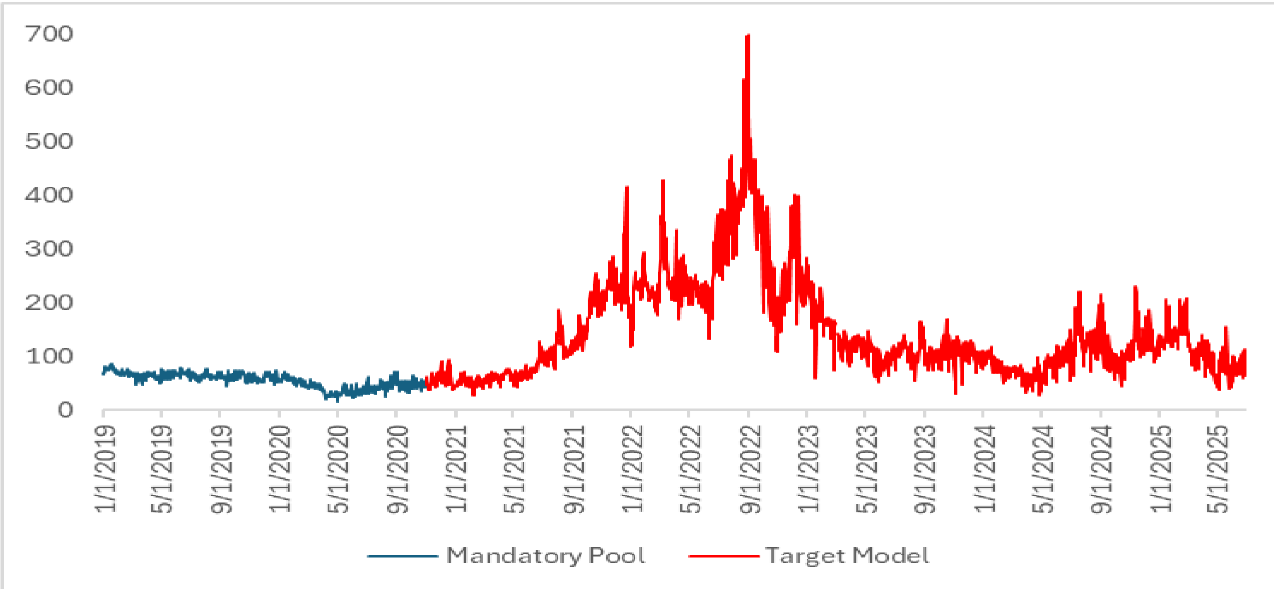

Figure 6 Average Daily MCP prices

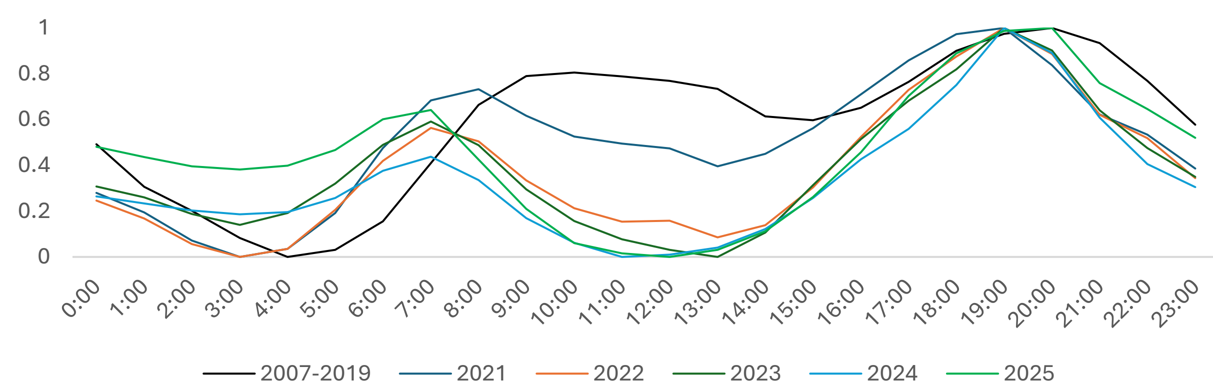

Figure 7 DAM price volatility during the day

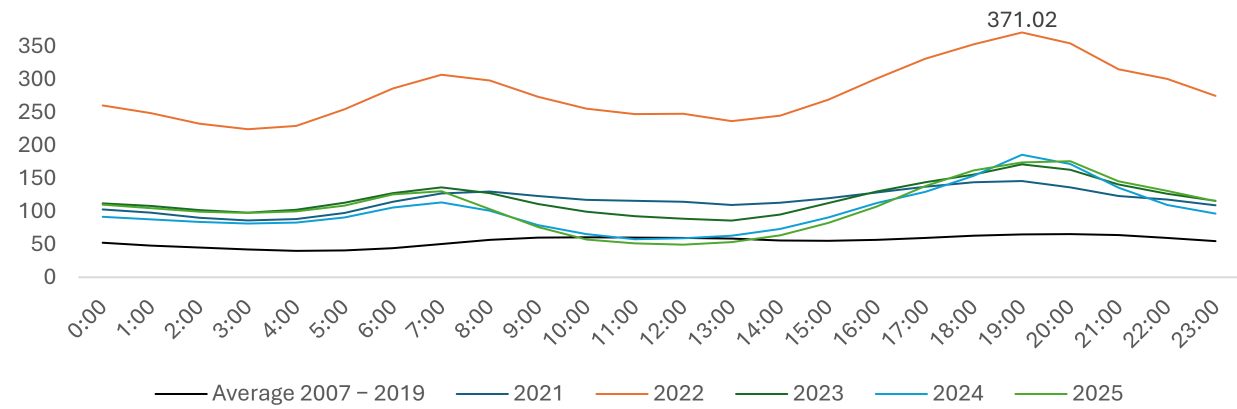

Figure 8 Average Hourly DAM prices€/MWh

Comparative Analysis with Selected EU Member States

To fully understand the complexities of the Greek electricity market, a comprehensive comparative analysis with other EU member states that both have a similar and opposite profile to Greece is crucial. Greece in this case will serve as the benchmark against countries that share similar geographic and market characteristics and contrast it with those that have fundamentally different energy profiles, highlighting the diverse challenges and opportunities within the EU.

The Greek electricity generation profile is heavily dependent non-dispatchable RES generation, but to balance any discrepancies NG generation is also closely related with the electricity mix. As NG is the cleanest fossil fuel, it acts as complementary for a smooth integration of RES (Figure 11). At the same time, Greece is also dependent on electricity imports from the interconnected countries, specifically Bulgaria that acts as the primary source of electricity inflows (Figure 9). Greece may hold a geographically strategic position, but the country has many lessons to learn from its close neighbor Albania, with an astonishing electricity mix based by 99% on Hydropower generation, and a small part on solar PVs.

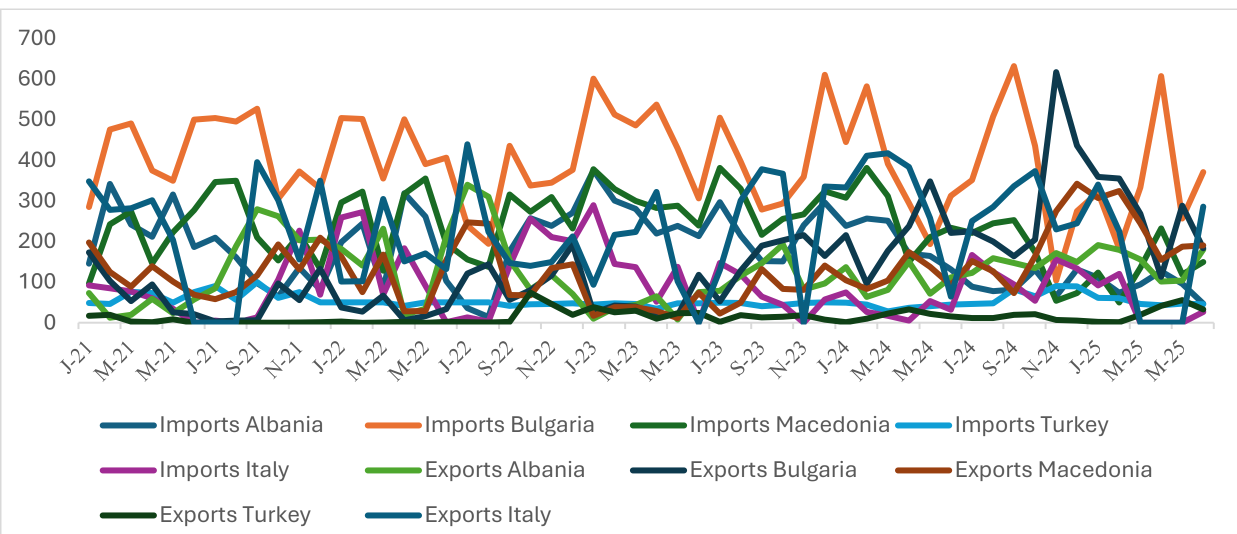

Figure 9 Interconnected Traded Volumes (MWh/Month), [Source: IPTO]

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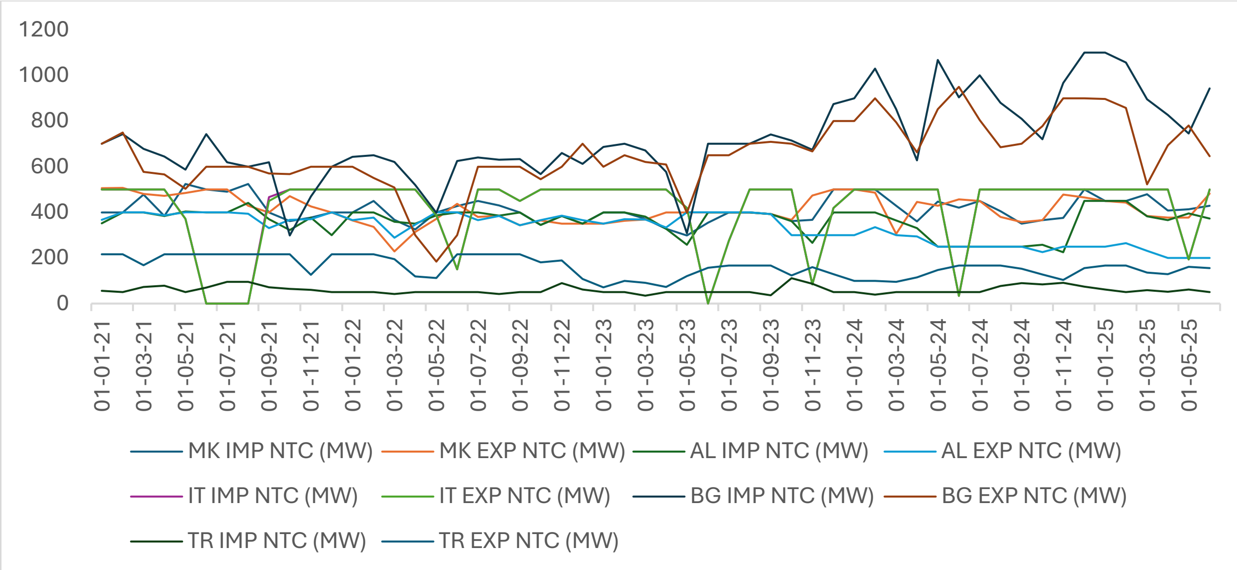

Figure 10 Average Monthly Net Transfer Capacity (MW), [Source: IPTO]

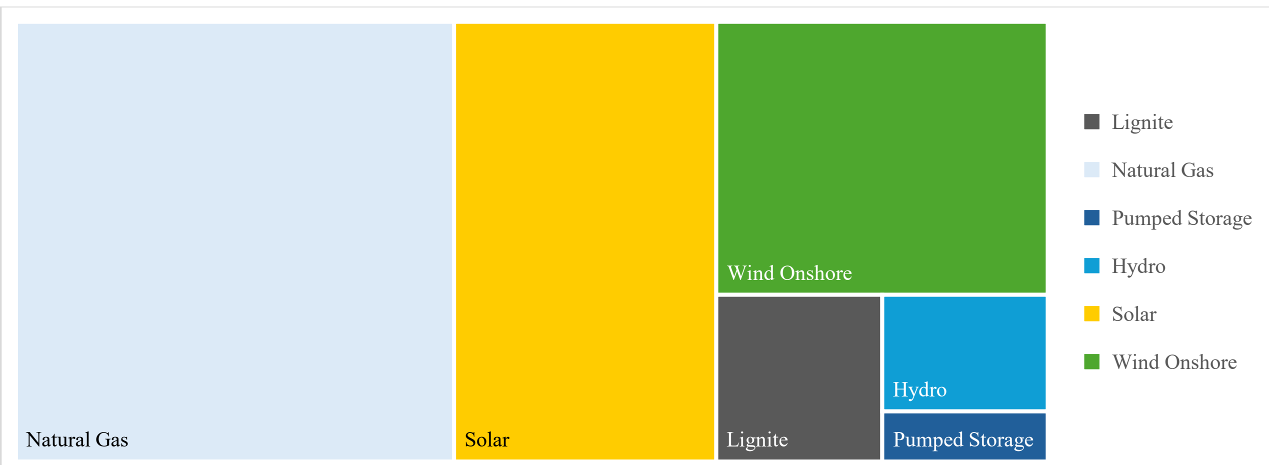

Figure 11 Greek Electricity Mix, Jan-Jul 2025 [Source: ENTSOE]

Italy: A Similar Mediterranean Profile

Greece and Italy, as sharing the Mediterranean region and being interconnected, both have a significant reliance on imported NG to meet a large portion of their electricity needs and thus the generation. This commonality makes both markets highly susceptible to global gas price discrepancies. As a result, both Greece and Italy have frequently seen their wholesale prices hover among the highest in Europe, but at the same time drop to zero and negative extents during peak PV generation hours of the day.

However, Italy's market is more deeply integrated with Central Europe, interconnected with France, Switzerland, Austria, Slovenia, Greece, and Montenegro. This allows the country to import cheaper electricity from countries like France and Switzerland, mitigating some of the price volatility and offering a level of resistance that Greece's more isolated system lacks. At the same time the Italian electricity mix is similar but more diverse than the case of Greece. The Italian case illustrates that while a similar fuel mix can lead to shared vulnerabilities, robust interconnections provide a vital safety valve.

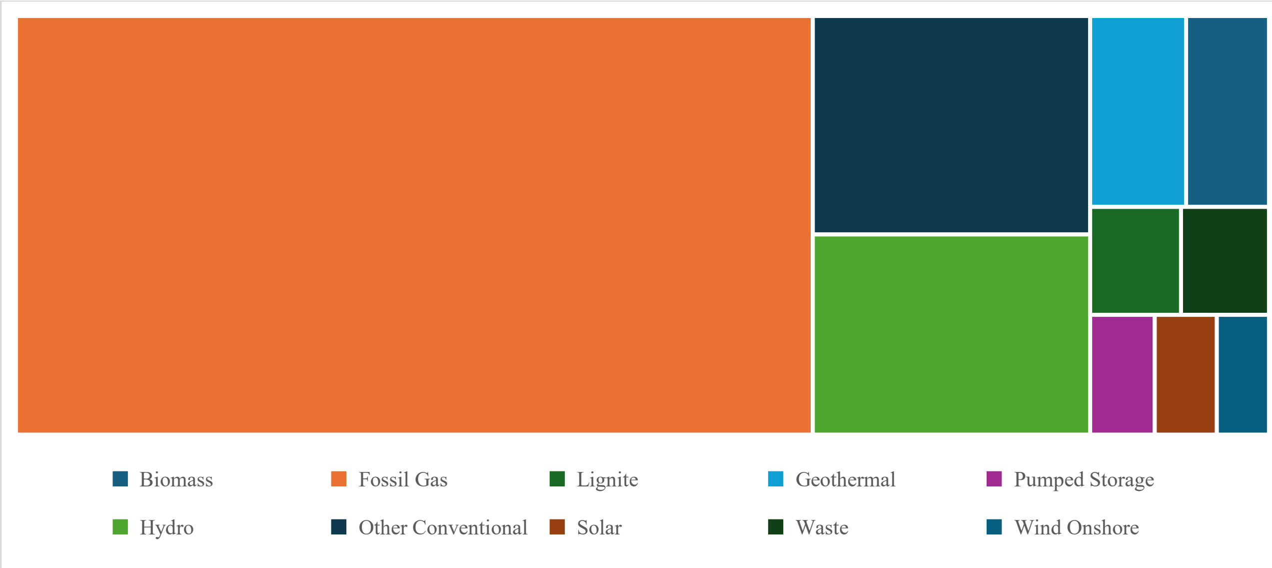

Figure 12 Italian Electricity Mix, Jan-Jul 2025 [Source: ENTSOE]

Bulgaria: Interconnection and a Shift from Coal

Bulgaria presents a relevant comparison as a neighboring and interconnected country with Greece. The Bulgarian market's price dynamics are shaped by a different set of factors, including a significant baseload (approx. 40%) from a nuclear power plant and an astonishing 28% of lignite-fired generation (Figure 13).

Though the EU is trying to shift further away from nuclear power generation, its presence often provides a more stable, lower-cost electricity supply, which can make Bulgarian prices more competitive than Greece's, particularly during periods of high NG prices. As depicted in Figure 9 Bulgaria is the primary importer of electricity for Greece, this means that Greece can import cheaper power from its neighbor to help meet demand. These dynamics highlights the importance of regional market integration and the potential for a country's energy mix to influence its neighbors.

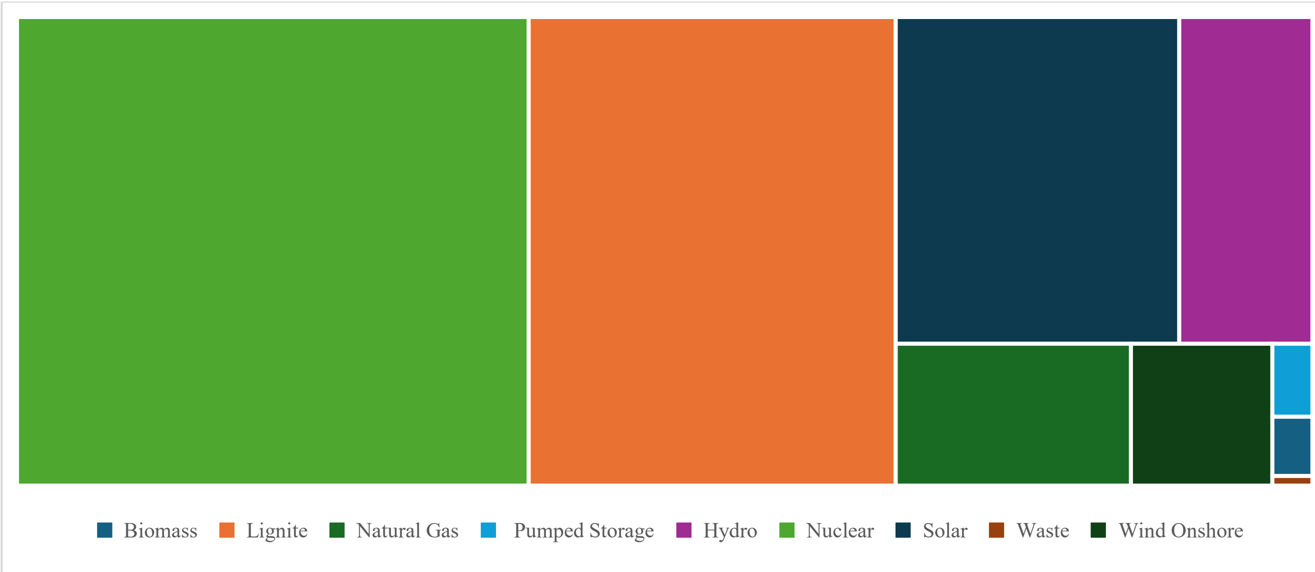

Figure 13 Bulgarian Electricity Mix, Jan-Jul 2025, [Source: ETSOE]

Spain: Decoupled Markets and the Blackout Incident

Spain, as a member of the Iberian Electricity Market (MIBEL), offers a unique case study in managing a high-renewable integration to the grid, as seen in Figure 14 the electricity mix in Spain is based almost 64% on renewables. During June of 2022 after the Russian invasion to Ukraine, NG prices skyrocketed. At that moment the EU Commission allowed Spain and Portugal to decouple the price of NG from electricity for 12 months, so called "Iberian exception", as the two countries have low gas in the energy mix. This has allowed Iberian power prices to diverge from other EU member state prices. The historically low interconnection capacity with the rest of Europe in reality let to the "Iberina exception", shielding the consumers from price spikes. This policy, however, highlighted the market's isolation.

The vulnerabilities of this isolation were starkly revealed on April 28, 2025, when a large-scale power outage affected the Iberian Peninsula. The incident, while complex, was caused by a cascading failure that led to the electrical disconnection of the Iberian grid from the rest of Continental Europe.

This blackout served as a powerful reminder that while market decoupling can offer price protection, it can also compromise grid security and resilience by limiting the ability to import power during a crisis.

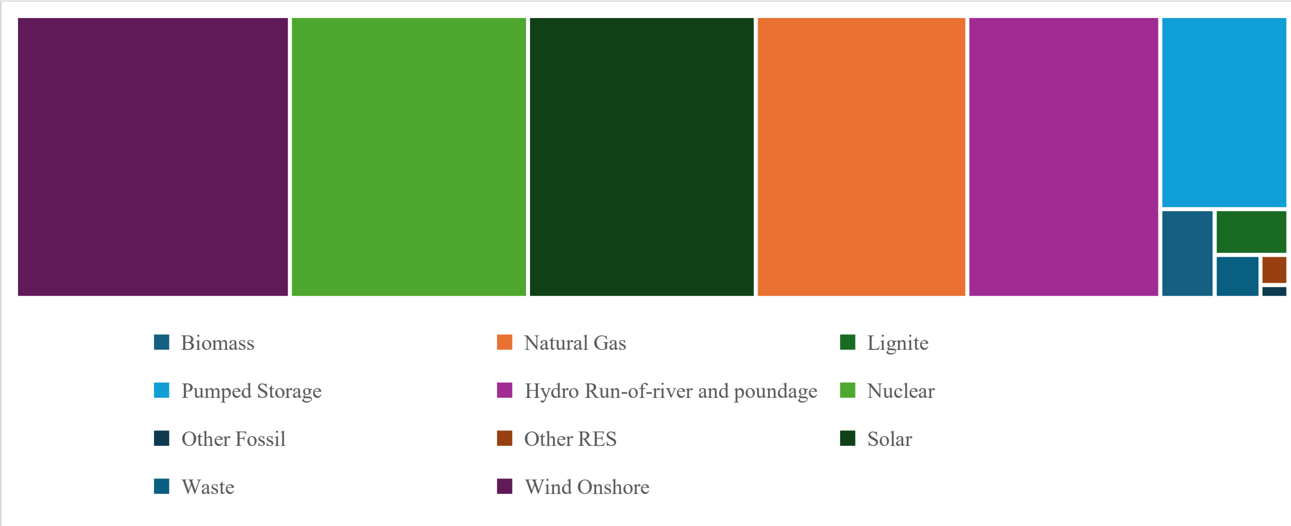

Figure 14 Spanish Electricity Mix, Jan-Jul 2025, [Source: ENTSOE]

France: A Nuclear Powerhouse with its Own Challenges

France is a nuclear powerhouse, with its fleet of over 50 reactors providing a stable, low-carbon baseload. Nuclear reactors when run under perfect conditions can provide stable and low cost electricity, as a result France has some of the lowest wholesale electricity prices in the EU. France's energy strategy has long been predicated on the reliability and affordability of its nuclear fleet.

However, as the nuclear fleet is aging, a number of reactors have faced issues with stress corrosion cracking, necessitating extended maintenance shutdowns and reducing their availability, causing historic lows in 2022 in nuclear generation in the country. This made France a net importer of electricity for the first time in the last 40 years, highlighting the risk of over-reliance on a single technology.

The case of France demonstrated that even a nuclear-dominant system is not without risk, and that a diversified and resilient energy mix is essential for long-term price stability.

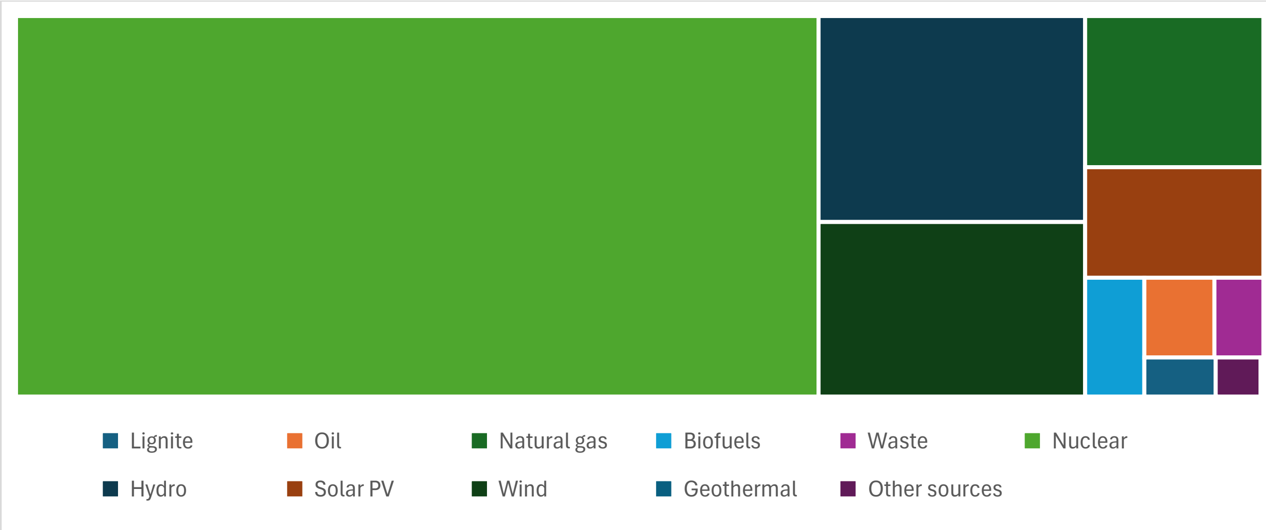

Figure 15 French Electricity Mix, 2023, [Source: IEA]

Hungary: A Central European Hub with a Nuclear-Gas Mix

Hungary serves as a particularly interesting comparison due to its strategic position in Central Europe and its diverse energy mix. Hungary's wholesale market is part of the 4M Market Coupling with the Czech Republic, Slovakia, and Romania, which gives it a high level of regional integration and a strong interconnection level. This allows for a more fluid and efficient exchange of electricity with its neighbors, as well as a reliant and diverse mix both of dispatchable and non-dispatchable energy sources.

Hungary's energy mix is also dominated by nuclear power, 46% of the generated electricity comes from nuclear reactors. This is supplemented by NG and solar PV generation, both accounting for 20% each. The combination of nuclear baseload and solar expansion allows Hungary to maintain relatively stable and low wholesale prices despite its reliance on NG.

The Hungarian case highlights that a diverse but balanced energy portfolio can be crucial for mitigating price volatility and reducing dependency on market-sensitive external fossil fuels.

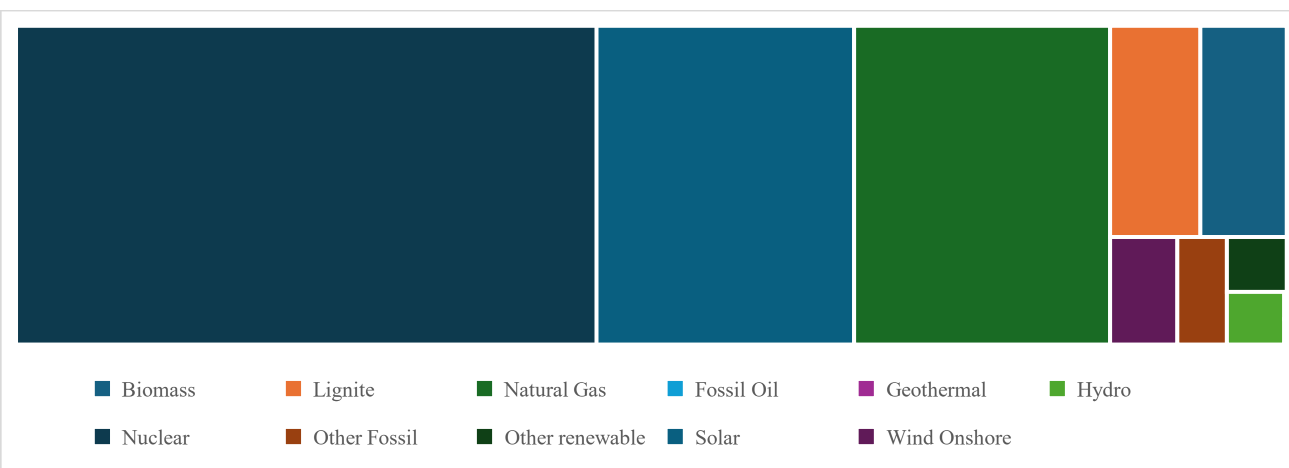

Figure 16 Hungary Electricity Mix Jan-Jul 2025, [Source: ENTSOE]

Denmark: The Wind-Hydro Paradox

Denmark is the global leader in wind energy, the country's electricity generation comes from onshore and offshore wind in an astonishing 56%, this has therefore significant periods of oversupply and low or negative wholesale prices.

However, Denmark has strong interconnections with the Nordic region, which is rich in flexible hydropower, allowing it to manage this intermittency with exceptional efficiency. At low wind production hours, Denmark can import cheap, dispatchable hydropower from the neighboring countries of Norway and Sweden, and vise-versa when wind generation is at surplus the country can export it to the same neighbors. This synergy creates a symbiotic relationship between the countries, balancing supply and demand while ensuring system stability.

In contrast, Greece lacks a similar large-scale, flexible, and low-cost neighbor underscoring a critical challenge of relying on a more expensive domestic flexibility energy generation solutions, or costly energy storage solutions to manage its own intermittency.

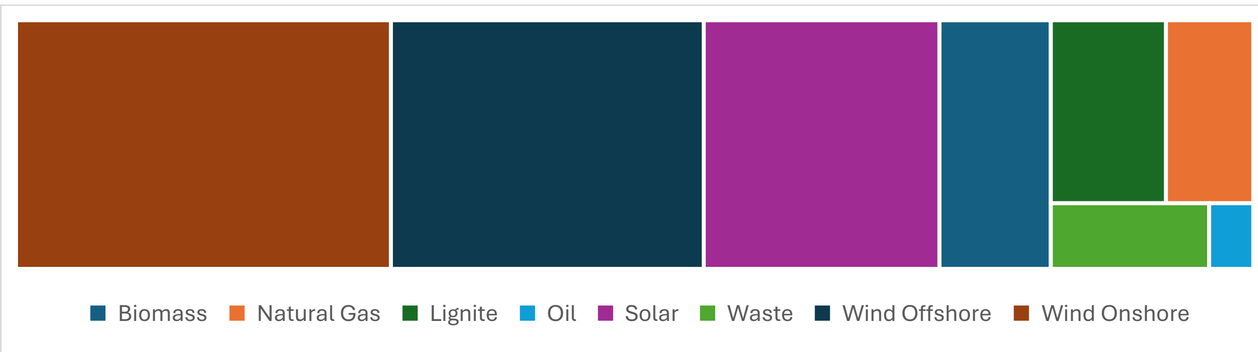

Figure 17 Danish Electrcitry Mix Jan-Jul 2025, [Source: ENTSOE]

Greece's market holds a strategic geographical position, but at the same time has it's own unique intersection of challenges:

i. Reliance on volatile fossil fuels,
ii. Rapidly growing but intermittent RES fleet,
iii. A peripheral position with less-developed interconnections compared to Central European hubs like Hungary.

The high price volatility and the disconnect between wholesale and retail prices are direct consequences of these structural factors, highlighting the need for strategic investments in interconnections, storage, and flexibility.

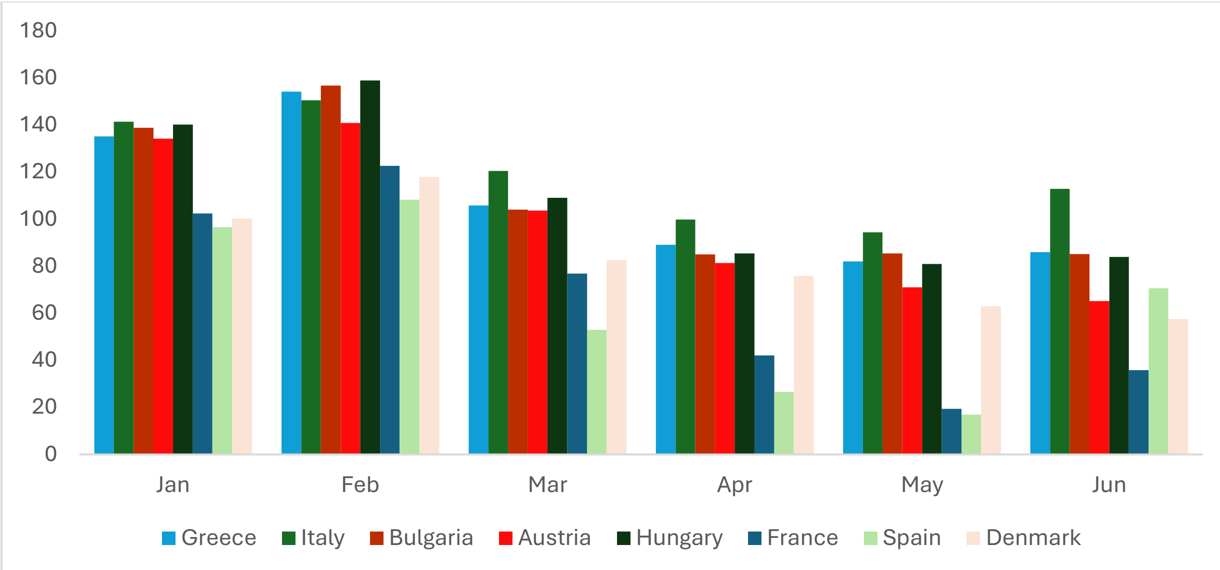

Figure 18 Monthly average DAM prices (€/MWh), 2025, [Source: ENTSOE]

Key Learnings and Policy Implications from the Greek Case

The case of Greece with the introduction of the Target Model offers a critical case study for any country transitioning its energy system toward a high-RES penetration. Although the gained insights are not unique to Greece, they are amplified by the structure of the System and the geographical characteristics. These aspects highlight the necessary policy interventions needed to fully realize the benefits of the clean energy transition.

The Critical Need for Flexible Resources and Storage

The analysis of price volatility in Greece and the comparative analysis with countries as Denmark and Spain underscores a foundational truth regarding the energy transition: a high penetration of variable renewables requires a highly flexible energy system. The Greek's electricity System designed to accommodate dispatchable and thus conventional energy sources highlighting the grid's reliance on imported NG to fill the gaps left by non-dispatchable RES (solar and wind) generation exposes it to global commodity price shocks.

- Energy Storage: The lack of utility-scale energy storage in Greece is a major bottleneck. Battery energy storage and pumped-hydro storage is vital for excess renewable generation absorption during the day and discharge during evening peaks. This action has two major positive outcomes, first the reduction of reliance on conventional energy generation, and second renewable energy generation curtailments, where clean energy is simply wasted to preserve grid stability.
- Modernizing the Grid: The existing grid infrastructure, designed for a centralized, one-way flow of electricity. The need to equip it as to handle decentralized, two-way flows from rooftop solar and other distributed energy resources and making the consumers into a new generation of "prosumers" is vital. Greece's policy must turn toward prioritizing and subsidizing investments in smart grid technologies (enabling better observability, control,

and efficiency across the network), and simplifying the permit process of net billing on household level.

Policy Implication: The Greek government's National Energy and Climate Plan (NECP) targets for energy storage must be aggressively implemented. Although at the moment over 57 GW of BESS and Pumped Hydro licenses have been granted, only 699MW of pumped storage are operational.

This can be achieved through a combination of auctions for storage capacity, including a 4th round, financial incentives, and regulatory certainty for investors-making the new technologies bankable. A capacity mechanism that appropriately values and compensates flexible resources is also crucial for ensuring system adequacy as conventional plants are phased out.

Enhancing Regional Integration and Interconnections

The comparative analysis highlighted the immense value of strong interconnections. Limited cross-border capacity can lead to market isolation and price divergence, wasting cheaper energy in one region while the other comes to consequence of high prices for conventional generation. The Spanish blackout incident serves as a powerful reminder that while market isolation can offer protection, simultaneously it compromises grid security and resilience.

Policy Implication: Greece should continue advocating and investing in projects that enhance its role as a regional energy hub, through projects as Greece-Egypt electrical interconnection (GREGY), and EuroAsia Interconnector-connecting Crete, Cyprus and Israel, creating a renewable energy corridor. This includes not only the physical infrastructure, but also the harmonization of market operational procedures with its neighboring countries. The goal should be creating a seamless renewable energy flow, optimizing the use of all available resources across the regions.

A successful energy transition is more than just a race to deploy renewables. It is a rather complex process that requires bold policy reforms, regional integration, and strategic investments in short- and medium to long-term storage technologies as to provide flexibility and stability to the grid. For Greece to successfully shift from a market structure extremely vulnerable to external factors, to a secure and sustainable energy system, the aforementioned aspects should be addressed, as Greece holds a rather strategic geographic position.

Interconnections and Cross-Border Energy Flows

Overview of Existing and Planned Interconnections

Greece's electrical interconnections are vital for regional energy trading and supply security. At the moment the country is interconnected with Albania, Bulgaria, North Macedonia, and Turkey via 400 kV overhead lines, and an asynchronous DC submarine cable also links Greece to Italy.

Simultaneously the project for interconnecting Crete to the mainland system has been completed and fully operational, both the interconnecting points with Peloponnese and Attica.

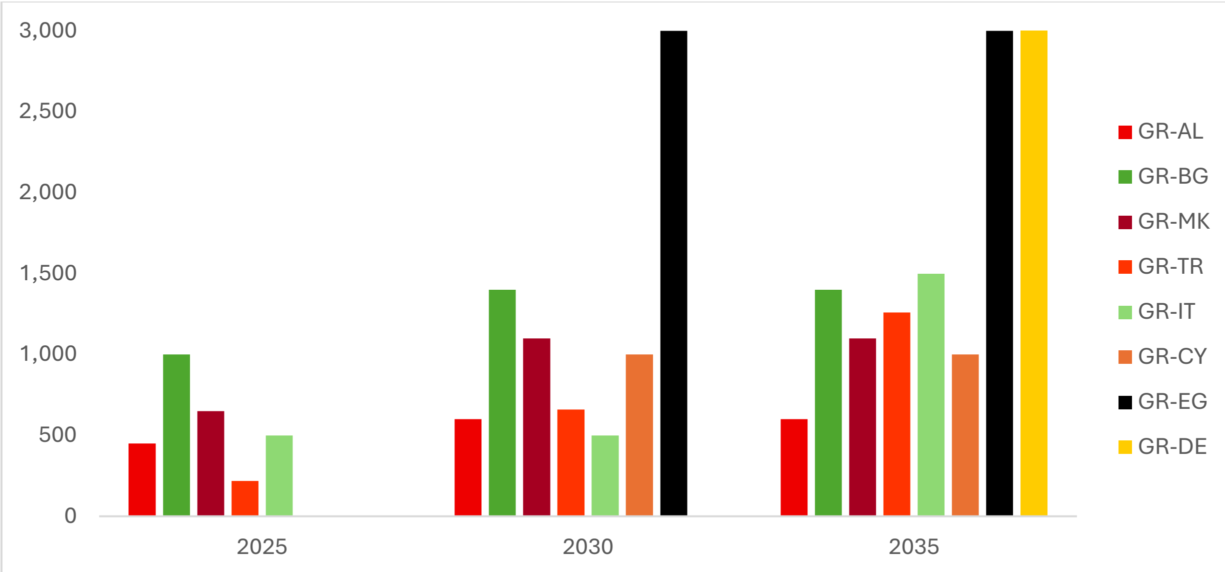

Figure 19 Existing and planned interconnection exports (MW), [Source: IPTO]

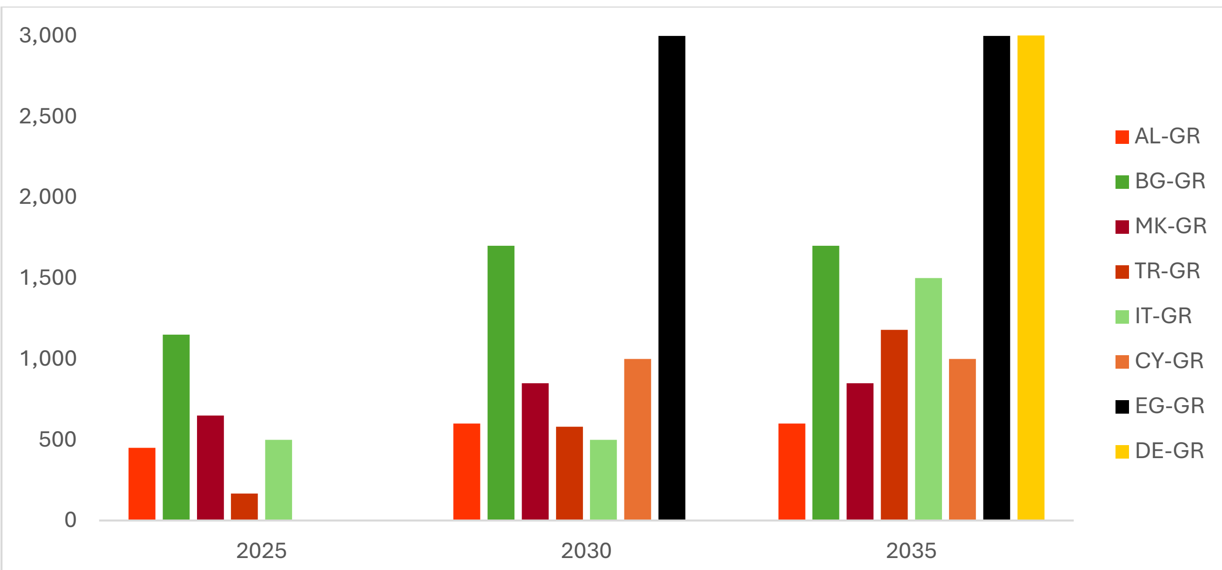

Figure 20 Existing and planned interconnection imports (MW), [Source: IPTO]

Future infrastructure plans are a strategic priority for Greece. Key projects include:

- Greece-Bulgaria (Second interconnection): IPTO has set plans for a new 400kV overhead line linking Nea Santa in Greece with Maritsa East 1 in Bulgaria with nominal transfer capacity of 2,000 MVA, significantly boosting trade between the two countries. As seen in Figure 9, Bulgaria is the primary energy importer for Greece.
- Greece-Egypt Interconnection (GREGY): A 3 GW submarine cable project connecting Egypt's North Mediterranean coast to Attica in Greece. This interconnection will serve as a "green energy bridge", making Greece a “renewable energy corridor”, strategically amplifying its place.

- EuroAsia Interconnector: A submarine cable that linking Greece-Cyprus-Israel, initially announced capacity of 1 GW, aiming to integrate the isolated grids of Cyprus and Israel into the European system.

Cross-border energy flows serve as a key mechanism for price convergence and supply security, linking the country to lower wholesale electricity prices, but at the same time exporting surplus renewable energy generated in the system. This trading dynamic serves as a key factor of Market Coupling. The successful completion of new interconnections, especially the ones with a large transfer capacity are expected to increase the volume of electricity traded and further align wholesale prices across regions. Yet, limitations in transmission capacity can act as bottlenecks, preventing optimal flows and creating a price separation effect between different bidding zones. These limitations serve as a reminder of the importance of insurance of optimal operation of the existing lines, but also the need for new projects, avoiding congestion bottlenecks.

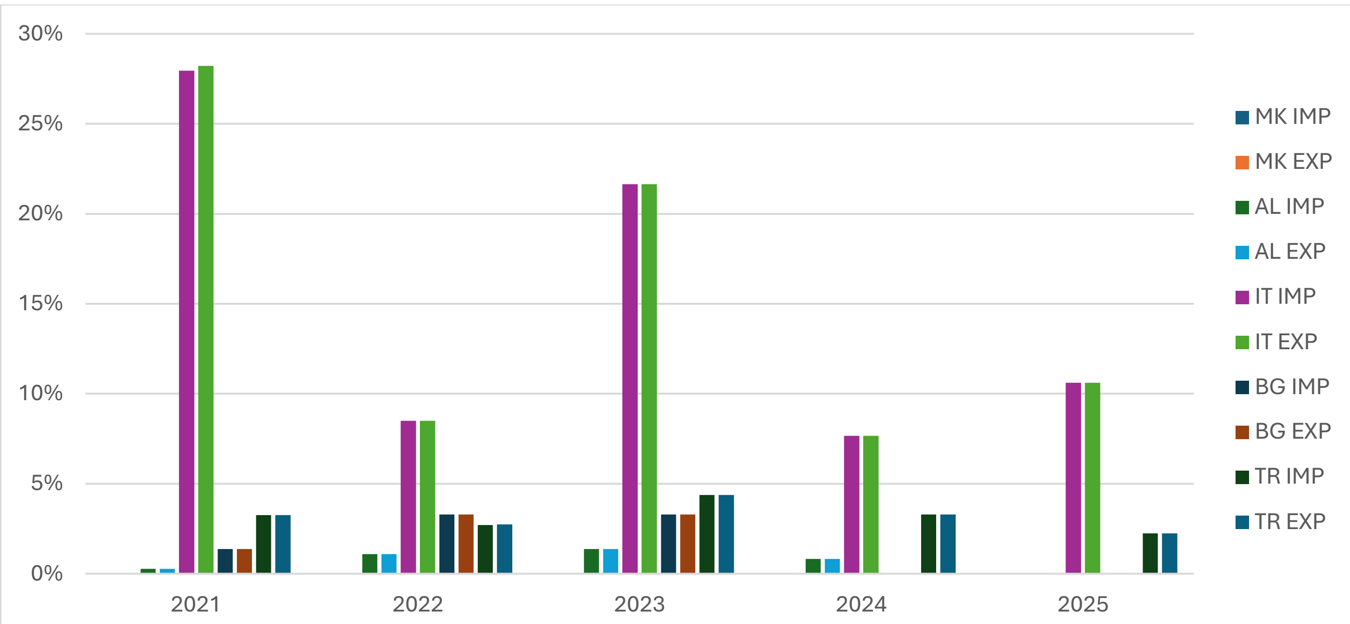

Figure 21 Share of time outage in interconnections (%), [Source: IPTO]

Energy Mix, Demand, and Fuel Price Impacts

Production Energy Mix and Supply-Side Dynamics:

Electricity demand in the Mediterranean region is subject to significant seasonal variations, due to temperature changes, and seasonal tourist attractions. For Greece the case is similar, as during the summer months electricity demand peaks are rather pronounces due to high temperatures and thus need for air-conditioning units, but also due to tourist inflows. During the winter months domestically due to electrification trends, a prodigious part of heating also comes from air-conditioning units. During January of 2025 the electricity demand on the mainland System almost reached 3.65 TWh.

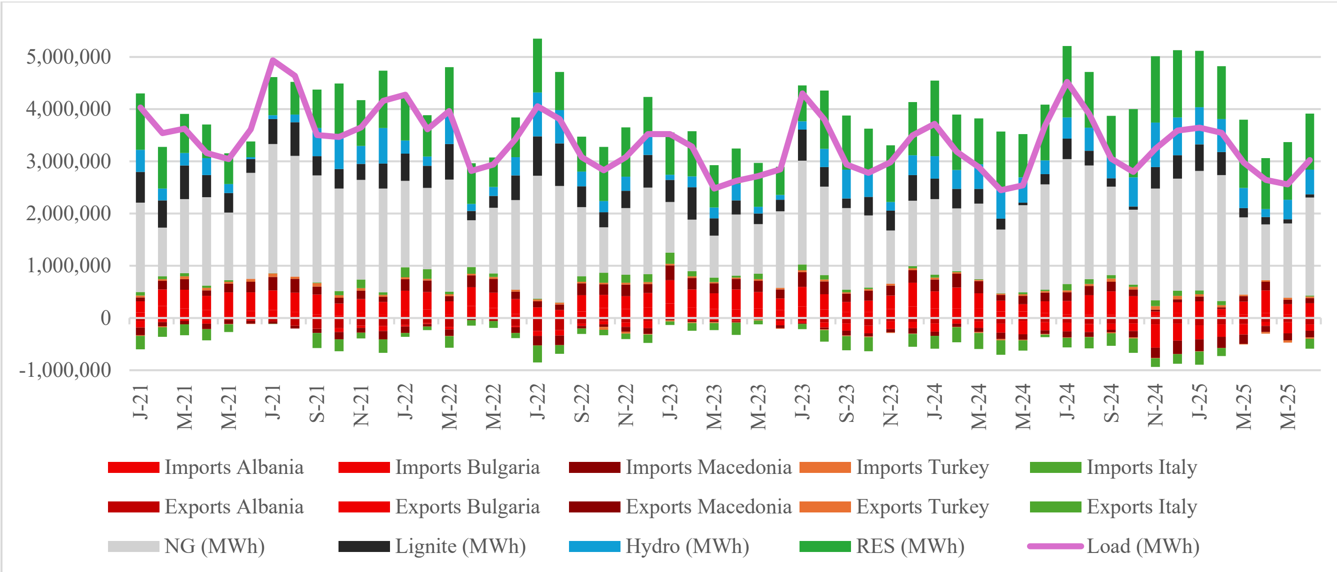

Figure 22 Electricity Mix and System Load for the Mainland Grid-Greece (MWh), [Source: IPTO]

Renewable Energy Sources (RES) Capacities and Generation

Greece has made notable steps in RES integration, this is especially noticeable in Figure 23, with almost 5GW of wind turbines installed and over 7GW of largescale solar PVs. This growth is the central pillar of the country's national climate strategy to meet climate goals and reduce reliance on fossil fuels.

If accounting for the installed RES capacities on the Non-Interconnected Greek islands as well, these numbers add up to 5.012GW for wind turbines and 7.197GW of large-scale solar PVs.

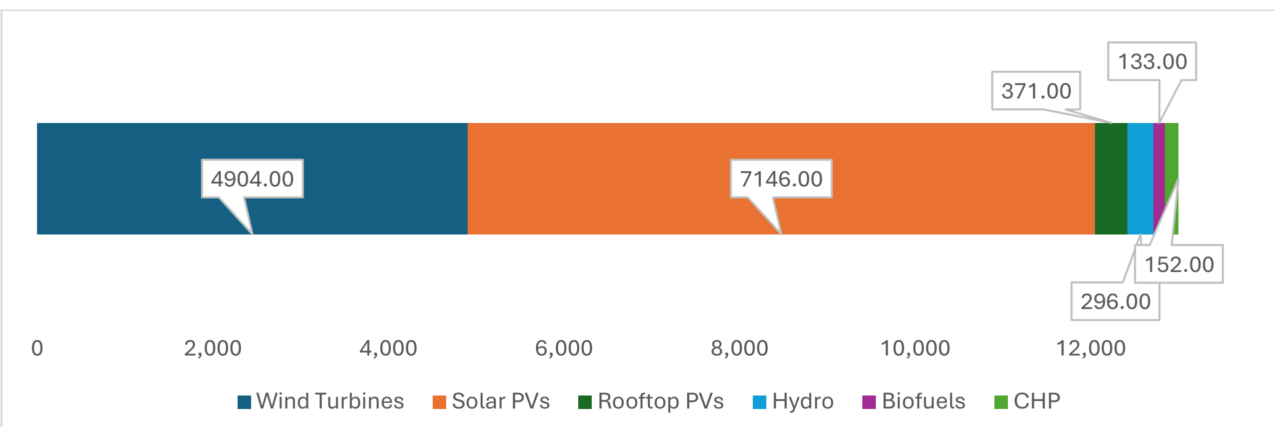

Figure 23 Installed capacities of RES and CHP in Greece (MW), July 2025, [Source: DAPEEP]

The combined effect of this rapid expansion is evident in Greece's electricity mix. For the first time, in 2024, the country not only produced over 50% of clean electricity (RES and Hydro combined), but also became a net-exporter due to this fact. In Q1 and Q2 of 2025, RES and Hydro combined, continued to hold a significant part of the domestic electricity mix. This has led to Greece over the last 3 years occasionally reaching 100% renewables for short time periods, starting from one hour and even reaching seven consecutive hours on March 28th, 2023.

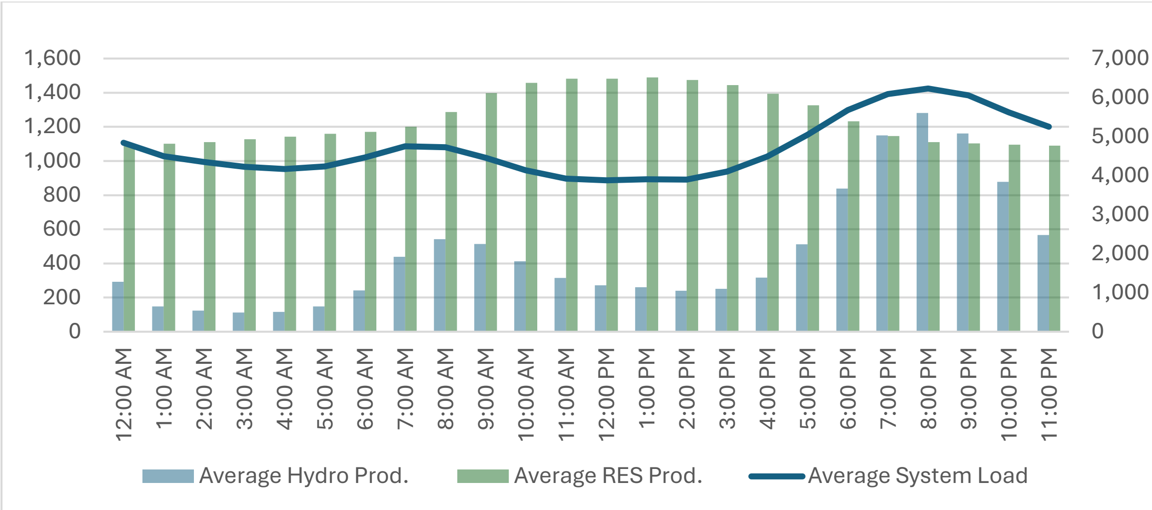

Figure 24 RES and Hydro Hourly Average Generation (MWh), Jan-Jul 2025, [Source: IPTO]

The influx of the zero-marginal-cost generation from non-dispatchable RES has a profound impact on wholesale electricity prices, frequently pushing them to zero or even negative values during periods of high solar irradiation and low demand. Despite this remarkable progress, this dynamic has created a significant and increasingly urgent challenge: the curtailment of renewable energy.

Curtailments occurs when a power plant, despite producing electricity, is forced by the System Operator (IPTO or HEDNO) to reduce its power output or even shut down entirely as the grid cannot absorb the excess generation. The uncontrolled power influx to the grid, can cause congestion problems and instability, as was the case for the Iberian blackout. This structural issue is directly linked to the rapid expansion of non-dispatchable RES without a proper grid infrastructure modernization, and sufficient energy storage deployment. Up to January 2025 RES plants were not obligated to have a Supervisory Control and Data Acquisition (SCADA) device. This caused the System operator to curtail solar PV plants at random, and not being able to calculate the exact curtailed amounts of generated energy.

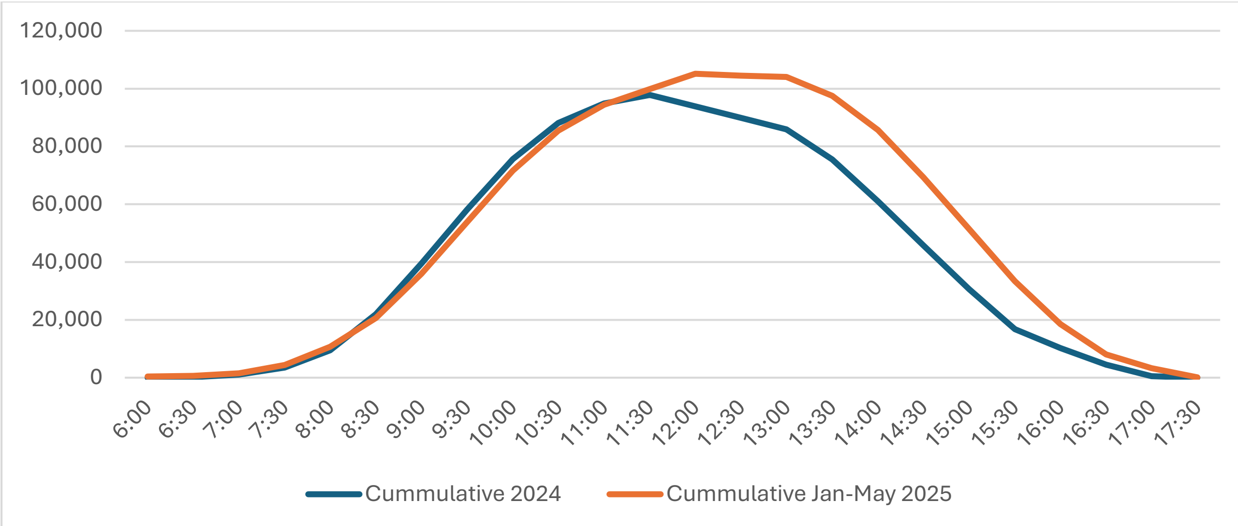

Figure 25 RES Energy Curtailments (MW), Jan 2024 - May 2025, [Source: IPTO]

RES curtailments in 2024 alone reached a high of 900GWh, in 2025 this number has already been surpassed reaching a new high of 1,327 GWh by the end of June. The months with the highest curtailments in 2025 was the Q2 of 2025 reaching 359.1 GWh, 382.5 GWh and 351.7 GWh for April, May and June respectively. Most of these events occurred between 10:00 am and 3:00 pm, when solar PV generation is at its peak, nevertheless the same issue was prominent during the night-hours when only wind turbines were operational.

Negative consequences of RES curtailments include: economic losses – especially for the producers as in most cases they are not compensated, waste of clean energy – the domestic system is forced to rely on expensive and carbon-intensive energy plants to meet the demand, and grid instability – the sudden need for grid operators to reduce RES outputs signifies a challenge for the optimal operation and stability of the grid.

As the installed RES capacities continue to grow, so will the curtailment volume, if key challenges are not addressed. The race toward net-zero does not consist only of new clean energy sources, but also keeping the system in balance.

Conventional Generation and Flexibility

While RES are rapidly expanding, thermal power plants remain the backbone of stability for the Greek electricity system. At the moment, only conventional generation plants can provide flexibility to the system, through ancillary services. The system's flexibility is its ability to adjust generation and respond to demand signal keeping the System in balance and avoiding a potential black-out. Ancillary services ensure grid stability through frequency regulation, voltage control and reactive power support.

The Greek electricity generation fleet relies heavily on NG fired-plants. These units are called to fille the gap between the System's demand and the RES generation. Peaker power plants can quickly respond to the systems needs, either producing, or halt energy generation. This allows IPTO to rapidly adjust generation compensating for sudden drops in non-dispatchable RES output, they are particularly implemented during the evening ramp-up period.

Despite the strong commitment of Greece to phasing out lignite-fired power plants, they still provide a significant part of the baseload power, ensuring a constant supply of electricity. Historically, the Greek electricity mix was lignite, as it was a good that was sourced domestically making it a safe option for any supply chain disruption. In 2010, over 50% of the generated electricity was from lignite-fired plants, that dropped to less than 10% in 2021. Although the last remaining lignite plants are scheduled to fully phase-out by 2028, this may not be the case if the System cannot support RES generated electricity alone.

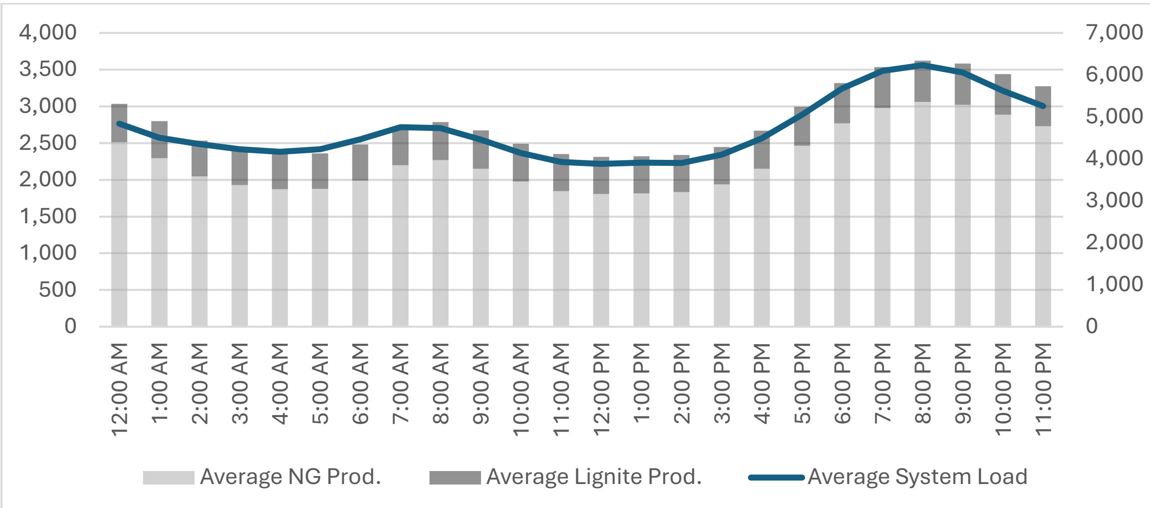

Figure 26 Hourly Average Conventional Generation and System Load (MWh), Jan-Jul 2025, [Source: IPTO]

Impact of Fossil Fuel Prices and EU ETS on Wholesale Prices

Due to the nature of the solution of the equation of the Market Clearing Price (MCP), this includes both prices in DAM and IDM, the selection follows the First Come-First Serve method in compliance with the cheapest order price. The procedure is easily understood from Figure 27 and Figure 28, where the Buy line is the System demand and the Sell line is the System's ability to produce. Every order before the interception of the Sell and Buy curves will be completed, any order to the right of the interception, will be rejected from the System's equation. Usually for the morning hours the Sell orders that hold a higher price are conventionally produced, while during the evening hours (as seen in *Figure 24*) these Sell orders can be either conventional or hydro production.

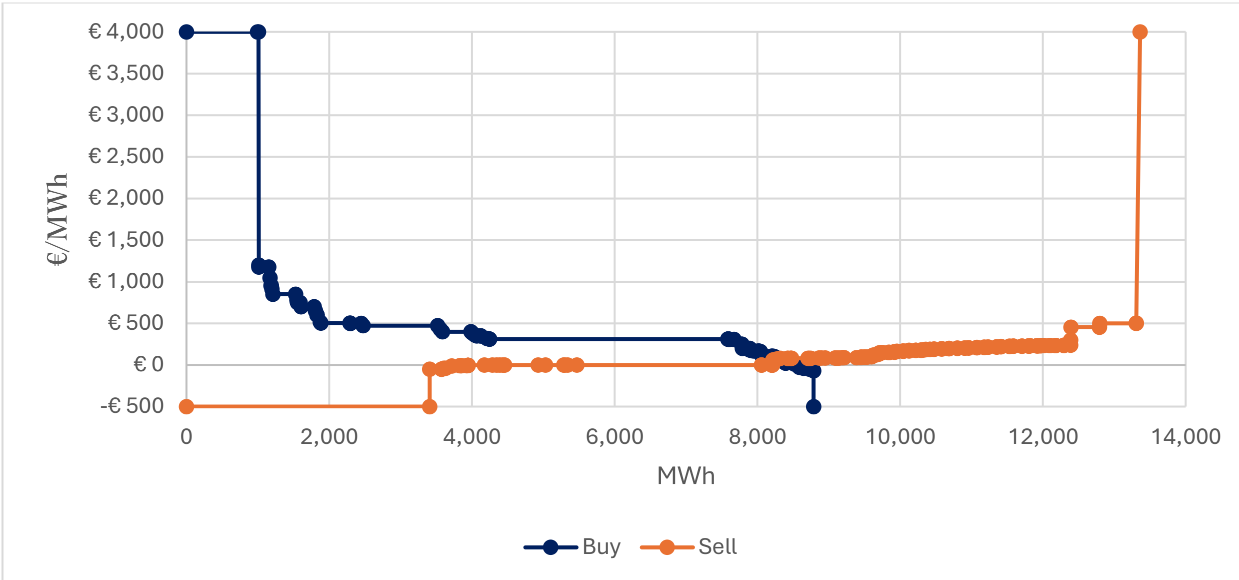

Figure 27 MCP determination for DAM (€/MWh), Sep. 5, 2025, 9:00, [Source: EnEx Group]

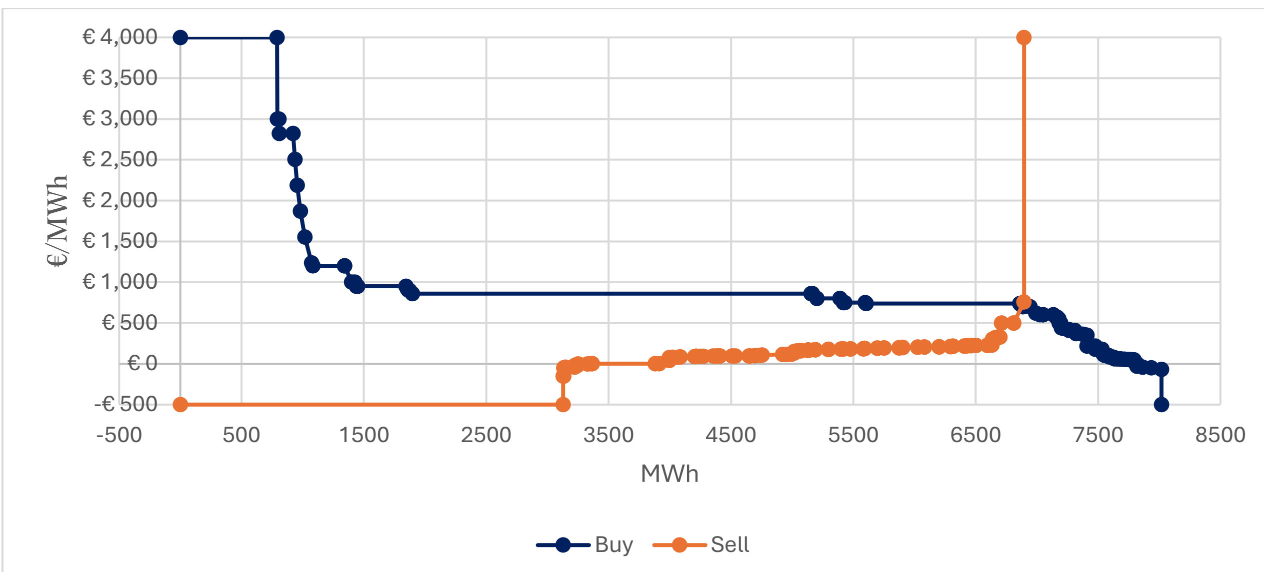

Figure 28 MCP determination for DAM (€/MWh), Sep. 5, 2025, 21:00, [Source: EnEx Group]

For the conventional sources to cover their production cost and keep a profit margin aspect as CO_2 prices and fuel prices should be taken into consideration. As these prices grow, the "asked" price in the Sell curve will also grow. The Figure 29 clearly explains the sudden spike in DAM prices in 2022 (Figure 6), as the domestic electricity mix relies on NG production, and the TTF price spiked, these consequences followed the production price, and thus the MCP across all markets in the wholesale electricity.

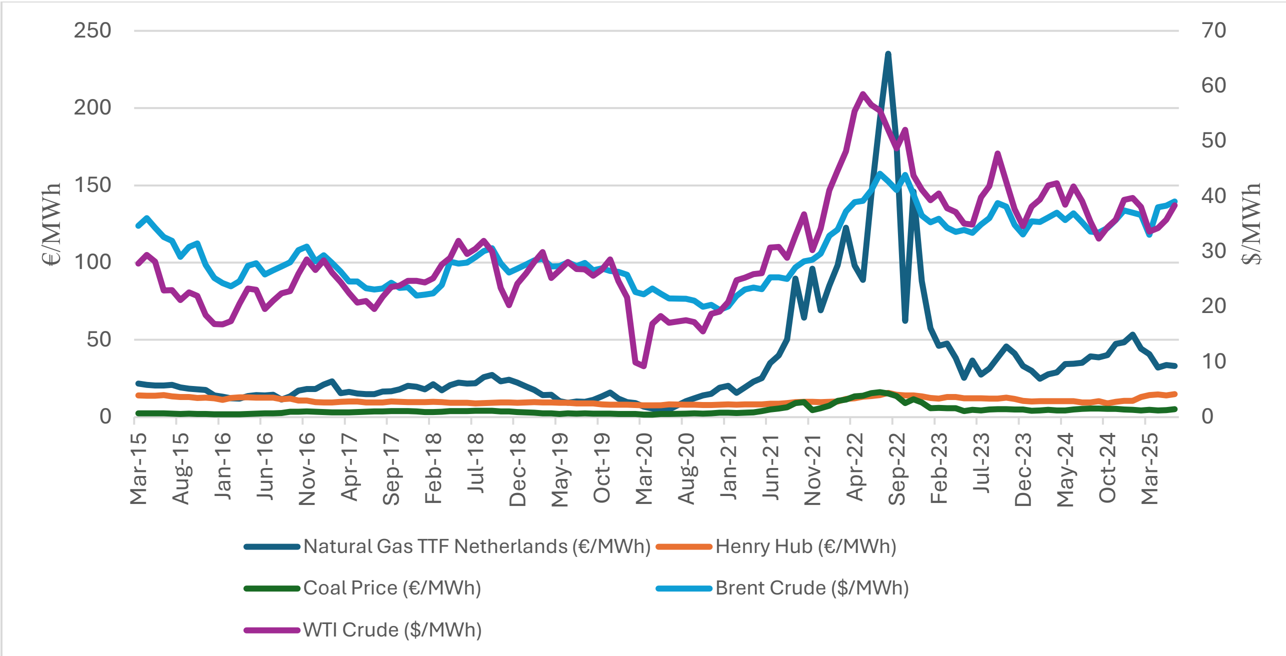

Figure 29 Fossil Fuel Prices, Mar. 2015 – June 2025

Another key driver of conventional plant production cost apart from the fuel price is also the CO_2 emissions per MWh of generated energy and their cost. The cost of CO_2 combined with the EU ETS emissions cap implemented by the EU Commission (first time in 2020), the demand in the wholesale electricity market (both domestic demand and export needs – they are solved in the same equation), and the profit margin, drive the prices in the wholesale electricity market.

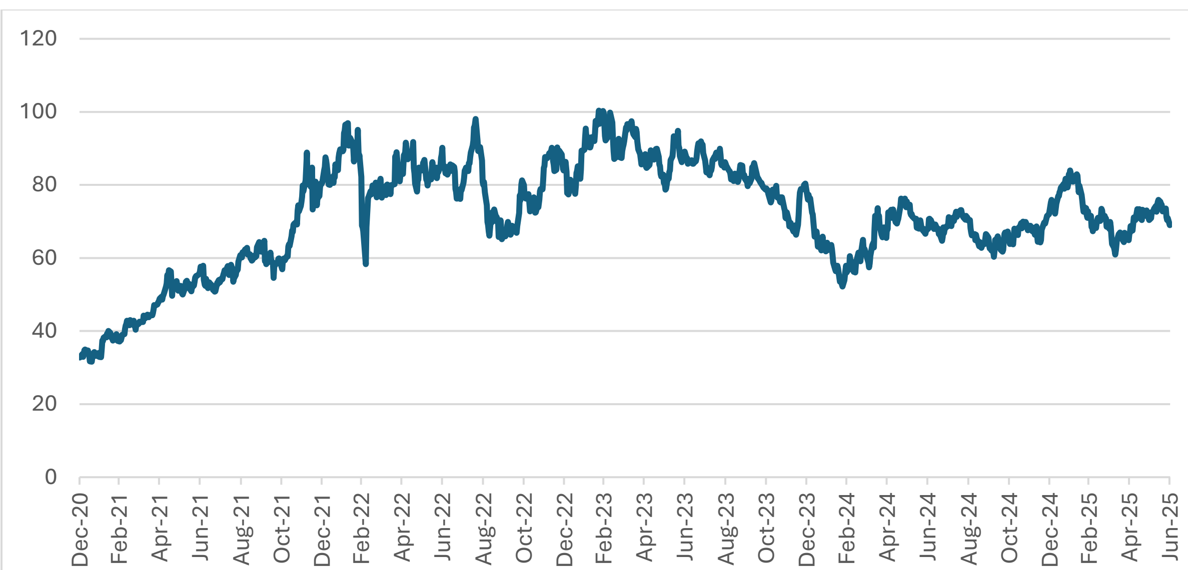

Figure 30 EU ETS prices (€/Tone), Dec 2020 - Jun 2025, [Source: STATISTA]

A predictive model for Day-Ahead Market Electricity Prices

The MCP of each market division is a complex and highly volatile variable influenced by a myriad of factors, both domestic and external. Since most traded quantities go through DAM, and the IDMs are mainly used for correction, we are focusing on DAM. While the marginal pricing mechanism provides a theoretical framework for price formation, real-world market dynamics are shaped by variables far beyond the simple interplay of supply and demand. This section examines these correlations and dependencies at an hourly level to develop a more robust predictive understanding of the Greek DAM's price behavior.

Our analysis considers a large set of variables, systematically excluding those with an insignificant impact on the MCP to focus on the key drivers. The model aims to dissect the intricate relationships between domestic generation, cross-border flows, and international commodity markets, which together define the Day-Ahead Price

Data and Methodology

The dataset used for this analysis spans from January 1, 2021, to July 14, 2025. This period was carefully selected ensuring the data reflects the full implementation of the Target Model in the Greek market. This timeframe also includes the pivotal operational dates of key interconnections with Italy (since 2021) and Bulgaria (since 2023), allowing for a more accurate assessment of their impact on the Greek market.

The following variables were included in the analysis:

1. MCP (€/MWh): The Day-Ahead Market price for each hourly interval, serving as the dependent variable.
2. Water Reservoir Level (MWh): A prediction of Greece's water reservoir levels for the next month, as hydropower generation can be scheduled based on anticipated water availability.
3. Difference with Average Water Reservoir [2018-2020] (%): This variable measures the statistical difference between current reservoir levels and the average levels of the same period three years prior.
4. Water Reservoir Level Shifted: Reservoir levels lagged by 1 to 12 months to explore potential long-term correlations.
5. Imports & Exports (MWh): Hourly energy flows with interconnected regions (Italy, Bulgaria, Turkey, Albania, and North Macedonia).
6. NTC (MW): The Net Transfer Capacity, representing the hourly available transmission capacity between Greece and its neighbors.
7. System Load (MWh): The mainland's hourly electricity demand.
8. NG Production (MWh): Electricity production from domestic natural gas plants.
9. Lignite Production (MWh): Electricity production from domestic lignite plants.
10. Hydro Production (MWh): Electricity production from domestic hydropower plants.
11. RES Production (MWh): Electricity production from wind and solar PV plants.

12. CO_2 price €/ton: The daily cost of carbon emissions under the EU Emissions Trading System (EU ETS).

13. Demand: The total demand in the wholesale market, including cross-border interconnection demand.

14. Demand Squared: A variable to capture potential non-linear effects and extreme demand fluctuations.

15. Demand PPT (Priority Price Takers): The volume of accepted orders at a fixed priority price, which can influence the final MCP.

16. RES with Hybrid Orders: A variable representing the more complex bidding behavior of renewable energy sources, which can use hybrid orders with a combination of fixed and variable price segments.

17. Residual Demand: The demand that is not met by renewable energy sources, and therefore must be supplied by conventional generation.

18. HU MCP (€/MWh): The Day-Ahead Market price in Hungary, with a 24-hour lag, to analyze price synchronization with Central European markets.

Correlation Analysis and Initial Findings

An initial correlation matrix was constructed to provide a high-level overview of the relationships between the variables. As depicted in Figure 31, the analysis revealed several key insights.

The highest correlations with the Greek DAM's MCP were observed with international commodity prices. The Hungarian MCP showed a very high correlation of 0.85, suggesting a strong price synchronization with Central Europe, even with a 24-hour lag. This highlights Greece's increasing integration into the broader European market. The strong positive correlations with the TTF and PSV (0.81 in both cases) NG price indices are particularly significant. This confirms that the Greek market's volatility is directly tied to the price of natural gas, which acts as the marginal price setter for the system. The correlation with CO_2 prices (0.36) also highlights the impact of the EU ETS on generation costs, making fossil fuels more expensive and pushing the merit order in favor of renewables.

Domestically, the variable with the highest correlation was Residual Demand (0.38), confirming its central role in price formation. When residual demand is high (i.e., when renewables are not generating enough power), the system must rely on expensive conventional plants, driving up the MCP. This is also reflected in the positive correlations with Lignite (0.36) and NG production (0.33).

Interestingly, the analysis also revealed some counterintuitive findings. For instance, the correlations for Imports from Bulgaria (-0.15) and Exports to Turkey (-0.26) are negative, while Exports to Albania (0.23) and Imports from Italy (0.26) are positive. This indicates a complex, bidirectional flow of energy that is not solely driven by a simple "high prices, import more" dynamic. Instead, it suggests a more nuanced interaction influenced by factors like congestion on interconnections and the specific needs of neighboring grids.

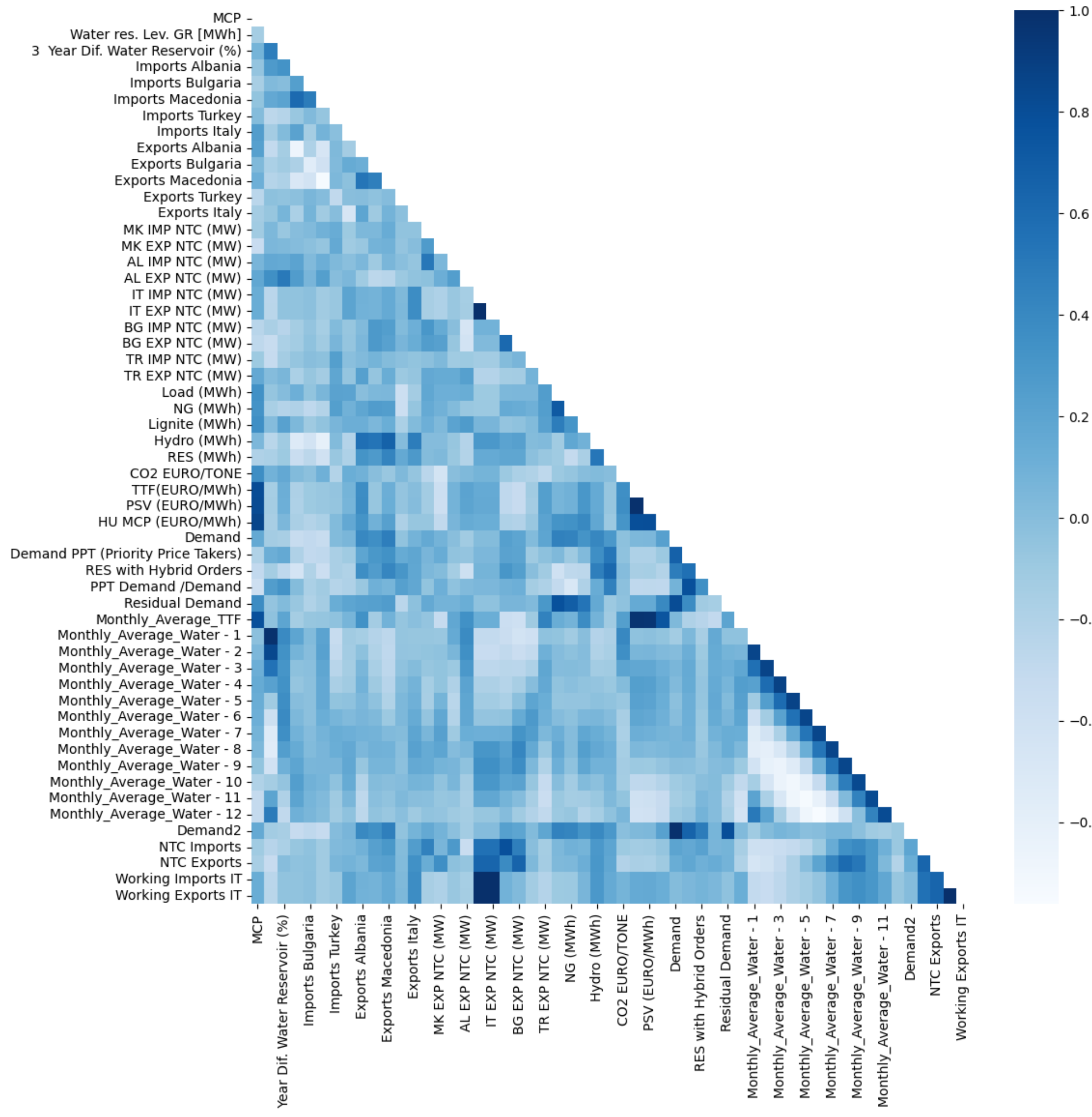

Figure 31 Visual representation of the Correlations of the variables used for the 24h period

Limitations of a Single-Set Analysis

While the overall correlation matrix provides valuable initial insights, a key limitation of analyzing the entire 24-hour period as a single set is that it obscures the distinct dynamics of different hours of the day. As extensive literature suggests, the factors influencing the DAM price in the morning are vastly different from those at midday (the "solar crash") or in the evening (the "duck curve" ramp-up). For example, the impact of solar production is highly correlated with the midday hours, but its influence is minimal at night. Similarly, the role of NG is amplified during peak demand hours. Therefore, to paint a clearer and more accurate picture, our next step will involve splitting the data into 24 individual hourly sets. This granular approach will allow us to build a more robust and granular predictive model that accounts for the unique characteristics of each hour.

We have chosen the 9:00 AM Market Time Unit (MTU), Greek time, for this specific regression analysis because it represents a critical transition period in the Greek electricity market. At 9:00 AM, the market is exiting the low-demand, low-price hours of the night and is entering a period of significant price and demand increases. This hour is characterized by a rapid surge in electricity consumption from residential, commercial, and industrial sectors as the country wakes up and operations begin.

This morning increase occurs before the peak solar PV generation which can significantly impact the market. Therefore, the 9:00 AM price is primarily influenced by the system's reliance on dispatchable conventional generation, particularly NG, to meet the rising demand. The analysis of this specific hour provides a clear picture of how prices are set by fundamental drivers, isolating the effect of demand and fossil fuel costs from the later, more complex interplay with solar power.

Model Selection

The predictive model was deliberately chosen for its simplicity and interpretability, allowing for a clear and direct translation of changes in input variables to the model's end results. To achieve this crucial objective, a Linear Regression (LR) model was selected as the optimal scenario for this work. This choice is predicated on three primary strengths that are essential for effective energy market analysis and policy recommendations.

LR's greatest advantage is the intuitive nature of its coefficients. Unlike more complex, "black-box" machine learning models, LR provides a transparent view of the relationship between each independent variable and the dependent variable. Each coefficient represents the average change in the predicted outcome for a one-unit change in the predictor, holding other variables constant. This allows us to directly infer the impact of each variable on the final electricity price. For example, the model clearly shows that a €1/MWh increase in NG prices leads to a predictable change in the DAM price. This direct, quantitative relationship is invaluable for policymakers and market analysts who need to understand not just what the price will be, but why it will be that price.

To make a fully adjusted model though, ensuring the best possible fit and explainability the Ordinary Least Squares (OLS) regression has been selected. This method combines the positive attributes of a LR, easily explaining changes in the deployed variables but at the same time ensures the best-fitting coefficients for the relationship though the process of minimizing the sum of squared residuals[1]. By squaring the residuals before summing them, OLS ensures that both positive and negative errors are treated equally and that larger errors are penalized more heavily. This minimization process yields the unique set of coefficients that creates the best-fitting straight line through the data.

The model is designed to exclusively interpret the price variation based on external factors—variables that do not directly participate in the supply-and-demand equation's solution in the DAM. The rationale behind this is to avoid multicollinearity and to isolate the drivers of the price. The variables that directly affect the DAM price, such as production from RES and thermal units, and system load, are an immediate result of the market's equation solution and are thus excluded from

[1] Residual: the vertical distance between an actual data point and the model's predicted line.

our model. Instead, we have selected external variables that influence the market's underlying conditions, thereby shaping the price indirectly. After consideration based on the p-value[2].

Explanation of Key Variables

The variables for the model were selected for their high correlation while ensuring the external nature:

- Italian NG and CO_2 prices, as expected a significant influencing factor of the MCP formulation is the cost of conventional fuels. As shown in Figure 26, NG is a major component of the Greek electricity mix. A direct impact of NG demand for the domestic electricity generation is the immediate correlation of the Italian PSV price, as Greece imports significant amounts of NG, largely from Italy. As PSV and TTF prices are both referring to NG prices and as depicted in Figure 31 they are strongly correlated, the PSV price could easily be substituted by the TTF index. Furthermore, due to emissions in conventional production, the cost of CO_2 is a crucial factor, directly increasing the operational costs of conventional fuel plants, making them the marginal price setters in high demand hours of the day.
- The Hungarian DAM price with a 24 hour lag was included because it experiences similar market movements showing a similar trend to Greece. Although Hungary has a different electricity mix (Figure 16), and is geographically to our north, when examining it on a dispatchable and non-dispatchable generation level it shows great similarity to the case of Greece. This suggests a broader regional price synchronization that is not immediately obvious from a geographic perspective. At the same time a model without the inclusion of this variable shows way less accurate results.
- The water reservoir levels in Greece play a vital role in the planning and scheduling of hydropower generation. The dispatch decision is often made months in advance, based on the expected conditions and past reservoir levels. The inclusion of the current reservoir level along with the level from 10 months ago helps the model capture both the immediate impact of available hydro energy and the long-term planning, including the problems of water-shortage (especially during the summer months) decisions that affect the market. Water-shortage in the reservoirs brings the MCP higher, as it is a zero-emission process, but contrary to wind and PV generation it is dispatchable.
- Although Turkey is not the primary electricity exporter for Greece, the availability of export capacity to Turkey is an attention-grabbing variable. The small but frequent exports to Turkey suggest that it acts as a valuable outlet for surplus electricity from other interconnections. This capacity allows Greece to sell excess energy that it might otherwise be forced to curtail, thereby generating revenue and increasing overall market efficiency.
- The domestic demand and supply quantities are what ultimately solve the market's price-setting equation. The inclusion of total demand in the wholesale market (including exports) allows the model capture the fundamental pull on the system, which determines the final MCP.
- The Residual Demand variable is the key to understanding the Greek market's structure. As RES producers submit their bids at very low prices (or even negative prices, as in the case with Renewable Energy Sources Operator & Guarantees of Origin (DAPEEP SA) to ensure market participation), they are always the first to be dispatched. This means that the final

[2] P-value: the probability of obtaining observed data, or data more extreme, assuming the null hypothesis is true. Any variable with p-value above 0.05 is excluded instantly.

price setting comes from the more expensive, dispatchable (both conventional and hydro) sources. The residual demand represents the load that these conventional plants must cover after all available RES have been utilized, making it a powerful proxy for the final price.

The model's R-squared of 0.807 for the test-set is a very strong result, demonstrating that a simple linear model can capture a large portion of the price volatility. A more complex model only marginally improves upon this; making it not be worth the added computational cost and loss of interpretability. OLS is a quick and efficient way to confirm that the chosen variables have a strong, linear relationship with the target variable-the MCP of DAM.

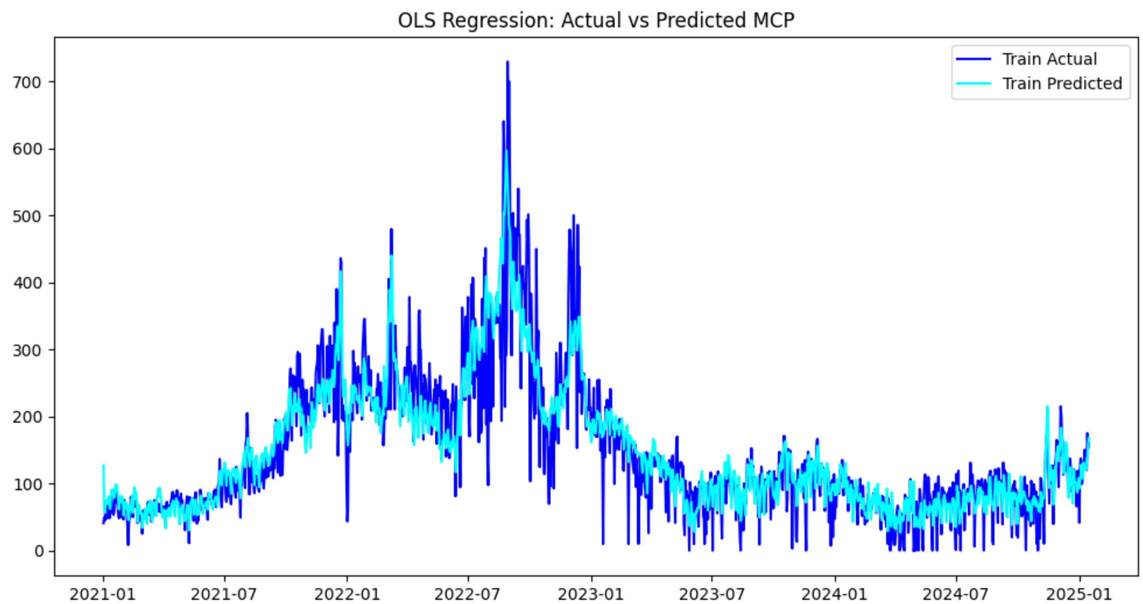

Figure 32 Actual vs Predicted values for the 9:00AM OLS model Train-set

When implementing the model to the test-set the R-squared value drops to 0.62, indicating a not as strong predicting power, but still explaining the relationships between the variables and their influence on the DAM's MCP, while at the same time a potential overfitting to past events (e.g. high NG prices during Q2-Q3 in 2022). The lower R-squared is also related to the fact that the Test-set is rather smaller and focused on a specific year (February-July 2025), making it rather biased.

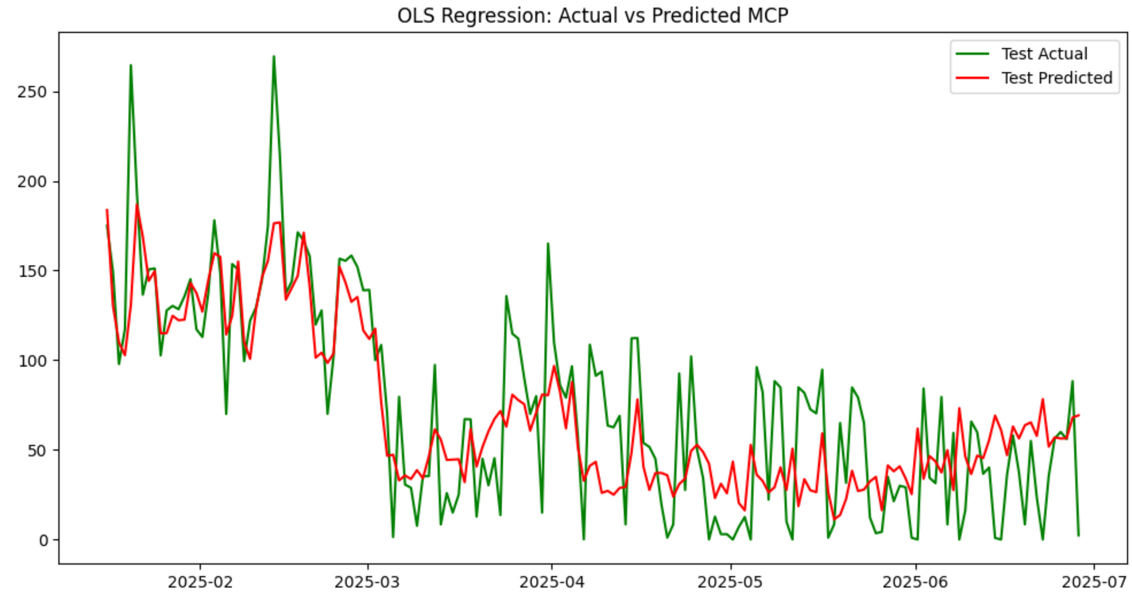

Figure 33 Actual vs Predicted values for the 9:00AM OLS model Test-set

Lessons Learned and Conclusions

Since the full implementation of the Target Model in the Greek wholesale electricity market, the journey can serve as a case study regarding the complexities a country can face in the energy transition. While the new framework was introduced to foster a more competitive and transparent process in the wholesale market, experience demonstrated a need in more than just simple RES integration for achieving energy transition while keeping the System stable, secure, and affordable. A stable transition demands new strategic investments, policy formulation - as to make the new technologies both achievable, but bankable as well, but also a holistic approach that will take into consideration the upcoming challenges.

Key Learnings

The rapid and effective deployment of wind turbines and solar PVs in Greece may supply a great part of the electricity demand, and achieving the climate goals set by the EU. However, the integration of non-dispatchable RES alone is not enough, as significant challenges of ever-growing PV generation curtailment for the mainland System, are increasingly visible with each passing year. New highs are reached each month with 1,327 GWh of curtailed RES energy by the end of June 2025, surpassing the cumulative curtailed energy in 2024. This waste of clean, zero-marginal-cost energy signifies economic losses both for RES producers but the country as well, while forces the System to keep relying on more expensive and carbon-intensive generation technologies to meet the demand. Even though up to this moment only solar PV curtailment was present in the mainland System, in the NIIs the problem is phased by wind turbines, signifying the need for change.

Price volatility analysis in Greece (including the "duck curve" and "canyon curve" phenomena) underscores a foundational truth: a high penetration of non-dispatchable renewables requires a highly flexible energy system. As thermal (lignite) plants are phasing out, Greece's grid, designed for dispatchable (conventional) sources, relies on peaker plants to fill the gaps. The lack of implemented utility-scale energy storage and a smart-grid infrastructure is a major bottleneck that prevents the

System from absorbing excess renewable energy during peak production and discharging it during high-demand (and thus high-cost) periods.

When comparing Greece to countries as Italy, Bulgaria, and Denmark a highlight of the immense value of strong cross-border interconnections arises. Limited cross-border capacity can lead to market isolation and price divergence, wasting zero-marginal cost energy in one region while facing high prices in another. The Iberian blackout incident serves as a powerful reminder that while market decoupling can offer price protection, it can also compromise grid security and resilience. For Greece, being more interconnected would allow for surplus renewable energy exports and cheaper power imports when it is most needed, thereby stabilizing prices and increasing supply security.

A crucial distinction is revealed between wholesale and retail markets. A retail consumer's bill is not a direct reflection of the volatile wholesale price, but also includes regulated network costs, taxes, and levies. While the merit-order effect of cheap RES pushes down the energy component of the bill, the costs associated with grid modernization, ancillary services, and system balancing can increase network charges and levies. A successful transition requires managing the full bill, not just the wholesale price.

Conclusions

The experience of Greece provides a fundamental case study showing that the energy transition is far more than a simple renewables deployment race. It rather is a complex, multi-faceted process calling for bold policy reforms, better regional integration, and major strategic investments in grid flexibility. To successfully transform the market and make it resilient to external distresses, Greece needs to address acute areas as to build a secure and sustainable energy system.

First, making grid flexibility and storage is paramount. Future policy must aggressively incentivize the deployment of utility-scale energy storage and smart grid technologies. This is the only path as to effectively address the growing problem of renewable energy curtailments, stabilize prices, and reduce the system's reliance on expensive and carbon-intensive conventional generation. By investing in technologies like battery storage and pumped hydro or green hydrogen (for short and medium-term solution), Greece can store excess renewable energy produced during the day and discharge it during evening peak demand, ensuring that each clean produced kWh of power is used efficiently.

Second, expedite strategic interconnection projects. The planned interconnections (GREGY and EuroAsia Interconnector) are strategic obligations. They will enable the country to function as a regional energy hub, optimizing the use of its clean energy resources and enhancing both price convergence and supply security across the Mediterranean and the rest of Europe. For a seamless, interconnected system that can handle the volatile, intermittent nature of renewables and provide a safety net against domestic supply disruptions such projects are invaluable.

Finally, the market structure itself calls for reforms to incentivize flexibility. The current market structure is not yet fully equipped to handle the unique challenges of a high-RES system. Future reforms should consider new capacity mechanisms that appropriately compensate flexible assets for their availability providing stability and reliability, especially as conventional generators are phased out. The value created by cheap renewable energy should be passed on to the final consumer in a transparent and sustainable manner, closing the gap between wholesale price volatility and retail prices. The future of electricity is not in a single technology, but in a dynamic, interconnected, and flexible system that can harness the full potential of its clean energy resources while ensuring security and affordability for its consumers.