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Ενεργειακά μοντέλα πρόβλεψης με έμφαση στη βιώσιμη ανάπτυξη και την κλιματική αλλαγή

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Energy forecasting models with emphasis on sustainable development and climate change

By Dimitrios Panagopoulos

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«Το έργο που εκπονήθηκε έχει γραφτεί από εμένα αποκλειστικά στο σύνολό της. Δεν έχει υποβληθεί ούτε εγκριθεί στο πλαίσιο κάποιου άλλου μεταπτυχιακού προγράμματος ή προπτυχιακού τίτλου σπουδών στην Ελλάδα ή στο εξωτερικό, ούτε είναι εργασία ή τμήμα εργασίας ακαδημαϊκού ή επαγγελματικού χαρακτήρα.

Οι πηγές στις οποίες ανέτρεξα για την εκπόνηση της συγκεκριμένης εργασίας αναφέρονται στο σύνολό τους, κάνοντας πλήρη αναφορά στους συγγραφείς, τον εκδοτικό οίκο ή το περιοδικό, συμπεριλαμβανομένων και των πηγών που ενδεχομένως χρησιμοποιήθηκαν από το διαδίκτυο. Παράβαση της ανωτέρω ακαδημαϊκής μου ευθύνης αποτελεί ουσιώδη λόγο για την ανάκληση του διπλώματός μου.»

Στους φάρους της ζωής μου, τους γονείς μου.

Ευχαριστίες

Θα ήθελα να εκφράσω τις θερμές μου ευχαριστίες προς τη Διευθύντρια του Μεταπτυχιακού Προγράμματος Σπουδών, κα. Κοτταρίδη, για το όραμα και την έμπνευση της στη δημιουργία του προγράμματος. Χάρη στη δική της πρωτοβουλία, είχαμε την ευκαιρία όχι μόνο να αποκτήσουμε πολύτιμες γνώσεις, αλλά και να απολαύσουμε ένα ξεχωριστό ακαδημαϊκό ταξίδι. Θα ήθελα επίσης να ευχαριστήσω όλους τους διδάσκοντες του προγράμματος για τις γνώσεις, την καθοδήγηση και την υποστήριξη που προσέφεραν κατά τη διάρκεια των σπουδών.

Τέλος, ένα ιδιαίτερο ευχαριστώ οφείλω στον επιβλέποντα της παρούσας εργασίας, κ. Πολέμη. Με την καθοδήγηση, τις παρατηρήσεις και την εμπιστοσύνη του έβαλε τον σπόρο από τον οποίο γεννήθηκε και αναπτύχθηκε η παρούσα διπλωματική εργασία.

«Παιδείας αι μεν ρίζαι πικραί, καρποί δε γλυκείς.»

- Αριστοτέλης

List of Abbreviations

Abbreviation	Definition
ACER	Agency for the Cooperation of Energy Regulators
ADMIE	Independent Power Transmission Operator
ADF	Augmented Dickey–Fuller Test
ARIMA	Autoregressive Integrated Moving Average
CCGT	Combined Cycle Gas Turbine
DAM	Day-Ahead Market
ENTSO-E	European Network of Transmission System Operators for Electricity
ETP	Extended Transition Point
EU	European Union
HEnEx	Hellenic Energy Exchange
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
MCP	Market Clearing Price
MWh	Megawatt-hour
PP	Phillips–Perron Test
RAE	Regulatory Authority for Energy
RES	Renewable Energy Sources
SARIMA	Seasonal Autoregressive Integrated Moving Average
TTF	Title Transfer Facility (Dutch Natural Gas Benchmark)

Ενεργειακά μοντέλα πρόβλεψης με έμφαση στη βιώσιμη ανάπτυξη και την κλιματική αλλαγή

Σημαντικοί Όροι:
Πρόβλεψη Τιμών Ηλεκτρικής Ενέργειας, Βιώσιμη Ανάπτυξη, Κλιματική Αλλαγή, Ελληνική Αγορά Ηλεκτρικής Ενέργειας, Τιμή Εκκαθάρισης Αγοράς (MCP), Ανανεώσιμες Πηγές Ενέργειας (ΑΠΕ), Ενεργειακή Μετάβαση, Φυσικό Αέριο

Περίληψη

Τα τελευταία χρόνια, οι αγορές ηλεκτρικής ενέργειας μεταβάλλονται με ταχύ ρυθμό. Οι Ανανεώσιμες Πηγές Ενέργειας διεισδύουν ολοένα και περισσότερο, οι αγορές γίνονται πιο διασυνδεδεμένες μεταξύ τους και οι τιμές των καυσίμων μεταφέρονται ευκολότερα από χώρα σε χώρα. Έχει πλέον διαμορφωθεί ένα περιβάλλον στο οποίο η πρόβλεψη των τιμών ηλεκτρικής ενέργειας γίνεται όλο και πιο δύσκολη. Αυτό σημαίνει ότι πρέπει να εξεταστεί το ενδεχόμενο αλλαγής της προσέγγισης που ακολουθείται στην πρόβλεψη των τιμών ηλεκτρικής ενέργειας. Χρειάζεται να αναπτυχθεί μια προσέγγιση που να υπερβαίνει τις συμβατικές μεθόδους.

Η παρούσα διπλωματική εργασία εξετάζει τη χονδρεμπορική αγορά ηλεκτρικής ενέργειας στην Ελλάδα. Η περίοδος μελέτης καλύπτει τα έτη 2012–2025 και διερευνά τον τρόπο με τον οποίο διαμορφώνονται οι τιμές ηλεκτρικής ενέργειας υπό τις συνθήκες της ενεργειακής μετάβασης. Στόχος της έρευνας είναι να επιχειρήσει να απαντήσει στο ακόλουθο ερώτημα: Είναι αρκετή η αύξηση του μεριδίου των Ανανεώσιμων Πηγών Ενέργειας ώστε να οδηγήσει την αγορά σε χαμηλότερες και σταθερότερες τιμές ή υπάρχουν και άλλοι μηχανισμοί που διατηρούν την αγορά σε κατάσταση αστάθειας;

Για τη μελέτη αυτή αναπτύχθηκε ένα οικονομετρικό μοντέλο πρόβλεψης, το οποίο βασίζεται σε μηνιαία δεδομένα από την ελληνική αγορά ηλεκτρικής ενέργειας και σε διεθνείς ενεργειακούς δείκτες. Στο πλαίσιο της ανάλυσης εξετάζεται πώς η Τιμή Εκκαθάρισης Αγοράς (Market Clearing Price - MCP) συνδέεται με τη ζήτηση ηλεκτρικής ενέργειας, τις τιμές του φυσικού αερίου, τη συμμετοχή των Ανανεώσιμων Πηγών Ενέργειας, τις συνθήκες εξισορρόπησης και τη λειτουργία της αγοράς. Παράλληλα, εξετάζεται αν η μεγαλύτερη συμμετοχή των ανανεώσιμων πηγών συνδέεται με πιο σταθερές τιμές ή αν δημιουργούνται νέες πιέσεις και περιορισμοί στο

σύστημα. Για τον λόγο αυτό εισάγεται ο Δείκτης Εκτεταμένου Σημείου Μετάβασης (Extended Transition Point - ETP).

Παρά τη σημαντική αύξηση των Ανανεώσιμων Πηγών Ενέργειας, η ελληνική αγορά εξακολουθεί να επηρεάζεται σε μεγάλο βαθμό από τις τιμές του φυσικού αερίου, τις ανάγκες εξισορρόπησης και την ευελιξία του συστήματος. Παράλληλα, προκύπτει ότι η μετάβαση σε καθαρότερες μορφές ενέργειας δεν αρκεί από μόνη της για να οδηγήσει σε χαμηλότερες ή σταθερότερες τιμές ηλεκτρικής ενέργειας. Η ανάπτυξη της αποθήκευσης ενέργειας, η μεγαλύτερη ευελιξία του συστήματος και η μικρότερη εξάρτηση από τα ορυκτά καύσιμα εξακολουθούν να έχουν καθοριστική σημασία.

Energy forecasting models with emphasis on sustainable development and climate change

Keywords: Electricity Price Forecasting, Market Clearing Price (MCP), Sustainable Development, Climate Change, Energy Transition, Renewable Energy Sources, Natural Gas, Greek Electricity Market.

Abstract

In recent years, electricity markets have been changing at a rapid pace. Renewable Energy Sources are penetrating increasingly, markets are becoming more interconnected with one another, and fuel prices are shifting more easily across countries. An environment has now emerged in which forecasting electricity prices is becoming progressively more difficult. This means that the possibility of changing the approach to electricity price forecasting must be considered. An approach should be developed that goes beyond conventional methods.

This dissertation examines the Greek wholesale electricity market. The period under study covers the years 2012–2025 and investigates the way electricity prices are formed under the conditions of the energy transition. The objective of this study is to attempt to answer the following question: Is a higher share of renewable energy sources sufficient to lead the market toward lower and more stable prices, or are there other mechanisms that keep the market in a state of instability?

To serve this purpose, an econometric forecasting model has been developed using monthly data from the Greek electricity market as well as international energy sources. The analysis links the Market Clearing Price to factors such as electricity demand, natural gas prices, renewable energy penetration, system balancing conditions, and market operation. At the same time, an effort is made to examine whether price behavior improves as electricity generation from renewable energy sources increases, or whether new pressures and limitations begin to emerge. For this reason, the study introduces the Extended Transition Point (ETP) Index.

The findings answer these questions and indicate the way forward. The Greek market is influenced to a decisive extent by natural gas prices, balancing requirements, and system flexibility, despite the expansion of Renewable Energy Sources. The

conclusion reached by this dissertation is that the transition to cleaner energy alone is not sufficient to achieve lower or more stable prices. The development of electricity storage, greater system flexibility, and reducing dependence on the influence of fossil fuels continue to play a significant role.

Table of Contents

List of Tables

List of Figures

CHAPTER 1: INTRODUCTION

1.1 Global Energy Transition and Sustainability Challenges

Over the last decade, the global energy sector has changed considerably. Climate change, concerns about energy security and technological progress have all contributed to this change. For many years, fossil fuels dominated electricity generation. Today, renewable energy sources account for a growing share of electricity production, while efforts to reduce emissions continue to increase. Sustainable development is therefore linked not only to environmental goals, but also to reliable electricity supply, long-term energy planning and well-functioning electricity markets (IEA, 2021; European Commission, 2023).

Many studies view the energy transition as a process that involves technological progress, environmental policy and changes in electricity markets (Zhou et al., 2022; European Commission, 2023). For this reason, the transition involves more than changes in electricity generation. It also affects the way electricity markets operate and respond to changing conditions.

Investment in wind and solar power has grown across Europe in recent years. This development has been supported by the Paris Agreement and the European Green Deal. The role of Renewable Energy Sources has expanded beyond environmental policy. They are now also important for energy security and economic strategy. This has been especially visible in countries that depend heavily on imported fossil fuels and are exposed to external price fluctuations (Zhou et al., 2022).

At the same time, the increase in renewable energy generation has created new challenges for electricity systems. Renewable Energy Sources operate with very low marginal production costs. However, thermal generation is still needed when renewable output varies and balancing needs increase. For this reason, natural gas units often continue to influence the marginal clearing price (IEA, 2021; IPCC, 2021).

Recent energy crises showed how exposed electricity markets can be to changes in natural gas prices. Such conditions are more common in electricity systems that continue to rely heavily on imported natural gas and fossil-fuel-based balancing technologies. Following the Russia–Ukraine conflict, natural gas prices in Europe increased significantly and electricity prices became more volatile across many wholesale markets. The experience of this period suggests that when balancing flexibility is limited, external fuel price increases can continue to affect electricity markets, even when renewable energy sources account for a large share of generation (IEA, 2022; ACER, 2022).

The result of this is that electricity price forecasting has evolved not only into an econometric issue, but also into an important challenge for energy policy and energy security.

These developments suggest that electricity forecasting models cannot rely only on traditional supply and demand assumptions or historical price patterns. Modern electricity markets are affected by fuel price volatility, renewable energy variability, hydroelectric balancing capacity, import dependence and regulatory developments. For this reason, forecasting models need to consider both market behavior and the pressures created by the energy transition.

This dissertation examines the relationship between sustainability-related variables and monthly Market Clearing Prices in the Greek wholesale electricity market. The study focuses on issues such as renewable energy expansion, dependence on fossil fuels and balancing conditions. It combines econometric analysis with a discussion of how the Greek electricity market evolved during the transition period.

1.2 Electricity Price Volatility in Liberalized Power Markets

With the liberalization of electricity markets in Europe, price formation mechanisms became significantly more sensitive to short-term fuel price shocks, cross-border energy flows and asymmetries in the generation mix. While public electricity systems were vertically integrated during previous decades, liberalized wholesale markets now operate under marginal pricing rules. In marginal pricing systems, the final market clearing price is usually set by the last and most expensive generating unit needed to meet electricity demand. The purpose of this mechanism is to promote competition and improve the allocation of resources. In practice, electricity markets have become more exposed to fuel price volatility and price fluctuations. According to the literature, market liberalization can increase competition, but it can also leave electricity markets more exposed to external commodity price shocks when domestic flexibility is limited (Oikonomou et al., 2021). In this market structure, higher renewable generation does not automatically result in lower electricity prices. Although renewable energy sources operate with almost zero marginal production costs, the simultaneous presence of natural gas units often results in these plants setting the marginal price. This usually occurs when renewable generation is lower, electricity demand is higher or hydroelectric generation is constrained. Wholesale electricity prices may remain high even when renewable energy generation represents a large share of electricity production.

The years 2021–2023 were a difficult period for European energy markets. Rising Dutch TTF natural gas prices were accompanied by higher electricity prices across many countries. Several interconnected countries also recorded exceptionally high average monthly clearing prices. These developments showed that, under marginal pricing systems, natural gas prices can continue to influence electricity prices even when renewable energy generation accounts for a growing share of electricity production.

The crisis also showed that fossil fuel costs can continue to affect electricity prices, even during periods of strong renewable energy expansion. This may create differences between progress in the energy transition and electricity affordability. Fuel prices, generation mix, demand conditions and balancing requirements all influence electricity prices in liberalized markets.

Electricity markets have become more complex as renewable generation and thermal backup units continue to operate together. Traditional forecasting approaches often focus on past price behavior or demand trends. However, they may not fully capture the effects of balancing costs, renewable energy variability and other changes linked to the energy transition. Traditional forecasting approaches may not be sufficient on their own. Additional variables related to the energy transition may also be needed

Electricity price volatility cannot be explained only through traditional market factors. Changes associated with the energy transition should also be taken into account. For this reason, this dissertation examines both conventional market variables and sustainability-related factors in the Greek electricity market.

1.3 The Greek Electricity Market as a Case Study

The Greek electricity market has undergone major changes during the last decade, making it a particularly important empirical case for the study of the sustainable energy transition. The restructuring of its generation portfolio took place at a rapid pace. Lignite generation declined significantly, electricity production from wind and photovoltaic systems increased, hydroelectric power acquired a more important role in system balancing, while natural gas evolved into a key driver of market operation. During the same period, the country became integrated into the European Target Model framework. This strengthened market coupling as well as exposure to international wholesale price fluctuations.

While the growth rate of renewable energy sources is among the fastest in Southeastern Europe, the Market Clearing Price (MCP) displays significant fluctuations. The price is often influenced by natural gas prices, system balancing requirements and the conditions prevailing in European markets.

What is particularly interesting is that, despite the clear increase in electricity generation from renewable energy sources, the electricity market still appears to be influenced by natural gas units, as these frequently determine the final clearing price through the marginal pricing mechanism. It appears that the relationship between the energy transition and lower electricity prices is not linear and is probably not such a simple puzzle to solve. Renewable energy sources, the need for thermal backup units, external fuel price shocks and the way they interact all affect this relationship.

There is one more reason that makes Greece a suitable case for study. The fact that it experienced institutional restructuring, implemented the Target Model, went through the 2021–2023 energy crisis, saw demand normalize after the pandemic and experienced rapid renewable energy expansion almost simultaneously. This constitutes a particularly unique and interesting environment.

For the above reasons, the present dissertation uses Greece as a case study in order to examine a broader question. Is the increase in renewable energy sources sufficient to lead the electricity market toward lower and more stable prices when pricing mechanisms continue to be significantly influenced by fossil fuels?

1.4 Research Objectives and Contribution of the Thesis

The main aim of this dissertation is to develop and assess an econometric framework for forecasting electricity prices, incorporating not only the traditional drivers of the wholesale electricity market but also the structural forces associated with the transition towards a sustainable energy system. More specifically, the research investigates how the Market Clearing Price (MCP) in Greece is affected by factors such as past market prices, natural gas prices, the share of renewable energy sources, hydroelectric generation, electricity imports, demand, and other mechanisms linked to the shift towards a more sustainable energy framework.

A further question addressed in this dissertation is whether the expansion of renewable energy sources actually results in lower electricity prices. Renewable energy sources have relatively low production costs. Even so, the actual behavior of electricity markets may be more complicated than theory suggests, especially in systems where natural gas units are still needed to provide balancing services. For this reason, the dissertation examines whether the energy transition automatically leads to cheaper electricity or whether new constraints and pressures emerge as the share of renewable energy sources increases.

To explore this question, the dissertation introduces the Extended Transition Point (ETP). The ETP is a transition index designed to capture the relationship between renewable energy expansion, the continued use of fossil fuels for balancing purposes and limitations in system flexibility. It is included in the econometric model as an explanatory variable rather than being used only as a descriptive indicator. An important issue is whether higher renewable energy penetration continues to reduce electricity prices or whether limited storage and balancing capabilities reduce this effect. Recent studies suggest that the success of the energy transition depends not only on renewable energy expansion, but also on the ability of the system to maintain flexibility and stable costs (Bunn, 2004; Maamoun, 2019; Weron & Misiorek, 2008).

Monthly forecasts for the Greek Market Clearing Price are also developed for 2026 under different energy conditions. The analysis considers three scenarios: a baseline scenario, a high natural gas pressure scenario and a green acceleration scenario with higher renewable energy penetration and lower reliance on natural gas for balancing. These scenarios provide an indication of how wholesale electricity prices in Greece may develop under different energy transition conditions.

Two main contributions emerge from this dissertation. The first is the development of a monthly econometric forecasting model tailored to the characteristics of the Greek electricity market. The second is the argument that renewable energy expansion alone may not be sufficient to stabilize electricity prices. Storage capacity, system flexibility and a lower dependence on natural gas in price formation may also play an important role.

The dissertation also approaches electricity price forecasting from a broader perspective. During the energy transition, forecasting is not only a matter of extending historical trends. It also involves understanding how electricity markets adapt to changes associated with climate and energy policy.

1.5 Structure of the Dissertation

The dissertation is divided into seven chapters.

Chapter 2 reviews earlier studies on electricity price forecasting, sustainable energy transition and the growing role of renewable energy sources in electricity markets. It also examines the link between marginal pricing systems and price volatility. A further topic discussed in this chapter concerns the debate over electricity prices. While some studies suggest that expanding renewable energy can make electricity more affordable, others argue that balancing requirements may allow fossil fuel costs to continue affecting market prices.

Greece serves as the main case study of the dissertation. Chapter 3 focuses on the changes that took place in the country's electricity sector during the study period. Changes in the generation mix, the implementation of the European Target Model and the expansion of renewable energy sources are among the main topics discussed. The chapter also briefly describes the market setting within which these developments have taken place.

The following chapter turns to the empirical part of the research. It presents the dataset, discusses the variables included in the analysis and describes the econometric approach used in the study. In addition, this chapter introduces the Extended Transition Point (ETP) Index, which is used as an additional tool for examining the relationship between energy transition and electricity prices.

The fifth chapter contains the main findings of the study. Alongside the econometric results, it discusses the factors that have influenced the Market Clearing Price over time. Monthly forecasts for 2026 are also presented, together with a comparison of electricity price behavior under different market conditions.

Chapter 6 moves from the results to a broader discussion. It considers what the findings may mean for energy policy, comments on the transition thresholds identified in the analysis and discusses the main limitations of the model.

The final chapter brings together the main conclusions of the dissertation. It also points to a number of issues that could be examined in future research on sustainable electricity price forecasting.

CHAPTER 2: LITERATURE REVIEW AND THEORETICAL BACKGROUND

2.1 Introduction

Electricity markets are not the same as they were a few years ago. The increasing use of renewable energy sources has changed many aspects of the power sector, including the way electricity prices are studied and forecasted. Things are no longer as straightforward as they once were. Renewable energy sources make up a larger part of electricity generation, and changes in weather can have a much stronger effect on production levels. At the same time, electricity markets have become more sensitive to events taking place outside the energy sector. Taken together, these developments have made price behavior less straightforward than it used to be.

As a result, looking at past price data is often not enough. It is also necessary to consider what is happening in the market and how the electricity system reacts when supply and demand are out of balance. Therefore, issues such as system flexibility, energy storage and renewable integration receive much more attention than they did in the past.

The discussion that follows provides the background needed for the rest of the dissertation. It begins with a review of the most common approaches used in electricity price forecasting and then examines issues related to energy transition, electricity market structure and the role of flexibility and balancing requirements in modern power systems.

2.2 Electricity Price Forecasting: International Approaches and Methodological Evolution

Electricity price forecasting has developed considerably over time. Researchers approach electricity price forecasting differently today than they did in the past. Statistical methods are still part of the forecasting process, but they are rarely used on their own. Researchers usually take a wider view of the market.

Electricity has a number of characteristics that set it apart from most other commodities. One obvious difference is that large amounts of electricity cannot be stored easily. Supply and demand must also remain in balance at all times, while market rules can influence the way prices are formed. For this reason, Weron (2014) argues that forecasting in liberalized electricity markets cannot depend on simple extrapolation methods alone. According to Weron (2014), electricity prices are shaped by “a dynamic mixture of temporal dependence, fuel cost transmission, weather uncertainty and institutional distortions”.

ARIMA, SARIMA and simple demand-based regressions were among the methods most often used in the early forecasting literature. This was also a period of fewer market disruptions, making such models a reasonable choice for short-term forecasting (Conejo et al., 2005).

Electricity markets did not remain unchanged. Over the years, electricity markets and fuel markets became more closely connected. This made forecasting more difficult. Models based mainly on past price movements often struggled when prices changed suddenly. Forecasting became more challenging as market conditions changed. Unexpected events could affect electricity prices quickly, sometimes within a very short period of time.

Under these circumstances, relying only on traditional forecasting models became increasingly difficult (De Gooijer and Hyndman, 2006; Hamilton, 1994). Karakatsani and Bunn (2008) note that electricity prices cannot be understood solely through their past values. Fuel costs, reserve margins, renewable generation variability and demand conditions are also part of the picture. Aggarwal, Saini and Kumar (2009) reach a similar conclusion. They suggest that forecasting models based on a single variable become less useful as electricity markets grow more complex. This issue becomes even more important during periods of regulatory change or technological transition. Conejo et al. (2005) make a related observation, noting that once fuel price volatility begins to affect electricity markets, external variables become increasingly important for forecasting performance.

Many researchers arrive at a similar conclusion. Electricity markets have become more difficult to forecast than they were in the past. Historical prices still provide useful information, but other factors also need to be taken into account. Changes taking place within the electricity system can eventually influence market prices. This is not only a forecasting issue. It also reflects wider changes taking place across electricity markets. Generation capacity remains important, but flexibility has become important as well. For that reason, forecasting methods have gradually moved away from simple time-series approaches and toward models that can account for changing market conditions.

Forecasting studies now consider more factors than they did in the past. Fuel prices, renewable energy indicators and market conditions appear regularly in the literature. The role of energy transition variables is less clear. Although many studies include them, they are often discussed more briefly than other influences on wholesale electricity prices. The present dissertation examines this issue in more detail.

2.3 Sustainable Energy Transition and Renewable Penetration in Electricity Markets

Much of the discussion surrounding sustainable energy transition is based on the idea that a higher share of Renewable Energy Sources will lead to lower electricity prices, lower system costs and greater market stability over the long term. Research supports this argument to some extent. Even so, experience from electricity markets suggests that the relationship is not always straightforward. Higher levels of renewable energy do not always result in lower electricity prices. What happens next depends on the wider electricity system. Even with higher levels of renewable generation, balancing is still required. The need for balancing can still create additional costs.

The Paris Agreement and the European Green Deal gave new momentum to the transition toward lower-carbon energy systems. Across Europe, investment in solar, wind and other low-emission technologies increased during this period. At the same time, the energy transition involves more than replacing one source of energy with another. The European Commission has repeatedly highlighted the importance of storage, interconnections, reserve capacity and balancing mechanisms for the effective operation of electricity systems. Mazzucato (2021) argues that the transition involves more than changes in the generation mix. It also requires wider changes across the electricity system.

Similar challenges are discussed by Morales et al. (2014), particularly in relation to the growing complexity of balancing electricity systems with higher shares of intermittent renewable generation. Sustainability involves more than increasing renewable capacity. Electricity systems must also be able to cope with higher levels of renewable generation. Related challenges have been observed in renewable-intensive electricity systems through the well-known "duck curve" phenomenon. As described by Denholm et al. (2015), periods of high solar generation during the middle of the day can coexist with steep increases in balancing requirements later in the evening.

This issue has received considerable attention in recent years. Maciejowska, Uniejewski and Weron (2022) note that renewable energy has expanded rapidly in recent years. The same cannot always be said for storage infrastructure and system flexibility. Balancing problems can remain, even in electricity systems with a growing share of renewable generation. In other words, a greener generation mix does not necessarily mean that the marginal pricing mechanism changes in the same way.

Similar arguments can also be found in the environmental economics literature. Research in this area points to a similar problem. The pace of technological change is often different from the pace of market adjustment in electricity markets. Renewable energy, meanwhile, may continue to expand. Emissions may fall as well. This does not necessarily mean that electricity prices become independent of thermal balancing resources (World Bank, 2020; IEA, 2021). This has become an important issue in the European energy transition. Oikonomou, Polemis and Soursou (2021) highlight a similar issue. In many cases, emissions decline before electricity markets adjust to climate-related commitments.

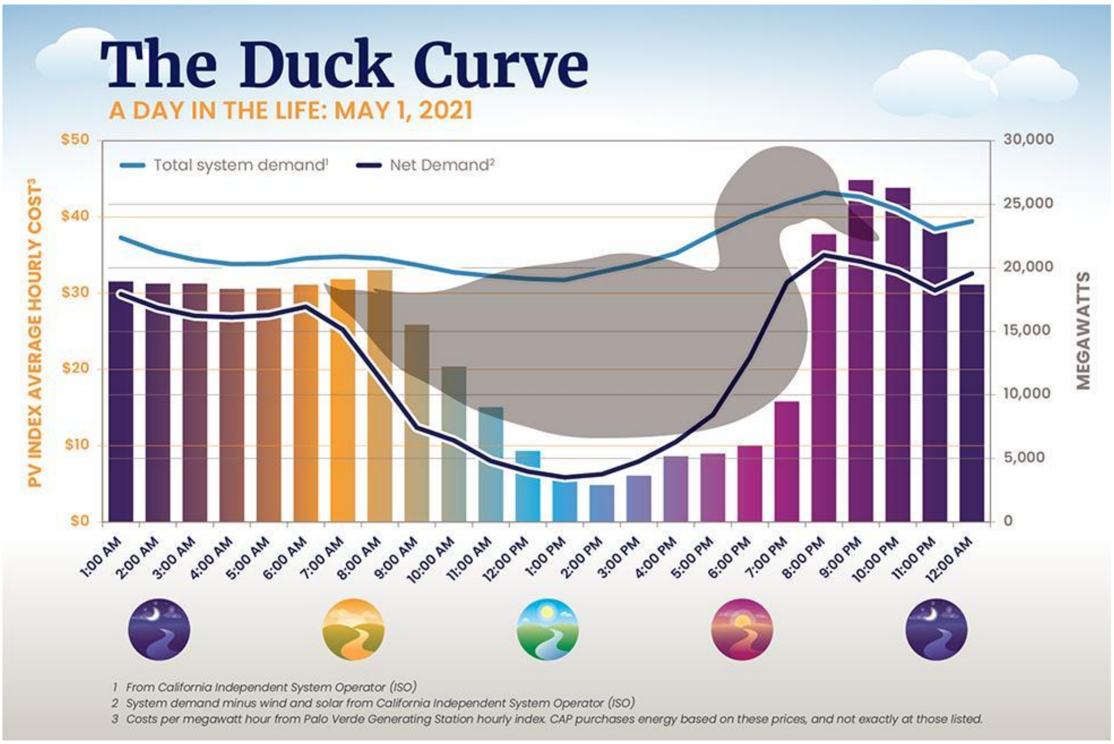
The importance of renewable energy in electricity markets is widely recognized. The picture becomes less straightforward at higher levels of renewable generation. If storage capacity does not expand at a similar pace, additional challenges may appear. Additional renewable capacity may continue to improve sustainability outcomes. Its effect on electricity prices, though, may become weaker. Renewable expansion can still contribute to lower prices. The link between renewable generation and electricity prices, though, becomes less clear as renewable shares continue to rise. Zhou et al. (2022) reach a similar conclusion in a broader international context. Their study suggests that low-carbon transitions require not only more renewable energy, but also substantial investment in flexibility resources if additional costs are to be avoided.

One example often discussed in the literature is the so-called "duck curve", which was first identified in electricity systems with high levels of renewable generation, such as California. The duck curve is observed when solar generation is high during the middle of the day, but balancing requirements increase later in the evening as solar production declines and electricity demand becomes higher. This example shows that adding more renewable energy does not remove all system pressures. Some of these pressures simply appear at different times of the day.

The duck curve points to an important issue. Renewable energy can continue to grow, but balancing needs do not disappear. During some hours of the day, they may become even more important. Gas-fired units, hydropower and storage technologies often become more important under these conditions. Without this kind of support, additional renewable capacity may create new challenges for the electricity system. Renewable generation can continue to grow, while balancing the system becomes more difficult.

The duck curve is also relevant for electricity price forecasting. The link between renewable generation and electricity prices is not always straightforward. Things can become less straightforward at higher levels of renewable energy. The duck curve can be viewed as an early sign of wider changes taking place during the energy transition. Some of these changes can be difficult to identify using conventional variables alone. One example is the Extended Transition Point (ETP) Index introduced in this study, which is designed to reflect the effects that may appear as renewable generation continues to expand.

Figure 2.1 Conceptual Representation of the Duck Curve under High Renewable Penetration



Source: https://jost.syr.edu/

The duck curve shows that renewable generation changes more than the amount of electricity supplied. It also affects when balancing is needed throughout the day. This makes the duck curve useful for electricity price forecasting. The share of renewable energy is important, but other factors also affect electricity prices.

The discussion does not end with the amount of renewable energy in the system. Renewable generation may continue to increase, but electricity prices can still be affected by balancing requirements. In some cases, fossil-fuel generation remains important when renewable output changes (Maciejowska et al., 2022; Weron, 2014). This is one reason why renewable energy does not always have the same effect on electricity prices. The share of renewable generation is important, but it is only part of the picture. The issue also extends beyond electricity generation itself. Interconnected electricity markets depend on coordination and adequate balancing resources. Ostrom (1990) examines the management of shared systems. This is also an important issue in electricity markets during the energy transition.

2.4 Marginal Pricing, Fossil Fuel Dependence and Structural Volatility

The European electricity market has changed considerably in recent years. Renewable energy plays a larger role in electricity generation than it once did. Even so, electricity prices can still be strongly influenced by fossil-fuel generation. This is linked to the way marginal pricing works. The final electricity price is not determined by the average cost of electricity production. In many cases, it is determined by the last and most expensive unit needed to meet demand.

More expensive generating units are often used less when renewable generation is high. This is often the case when weather conditions are favorable and renewable output is high. This is not always the case when renewable output falls and electricity demand increases. Combined Cycle Gas Turbine (CCGT) units often become more important at these times. For this reason, a market can become greener over time while electricity prices continue to be influenced by gas-fired generation. A lower-carbon generation mix does not automatically mean that electricity prices are no longer linked to fossil fuels. This issue appears in many studies of electricity markets, especially those focusing on the role of the marginal unit in setting prices.

This became easier to see during the European energy crisis. Dutch TTF natural gas prices increased sharply, and electricity prices moved higher across many European markets. Even countries with a growing share of renewable energy were affected. The crisis showed that increasing renewable generation is only part of the transition process. Changes in balancing arrangements and system flexibility did not always keep pace with the growth of renewable energy. For this reason, electricity prices could still be strongly affected by gas prices. The share of fossil fuels in electricity generation became smaller, but gas-fired generation often continued to affect wholesale electricity prices.

Marginal pricing continues to play an important role in electricity markets, but its effects can become more complex during the energy transition. Higher costs from thermal generation can still have an effect on electricity prices. Newbery (2016) notes that this can become more noticeable when system flexibility depends on a small number of thermal technologies (Fanone et al., 2013; Higgs & Worthington, 2008). Under these conditions, a relatively small part of the generation mix can have a strong influence on electricity prices. Similar findings have been reported in several European electricity markets, particularly where balancing flexibility remains limited (Clò et al., 2015). During periods of high volatility, electricity prices can move away from average production costs for a period of time.

The situation can be more difficult in countries that depend heavily on gas-fired generation for balancing. In these systems, having enough electricity is only part of the picture. What also matters is whether flexible generation is available when it is needed. Having enough electricity over the course of a year does not always mean that the system can respond easily to changes in demand and renewable output. What also matters is whether enough flexible generation is available when it is needed. As a result, lower emissions and higher shares of renewable energy do not always lead to lower electricity prices. Some electricity systems can increase the share of renewable energy while electricity prices remain high.

On this basis, the role of fossil fuels cannot be assessed only through their share in electricity generation. The amount of gas used in the system is important, but it is only part of the picture. What also matters is how often gas-fired generation continues to influence electricity prices (Newbery, 2016; Weron, 2014; European Commission, 2023).

2.5 Existing Research Gaps and the Need for a Transition-Oriented Forecasting Framework

Research on electricity price forecasting has grown considerably over the last two decades. Some studies focus mainly on forecasting performance, while others pay more attention to renewable energy and the energy transition. Renewable generation is often included in forecasting models. Less attention is given to whether the relationship between market conditions and electricity prices changes as renewable energy expands.

This issue goes beyond forecasting methods. Many studies assume that higher levels of renewable energy lead to better outcomes in electricity markets. Nevertheless, fossil fuel variables continue to play an important role in forecasting models. Less attention is given to what happens as renewable energy continues to expand. Renewable generation can continue to grow, but the effects may not remain the same at higher levels of renewable penetration. This may be especially important when storage capacity and balancing resources do not expand at the same pace.

Many studies examine how electricity prices respond to different factors. Less attention is given to whether these relationships remain the same as the energy transition progresses. This is an important issue when forecasting electricity prices. Forecasting is not only about understanding how electricity prices respond to existing market conditions. It is also about recognizing when those relationships begin to change. Maamoun (2019) reaches a similar conclusion in an empirical study of the Kyoto Protocol. The study suggests that progress in transition policies can take place more quickly than changes in market behavior. As a result, renewable energy can continue to expand while electricity markets continue to change more slowly.

Many studies continue to rely on forecasting models that focus mainly on prediction. Some improve forecasting performance, but provide less information about the factors behind electricity price movements. Forecasting accuracy is important, but it is not the only issue. Understanding why electricity prices change is also important, especially during the energy transition. This can help identify the factors that continue to influence electricity prices even as renewable energy expands.

This dissertation focuses on this issue. The Extended Transition Point (ETP) Index is introduced to examine the role of the energy transition in electricity price forecasting. This study focuses on the role of renewable energy as its share continues to increase. Particular attention is given to whether the relationship between renewable generation and the Market Clearing Price changes when storage capacity and balancing resources do not increase at the same pace. In this way, the study combines electricity price forecasting with the wider changes taking place in electricity systems during the energy transition.

The dissertation goes beyond forecasting future electricity prices in Greece by also exploring whether the relationship between the energy transition and electricity prices changes as renewable energy penetration increases or under different system conditions. To examine this issue, the ETP framework is incorporated into the econometric model, providing an additional framework for analyzing how transition-related factors are associated with electricity price behavior.

2.6 Chapter Recapitulation

The studies discussed in this chapter point to a number of common findings. Electricity price forecasting is not only a statistical exercise. Developments in renewable energy, electricity market design and balancing requirements continue to influence electricity prices. The literature also shows that the relationship between renewable energy and electricity prices is not always straightforward. Renewable generation can continue to grow, but further increases do not always lead to the same changes in electricity prices.

For this reason, electricity price forecasting requires more than accurate predictions. It also requires an understanding of the factors that continue to influence electricity prices during the energy transition.

CHAPTER 3: THE GREEK ELECTRICITY MARKET AND THE SUSTAINABLE TRANSITION FRAMEWORK

3.1 Introduction

The Greek electricity market has changed in recent years. Renewable energy now plays a more important role in electricity generation than in the past. At the same time, changes in European market rules and developments in international fuel markets have affected the way electricity prices are formed.

As a result, electricity prices are influenced by a wider range of factors than in the past. The amount of electricity produced remains important, but it is only part of the picture.

The transition to a more sustainable electricity system does not automatically make electricity markets simpler or less expensive. As renewable generation increases, balancing requirements, system flexibility and electricity market design become more important.

This chapter presents the main characteristics of the Greek electricity market and the context in which the energy transition has taken place. It also examines the factors that continue to influence electricity prices and explains why these factors are important for electricity price forecasting.

3.2 Institutional Evolution of the Greek Wholesale Electricity Market

The Greek wholesale electricity market has changed significantly over the last fifteen years. In the past, the Greek electricity system was more regulated than it is today. Public electricity generation and domestic lignite played an important role in the electricity sector. Electricity prices were influenced more by regulation and long-term planning than by competitive market trading.

Many of these changes were connected to electricity market reforms across the European Union. One of the main objectives was to increase integration between national electricity markets. Generation, transmission and market operation gradually took on separate roles within the electricity market. New institutions also took on a more important role in the Greek electricity market. Three important institutions were the Regulatory Authority for Energy (RAE), the Independent Power Transmission Operator (ADMIE) and the Hellenic Energy Exchange. These institutions became responsible for different aspects of market operation, including system balancing, electricity trading and market supervision.

An important change took place with the introduction of the European Target Model. The Greek electricity market became more connected to other European electricity markets. This was supported by the introduction of the day-ahead market, the intraday market and cross-border trading. This change increased integration between electricity markets and improved market transparency. Over the same period, electricity prices in Greece became more sensitive to developments outside the country. As a result, electricity prices no longer depended only on developments within Greece. Fuel prices and conditions in other European electricity markets also played an important role.

From that point onward, the Greek Market Clearing Price was influenced by a wider range of factors than in the past. Electricity prices became more sensitive to changes in natural gas prices, electricity imports and renewable generation. Balancing requirements and interconnection conditions also affected electricity prices. As a result, electricity prices were influenced by more factors than under the previous regulated system.

These changes are important for the present study. Forecasting electricity prices in Greece after the introduction of the Target Model requires a different approach from earlier studies. The Greek electricity market is now more closely connected to other European electricity markets. At the same time, system flexibility and balancing requirements remain important issues for the Greek electricity market. Joskow (2008) reaches a similar conclusion. The study suggests that electricity markets can become more complex when market reforms progress more quickly than improvements in flexibility and reserve capacity.

These institutional changes remain important for electricity price forecasting in Greece. Changes in market structure can affect electricity prices and market volatility (ENTSO-E, 2023; ACER, 2022). Polanyi (1944) reaches a similar conclusion. Markets are influenced by the institutions within which they operate. This is also relevant for electricity markets.

3.3 Transformation of the Domestic Electricity Generation Mix (2012–2025)

Electricity generation in Greece changed substantially between 2012 and 2025.Within a relatively short period of time, lignite became less important, while renewable energy, hydropower and natural gas played a larger role in electricity generation. The way electricity was produced changed considerably over this period. Electricity prices did not always change in the same way.

At the beginning of the period, more than half of Greece's electricity came from lignite. Natural gas was also used for electricity generation, although it was less important than lignite. Renewable energy and hydropower were less important at that time and together produced less than one-fifth of all electricity. Most electricity was still produced by conventional thermal power plants. The picture was very different by 2024–2025. By that time, lignite was no longer a major source of electricity generation. Renewable energy and hydropower together became the largest sources of electricity production. Natural gas remained important for balancing the electricity system.

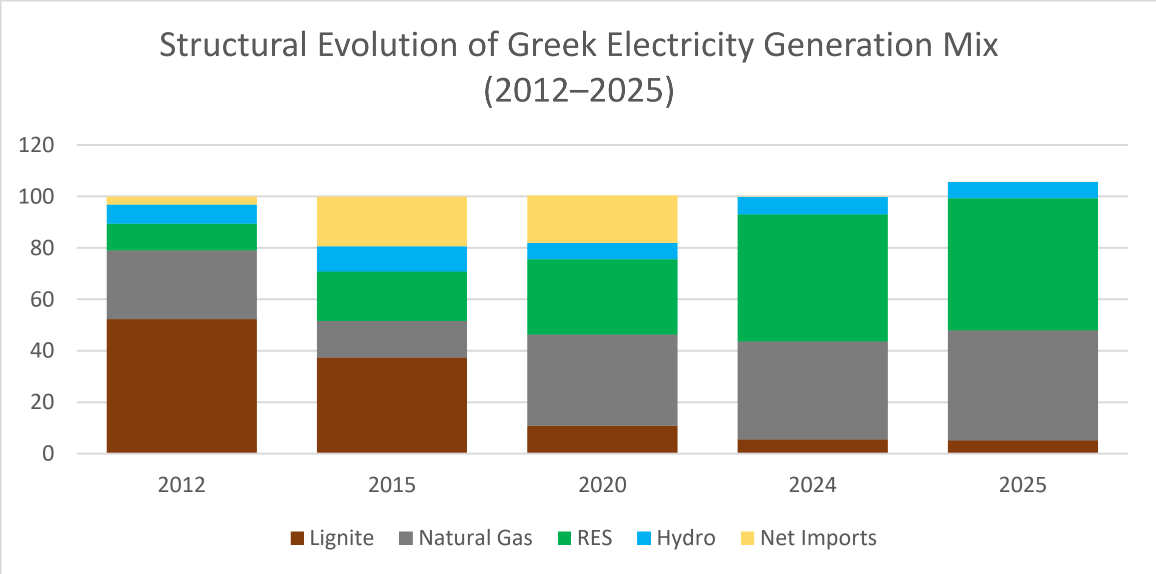
These changes were not limited to electricity generation shares. The role of different technologies within the electricity system also changed. As lignite declined and renewable generation expanded, balancing requirements became more important. For this reason, natural gas continued to play an important role in the electricity system.

Table 3.1 summarizes this long-run structural change.

Year	Lignite	Natural Gas	RES	Hydro	RES+Hydro	Net Imports
2012	52.3	26.7	10.4	7.4	17.8	3.1
2015	37.3	14.3	19.2	9.8	29	19.3
2020	10.8	35.5	29.3	6.3	35.6	18.5
2024	5.5	38.1	49.4	6.8	56.2	0.1
2025	5.1	42.8	51.4	6.3	57.7	-7

Source: Author's calculations based on ADMIE monthly electricity generation bulletins (2012–2025)

Figure 3.1. Evolution of electricity generation by source in Greece during the period 2012–2025.



Source: Author’s calculations based on ADMIE monthly electricity generation bulletins (2012–2025)

Figure 3.1 shows the changes in electricity generation between 2012 and 2025. Lignite became less important, while renewable energy played a larger role. As a result, renewable energy became the largest source of electricity generation by the end of the period.

Between 2012 and 2025, lignite lost more than forty-seven percentage points of its share in electricity generation. Renewable energy and hydropower increased by about forty percentage points over the same period. Based on these changes, lower and more stable electricity prices might be expected. This expectation is related to the merit-order effect, which suggests that higher levels of renewable energy can help reduce electricity prices (Sensfuß et al., 2008). However, the results show that this effect was only partly observed in the Greek electricity market (Eurostat, 2023; Ministry of Environment and Energy, 2022).

Natural gas continued to play an important role in the Greek electricity system. Renewable energy increased over the period, but natural gas remained important when renewable generation could not meet demand on its own. For this reason, electricity prices continued to be influenced by developments in international fuel markets.

It follows that the changes in the Greek electricity generation mix should not be viewed only as a shift towards lower emissions. Renewable energy increased rapidly, but balancing requirements continued to play an important role. In many cases, changes in electricity generation took place more quickly than changes in the resources needed to support the system. This issue is closely related to the main objective of the present study.

3.4 Renewable Expansion, Natural Gas Balancing and the Persistence of MCP Volatility

The increase in renewable energy did not lead to a steady decline in electricity prices. Renewable energy and hydropower became more important, but large changes in electricity prices continued to occur. This suggests that changes in electricity generation alone were not enough to remove all sources of price instability. Balancing requirements continued to play an important role in the electricity market.

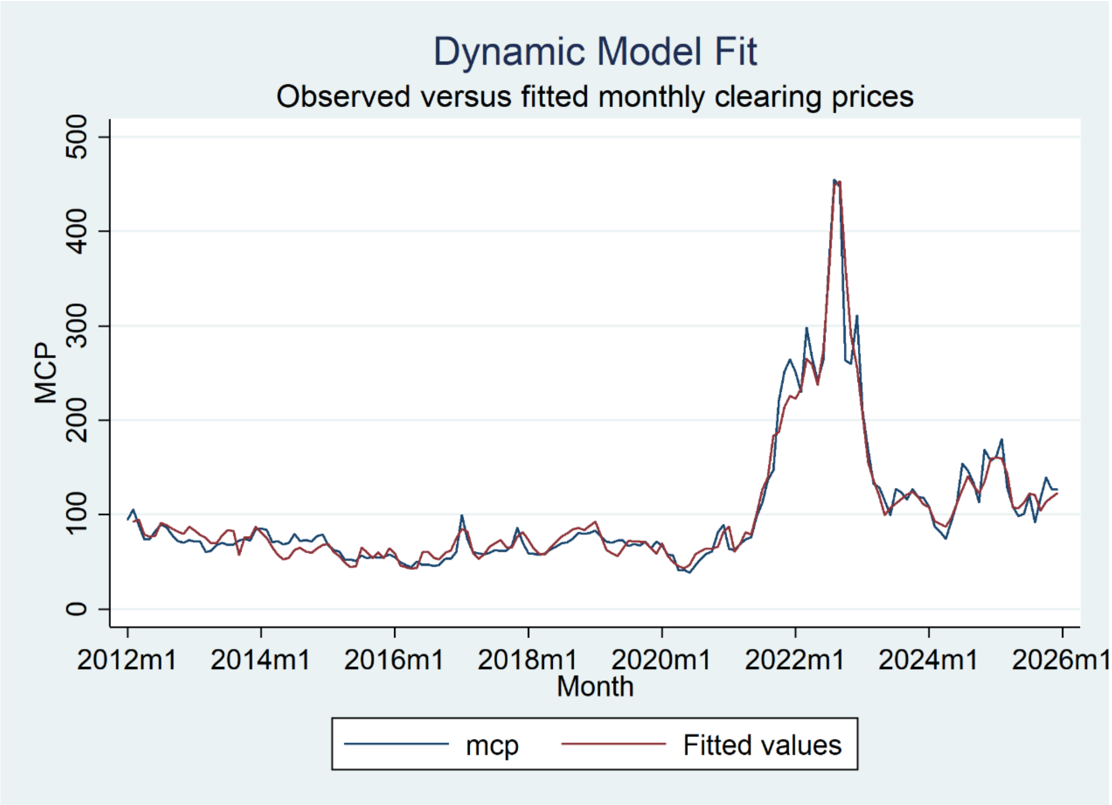
Natural gas remained an important part of the Greek electricity system between 2012 and 2025. Its role became even more significant after 2020. Natural gas remained important when renewable generation and hydropower production were lower or when electricity demand increased. As a result, it continued to influence the Market Clearing Price despite the growth of renewable energy.

This could be seen clearly during the energy crisis years. Electricity prices increased sharply despite the growth of renewable energy. One reason is the way electricity prices are determined in the market. Lower-cost electricity does not always lead to lower prices when more expensive sources of electricity remain important. This means that electricity prices can remain high even when renewable energy plays a larger role in electricity generation.

For this reason, the relationship between renewable energy and electricity prices is not always the same. Renewable energy can help reduce electricity prices. However, electricity prices do not always fall when balancing requirements become more important. As a result, lower electricity prices are not guaranteed as renewable energy continues to expand.

Figure 3.2 shows the evolution of the Greek Market Clearing Price between 2012 and 2025.

Figure 3.2 Historical Evolution of Observed and Fitted Greek Market Clearing Prices (2012–2025)



Source: Author's econometric estimations based on monthly MCP data from ADMIE and model fitted values

As shown in Figure 3.2, three broad phases can be identified in the evolution of the Greek Market Clearing Price. The first phase includes the years from 2012 to 2020, when electricity prices remained relatively stable from month to month. The second phase includes the energy crisis years. Electricity prices rose sharply during this period and reached levels not seen before. The third phase reflects the period after the energy crisis. Electricity prices declined from their peak levels, but volatility remained higher than in the years before the crisis.

These developments provide useful information about the Greek electricity market. After the peak of the energy crisis, electricity prices declined. However, the market did not return to the same level of stability that existed before the crisis. Electricity prices continued to fluctuate more than in earlier years. This suggests that balancing requirements continue to play an important role despite the growth of renewable energy.

The observed and fitted values are also relatively close to each other. This suggests that the model is able to explain a large part of the historical movement in the

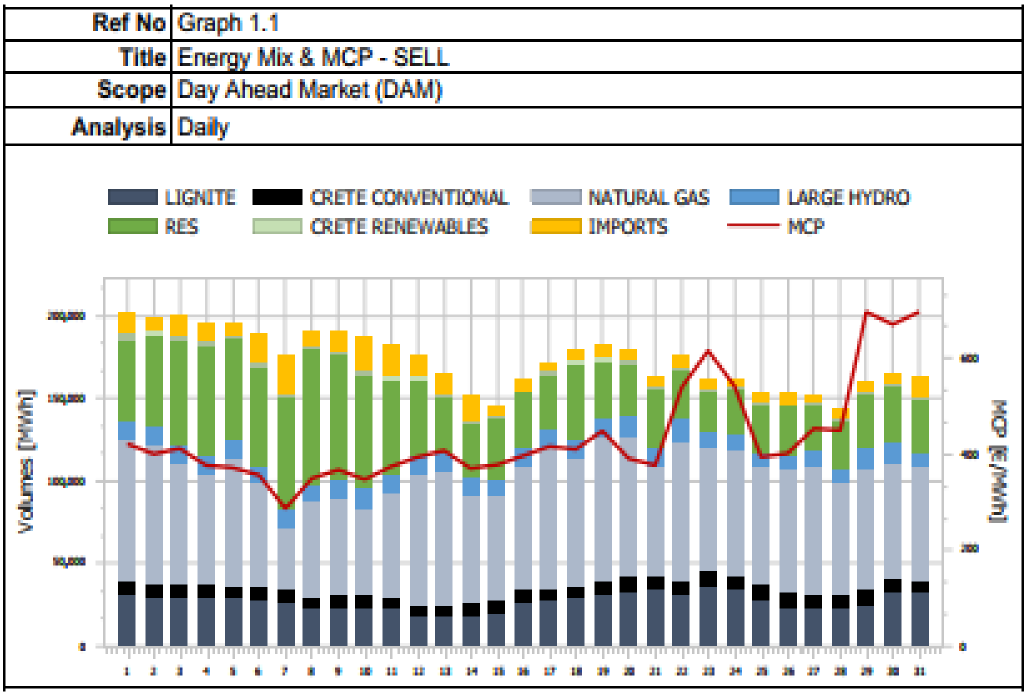
Market Clearing Price. This is important for the forecasting analysis presented in Chapter 5.

3.5 Visual Evolution of Greek DAM Market Structure Across Transition Phases

The figures in this section show the main changes in the Greek electricity market over time. They focus on three different periods: the period after the introduction of the Target Model, the energy crisis period and the recent period with higher renewable energy participation.

Figure 3.3 shows the Greek Day-Ahead Market in November 2020. During this period, electricity prices remained at moderate levels and the electricity generation mix was different from that of later years. HEnEx data show an average monthly Market Clearing Price of €52.66/MWh. Natural gas accounted for 40.13% of total electricity generation. Renewable energy accounted for 31.53%, while imports accounted for 13.34%. Natural gas and imports continued to play an important role in the market during this period. At the same time, the market had not yet experienced the conditions that developed during the energy crisis.

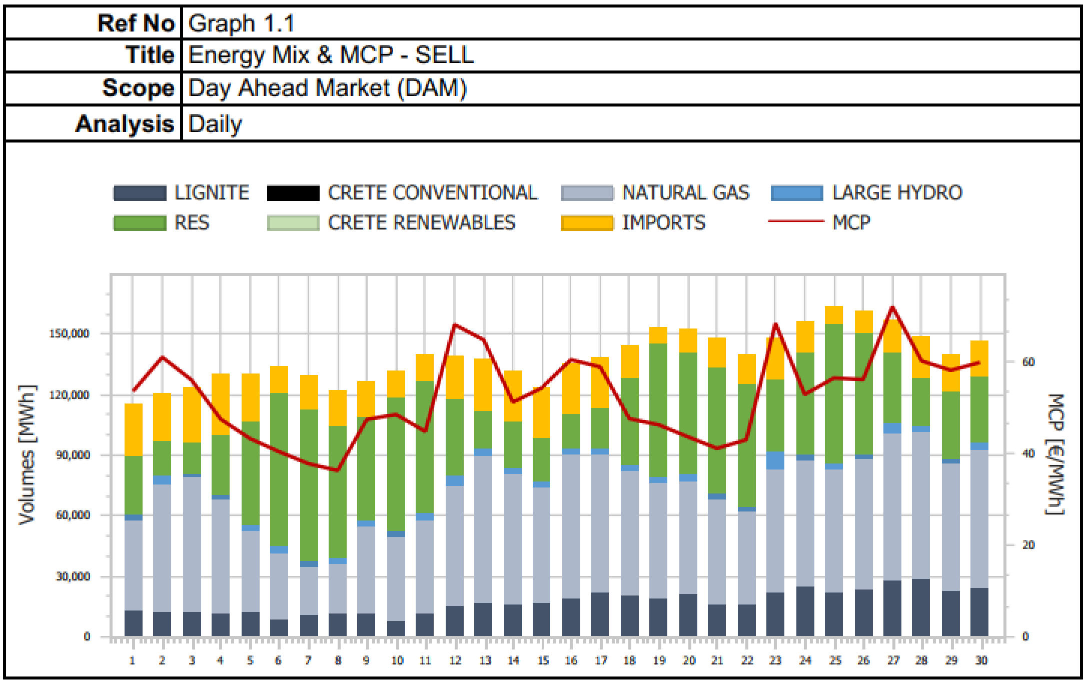
Figure 3.3 Indicative DAM Dispatch Composition during the Early Post-Target Model Period (November 2020)



Source: Regulatory Authority for Energy, Waste and Water (RAAEY) Wholesale Electricity Market Reports

Figure 3.4 presents the Greek Day-Ahead Market during the 2022 energy crisis. During this period, natural gas played a much larger role in the electricity market. Imports continued to contribute to the market, while electricity prices rose sharply. The Greek electricity market was affected by changes in international fuel prices. As a result, electricity prices were influenced to a large extent by natural gas costs.

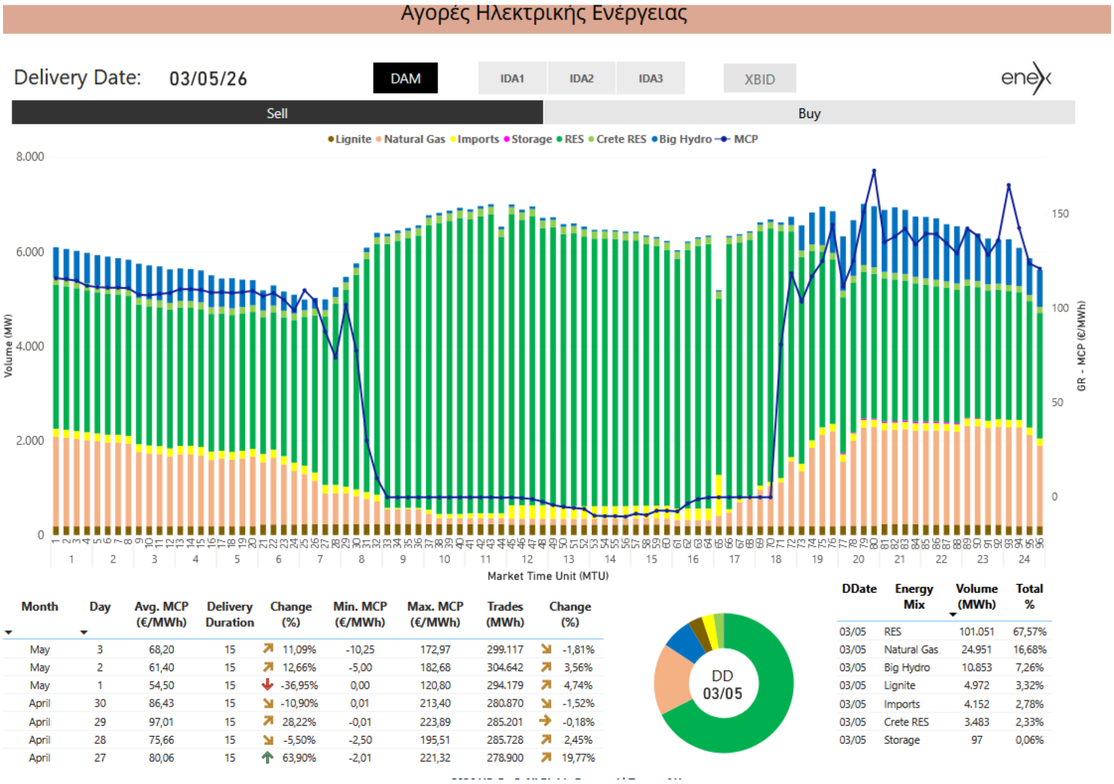
Figure 3.4 Indicative DAM Dispatch Composition under Gas Crisis Stress Conditions (August 2022)



Source: Regulatory Authority for Energy, Waste and Water (RAAEY) Wholesale Electricity Market Reports

Figure 3.5 presents the Greek Day-Ahead Market in May 2026. By this period, renewable energy had become the largest source of electricity generation. The role of natural gas was smaller than in the previous two periods. However, electricity prices did not remain at low levels throughout the day. Large differences in electricity prices were still visible across different hours of the day. This suggests that balancing requirements, hydropower limitations and natural gas continued to influence electricity prices.

Figure 3.5 Indicative DAM Dispatch Composition under High Renewable Penetration (May 2026)



Source: Hellenic Energy Exchange Day-Ahead Market snapshot, 03 May 2026.

Taken together, these three figures show the main changes that took place in the Greek electricity market. Renewable energy became more important, while the role of fossil fuels declined. However, these changes in electricity generation did not lead to the same changes in electricity prices. The electricity system became more dependent on renewable energy, but balancing requirements remained important.

Renewable energy played a larger role as the period progressed. However, system flexibility did not improve at the same rate. This issue is closely related to the main objective of the present study and is examined in the following chapters.

3.6 The Greek Market as a Transition Stress Laboratory

The previous analysis shows that the Greek electricity market cannot be viewed as a typical case of energy transition. Several important changes have taken place at the same time. Renewable energy has expanded rapidly, lignite participation has declined, and natural gas continues to play an important role in balancing the electricity system. In parallel, the Greek market has become more closely connected to other European electricity markets.

Another factor that may help explain this situation is the duck curve phenomenon discussed in the previous chapter. This phenomenon has become more common in electricity systems with a high share of renewable energy. When solar and wind generation is high, the need for conventional electricity generation becomes lower. However, when renewable generation falls, additional electricity must be supplied quickly in order to meet demand. In many cases, this electricity comes from natural gas plants or hydropower. When renewable generation is lower, natural gas and hydropower continue to play an important role in the electricity system.

This issue is particularly relevant to Greece. Renewable energy became more important over time, but energy storage did not develop at the same rate. As a result, balancing requirements continued to play an important role. As renewable generation changed, electricity prices could still be affected by the ability of the system to meet demand.

The Greek electricity market is useful for studying these issues. Renewable energy became more important over time, but energy storage and system flexibility remained important issues. Balancing requirements also continued to play an important role. This allows a better understanding of how electricity prices behave during a period of energy transition.

Renewable energy became more important and lignite participation declined. At the same time, balancing requirements continued to play an important role. As lignite became less important, natural gas and imports remained necessary for supporting the electricity system. Against this background, the Greek electricity market continued to be affected by changes in international fuel markets despite the growth of renewable energy.

This is why the Greek electricity market provides a useful case for analysis. It allows the examination of how variables related to the energy transition may affect electricity prices. The forecasting model presented in the next chapter is based on this idea.

3.7 Chapter Recapitulation

The analysis of the Greek electricity market shows that the energy transition is still in progress. Renewable energy became more important, but balancing requirements continued to play an important role. For this reason, the Greek case is useful for examining the relationship between energy transition and electricity prices. It also provides a suitable basis for the forecasting model developed in the present study.

CHAPTER 4: DATA DESCRIPTION AND METHODOLOGICAL DESIGN

4.1 Introduction

The previous chapters examined the main developments in electricity markets and the changes associated with the energy transition. However, these developments need to be represented by measurable variables.

For this reason, this chapter presents the methodology used in the present study. It describes the variables included in the analysis and explains their relationship with the Market Clearing Price.

Special attention is given to variables related to the energy transition. The aim is to examine whether these variables can improve the understanding of electricity price behavior. This chapter therefore presents the framework used for the empirical analysis of the dissertation.

4.2 Data Sources and Variable Construction

The empirical analysis of this dissertation is based on monthly data covering the period from January 2012 to December 2025. This period includes both the years before the energy crisis and the years that followed. Monthly data were selected because they provide a balance between short-term market movements and longer-term developments. Daily or hourly data often contain large short-term fluctuations, while annual data may hide important changes that take place within the year. Given this observations, monthly observations were considered the most appropriate for the purposes of the present study.

Monthly Market Clearing Price (MCP) data were obtained from ADMIE and the Hellenic Energy Exchange. Dutch TTF natural gas prices were included in the dataset because they are commonly used as a reference price for natural gas in Europe. Monthly ADMIE reports were used to obtain data on lignite, natural gas, renewable energy, hydropower and electricity imports. Domestic electricity demand was also included in the analysis. A crisis dummy variable was also tested for the 2021–2023 energy crisis period. However, only the variables that contributed to the final model were retained.

The Extended Transition Point (ETP) Index was developed as part of the present study. The purpose of this index is to capture the relationship between renewable energy growth, balancing requirements and the continuing role of fossil fuels in the electricity system.

The ETP Index is based on the idea that the progress of the energy transition cannot be measured only by the share of renewable energy. As renewable energy becomes more important, balancing requirements may also become more important. For this reason, the index examines when balancing requirements begin to affect the relationship between renewable energy and electricity prices.

Table 4.1 summarizes the variables employed in the econometric estimation together with their operational definitions.

Table 4.1 Definition of Variables and Expected Impact on MCP

Variable	Description	Expected Effect on MCP
MCP	Monthly Greek Market Clearing Price (EUR/MWh)	Dependent Variable
L_MCP	Lagged one-month MCP	Positive
TTF	Dutch TTF monthly natural gas benchmark price	Positive
GAS_SH_D	Natural gas generation share in domestic mix	Positive
RES_SH_D	Renewable energy share in domestic mix	Negative / Nonlinear
HYDRO_SH_D	Hydroelectric generation share	Negative
IMPORTS_SH_D	Net electricity imports share	Ambiguous
DEMAND	Monthly domestic electricity demand (MWh)	Positive
CRISIS	Initially tested binary dummy for 2021-2023 energy shock	Positive
ETP_INDEX	Extended Transition Point synthetic transition index	Positive after threshold
ETP2	Squared ETP term for nonlinear transition effect	Positive

Source: Author's variable construction based on ADMIE, HEnEx and TTF monthly market data

4.3 Descriptive Statistical Properties of the Dataset

Table 4.2 reports descriptive statistics for the variables used in the study. The main variables are based on 180 monthly observations. The lagged and nonlinear variables are based on a slightly smaller number of observations because they use information from earlier periods.

One of the first observations from Table 4.2 concerns the behavior of the Market Clearing Price. The average monthly value was EUR 101.8/MWh, while values ranged from EUR 38.7/MWh to EUR 455/MWh. This suggests that electricity prices changed significantly over time and did not remain within a narrow range.

A similar pattern can be observed for Dutch TTF natural gas prices. The average monthly value was EUR 32.8/MWh, whereas the highest value was above EUR 239/MWh. These figures show that natural gas prices varied substantially over time. They also reflect the large increases in gas prices that occurred during the European energy crisis.

Approximately 33% of domestic electricity generation came from natural gas. Renewable energy generated about 31.5% of total electricity, while hydropower generated around 9%. These values suggest that renewable energy became an important part of the electricity system. At the same time, natural gas continued to play an important role in electricity generation. The relatively high standard deviations of these variables indicate that important changes took place during the period examined.

Additional information can be obtained from the ETP variables. The ETP Index ranges from negative to positive values. The squared ETP term also varies considerably across the sample. This suggests that the effect of the energy transition on electricity prices may change as the transition progresses. The descriptive statistics therefore provide some initial support for the inclusion of nonlinear transition effects in the analysis.

Table 4.2 summarizes these descriptive properties.

Table 4.2 Descriptive Statistics of Model Variables (STATA Output)

variable	mean	sd	min	max
mcp	101.8174	68.14127	38.68	454.97
L_mcp	100.7829	70.64647	38.68	454.97
ttf	32.78869	32.58995	4.385	239.907
gas_sh_d	.3295016	.1076231	.0321399	.5392037
res_sh_d	.3150099	.1250089	.0834314	.5959722
hydro_sh_d	.0901402	.0404272	.0321751	.2845795
imports_sh_d	.0841547	.1113425	-.1620368	.2726964
demand	4276049	492284.9	3129482	5802640
etp_index	-1.83e-10	.5110584	-1.184142	2.276994
etp2	.259626	.5399313	3.28e-07	5.184701

Source: Author’s calculations from STATA descriptive output.

4.4 Correlation Structure and Preliminary Market Relationships

The relationships between the main variables are first examined through correlation analysis. Correlations do not show causality, but they can provide a first indication of how the variables are related to each other. They also help determine whether the results are consistent with the assumptions of the model.

One of the strongest relationships in the correlation matrix is observed between the Market Clearing Price and its lagged value (0.9366). This suggests that price movements were not limited to a single month. Current prices remained closely related to prices observed in the previous month.

The Market Clearing Price also shows a very strong positive correlation with Dutch TTF gas prices (0.9367). This suggests that electricity prices and natural gas prices moved closely together during the period examined. The results also indicate that developments in the European natural gas market continued to affect electricity prices in Greece.

The correlation between the Market Clearing Price and the renewable energy share is positive but considerably weaker (0.4072). This result should not be interpreted as evidence that renewable energy increases electricity prices. Renewable energy expanded during the same period as the energy crisis and other important changes in the electricity market. As a result, the correlation coefficient may reflect the influence of several factors at the same time. For this reason, a simple correlation analysis is not sufficient to examine the relationship between renewable energy and electricity prices. A multivariate approach is therefore required.

Hydropower and electricity imports both show negative correlations with the Market Clearing Price. This suggests that electricity prices tended to be lower when hydropower generation and electricity imports were higher. The ETP Index is positively correlated with the Market Clearing Price (0.6064). The squared ETP term is also positively correlated with electricity prices. These results suggest that nonlinear transition effects may play a role in electricity price behavior.

Table 4.3 presents the full pairwise correlation matrix.

Table 4.3 Pairwise Correlation Matrix (STATA Output)

	mcp	L_mcp	ttf	gas_sh_d	res_sh_d	hydro_~d	import~d
mcp	1.0000						
L_mcp	0.9366	1.0000					
	0.0000						
ttf	0.9367	0.8771	1.0000				
	0.0000	0.0000					
gas_sh_d	0.3248	0.2401	0.2025	1.0000			
	0.0000	0.0018	0.0064				
res_sh_d	0.4072	0.4744	0.3202	0.3952	1.0000		
	0.0000	0.0000	0.0000	0.0000			
hydro_sh_d	-0.1653	-0.1542	-0.0990	-0.4184	-0.2121	1.0000	
	0.0266	0.0466	0.1859	0.0000	0.0043		
imports_sh_d	-0.3225	-0.2512	-0.2502	-0.4650	-0.2189	0.2404	1.0000
	0.0000	0.0011	0.0007	0.0000	0.0031	0.0012	
demand	0.0494	-0.0469	0.0029	0.2095	-0.2272	0.0532	-0.0902
	0.5099	0.5476	0.9696	0.0048	0.0022	0.4783	0.2286
etp_index	0.6064	0.4545	0.5979	0.6562	-0.0655	-0.1989	-0.3455
	0.0000	0.0000	0.0000	0.0000	0.3990	0.0098	0.0000
etp2	0.5969	0.4371	0.7075	0.0568	0.0855	0.0387	-0.1694
	0.0000	0.0000	0.0000	0.4643	0.2703	0.6183	0.0282

	demand	etp_in~x	etp2
demand	1.0000		
etp_index	0.6086	1.0000	
	0.0000		
etp2	0.1069	0.4570	1.0000
	0.1678	0.0000	

Source: Author's STATA pairwise correlation estimations

Overall, the correlation results show that electricity prices are related to several market and transition variables. They also suggest that several factors may affect electricity prices at the same time. For this reason, a multivariate approach is used in the following analysis.

4.5 Econometric Model Specification

The purpose of this model is to examine the main factors that influence the Greek monthly Market Clearing Price. A multivariate econometric model is used because electricity prices are affected by several factors at the same time. This specification was selected on the basis of the results presented in the previous sections. The correlation analysis showed that electricity prices were strongly related to their previous values and to natural gas prices. The results also suggested that nonlinear transition effects may be present.

The dependent variable of the model is the monthly Greek Market Clearing Price. The explanatory variables include lagged MCP, Dutch TTF natural gas prices, renewable energy share, hydropower share, electricity imports, electricity demand and the ETP variables. The econometric model can be expressed as follows:

$$\begin{aligned} MCP_t = \alpha + \beta_1 MCP_{t-1} + \beta_2 TTF_t + \beta_3 RES\_SH\_D_t + \beta_4 HYDRO\_SH\_D_t \\ + \beta_5 IMPORTS\_SH\_D_t + \beta_6 DEMAND_t + \beta_7 ETP\_INDEX_t \\ + \beta_8 ETP2_t + \varepsilon_t \end{aligned}$$

In this equation, MCP_t is the monthly Greek Market Clearing Price and MCP_{t-1} is the lagged value of MCP. TTF_t refers to Dutch TTF natural gas prices. The remaining variables represent renewable energy share, hydropower share, electricity imports, electricity demand and the ETP variables. ETP_INDEX_t and $ETP2_t$ are both included in order to examine whether the effect of the energy transition on electricity prices remains constant or changes as the transition progresses.

A crisis dummy variable was also tested for the 2021–2023 energy crisis period. However, it was not retained in the final model because its effect was already captured by variables such as TTF prices, lagged MCP and the ETP variables. This helped keep the model as simple as possible while retaining the most important explanatory variables.

Robust standard errors were used in the final estimation because electricity prices were more volatile during some periods than others. This helps make the coefficient estimates more reliable. This is particularly important in electricity markets, where large price increases can affect the results of conventional estimation methods (Engle, 1982; Bollerslev, 1986).

The model includes a lagged value of electricity prices. This means that current prices are allowed to depend on prices observed in the previous month. In other words, the model does not assume that each month starts from the same point.

The model is used to examine the relationship between the selected variables and electricity prices. It also forms the basis of the forecasting analysis presented in the following chapter.

ARDL, VAR and machine learning techniques represent possible alternatives for analyzing electricity prices. The approach adopted in this dissertation was chosen because it provides a straightforward framework for studying the relationship between electricity prices and the proposed ETP Index while being appropriate for the available monthly data. The focus of the dissertation is to understand the role of transition-related variables, particularly the ETP framework, rather than to compare the performance of different forecasting algorithms.

4.6 Stationarity and Unit Root Diagnostics

As an initial step, all variables were checked for stationarity. This procedure was carried out to examine the behavior of the series over time and to reduce the risk of obtaining misleading estimates. The dataset uses monthly observations covering the period 2012–2025. Thus, the behavior of each series was checked before proceeding with estimation. Three tests were applied. The Augmented Dickey–Fuller (ADF) test was used to identify possible unit roots. The Phillips–Perron (PP) test was used to examine whether similar results were obtained using a different testing approach. The KPSS test was also applied because it is based on a different null hypothesis than the ADF and PP tests. Conclusions were drawn after considering the outcome of all tests together. Full results are available in the Appendix.

Table 4.4 Summary of Stationarity and Unit Root Tests

Variable	ADF	PP	KPSS	Final Decision
MCP	Non-stationary	Non-stationary	Trend-stationary	Mixed evidence
TTF	Non-stationary	Non-stationary	Trend-stationary	Mixed evidence
Gas Share	Non-stationary	Stationary	Mixed evidence	Mixed evidence
Res Share	Non-stationary	Non-stationary	Mixed evidence	Mixed evidence
Demand	Stationary	Stationary	Stationary	Stationary
ETP index	Non-stationary	Stationary	Trend-stationary	Mixed evidence

4.7 Multicollinearity and Diagnostic Testing

The explanatory variables were examined for possible multicollinearity. Correlation patterns and Variance Inflation Factor (VIF) values were reviewed during the development of the final model. The aim was to avoid including variables that provide largely the same information. Variables were selected on the basis of both statistical performance and economic relevance. Additional diagnostic tests were also carried out to assess the robustness of the final model.

Table 4.5 Multicollinearity Diagnostics (Variance Inflation Factor)

Variable	VIF	Interpretation
ETP Index	3.87	Acceptable
TTF	2.72	Acceptable
Demand	2.34	Acceptable
RES Share	1.27	Low

4.8 Autocorrelation and Heteroskedasticity Diagnostics

Additional diagnostic tests were performed after model estimation. Since the analysis is based on time series data, possible autocorrelation and heteroskedasticity were also examined. The residuals were also examined during this process. A Newey–West estimation was used as an additional robustness check. The adjustment had only a limited effect on the overall results, although some transition variables became less statistically significant. Detailed results are reported in the Appendix.

Table 4.6 Diagnostic Summary

Diagnostic	Purpose	Outcome
Residual analysis	Examination of residual behavior	No critical instability observed
Newey-West estimation	Robustness to autocorrelation and heteroskedasticity	Results remained broadly consistent

4.9 Lag Selection and Model Selection

Different model specifications were compared during the estimation process. Different lag structures and combinations of explanatory variables were examined before selecting the final model. Lag selection was supported by AIC, HQIC and SBIC. Both statistical and economic considerations were taken into account when selecting the final model. The detailed outputs can be found in the Appendix.

Table 4.7 Model Selection Summary

Criterion	**Role in Selection**
AIC	Comparison of alternative specifications
HQIC	Selection under model complexity considerations
SBIC	Preference for more parsimonious specifications
Economic interpretation	Consistency with theoretical expectations
Diagnostic performance	Support of final specification

4.10 Model Validation and Study Limitations

The dataset used in this study covers the period 2012–2025 and is based on monthly observations. The dataset extends over several years, while the number of observations remains relatively low. The findings are linked to the data and modelling approach used in this study. Different data or a different specification could produce different results. Future work could explore these issues using alternative datasets and a broader range of variables.

Table 4.8 Summary of Validation Approach and Study Limitations

Aspect	**Description**
Validation approach	Pseudo out-of-sample comparison
Data frequency	Monthly
Sample period	2012-2025
Potential limitation	Limited number of observations
Interpretation	Empirical rather than causal

4.11 Construction of the Extended Transition Point (ETP) Index

The structure of electricity systems has changed considerably in recent years. Meanwhile, the need for balancing resources has increased as renewable generation has expanded. In light of these findings, the present study introduces the Extended Transition Point (ETP) Index. The index is used to examine the relationship between renewable energy expansion and the continuing role of balancing resources within the electricity system.

The ETP Index is defined as:

$$ETP\_INDEX_t = \frac{RES\_SH\_D_t + HYDRO\_SH\_D_t}{GAS\_SH\_D_t + |IMPORTS\_SH\_D_t|}$$

where:

- $RES\_SH\_D_t$ represents the share of renewable energy generation,
- $HYDRO\_SH\_D_t$ represents the share of hydroelectric production,
- $GAS\_SH\_D_t$ captures the share of natural gas generation,
- $IMPORTS\_SH\_D_t$ reflects the share of net electricity imports in absolute terms.

The index measures the relationship between renewable and hydropower generation on one side and natural gas generation and electricity imports on the other. The numerator represents cleaner sources of electricity generation, while the denominator represents sources that continue to play an important role in balancing the system and meeting electricity demand.

The ETP Index is based on the idea that the energy transition involves more than increasing renewable generation. As renewable generation expands, balancing resources continue to play an important role in meeting electricity demand. For this reason, the relationship between the energy transition and electricity prices may not always be linear. This may be particularly important when renewable expansion is not accompanied by similar growth in storage capacity or system flexibility.

Rather than focusing only on renewable energy penetration, the proposed ETP Index also takes into account the resources that help maintain system balancing and flexibility. Two electricity markets with similar renewable energy shares may still rely on very different combinations of balancing resources. For example, one system may depend much more heavily on natural gas generation or electricity imports than another.

The ETP Index combines these elements into a single measure in order to provide a broader view of transition conditions and their possible connection with electricity price behavior. This means that the ETP Index goes beyond renewable energy penetration alone by also considering factors related to system balancing and support.

To test for this possibility, both the ETP Index and its squared term are included in the model:

$$ETP2_t = (ETP\_INDEX_t)^2$$

The squared term is included to examine whether the relationship between the energy transition and electricity prices remains the same as renewable participation increases.

The ETP Index does not represent a specific point at which the energy transition changes direction. It is used as an indicator of the relationship between renewable expansion and balancing dependence. On this basis, its interpretation depends on the results of the econometric analysis.

The ETP Index is included in order to examine whether changes in the energy transition are associated with changes in electricity prices.

4.12 Chapter Recapitulation

This chapter presented the data, variables and econometric methods used in the analysis. It also introduced the ETP Index, which was included in order to examine whether changes in the energy transition are associated with changes in electricity prices. The next chapter presents the empirical results and forecasting analysis.

CHAPTER 5: ECONOMETRIC RESULTS, MODEL VALIDATION AND 2026 FORECAST SCENARIOS

5.1 Introduction

The theoretical background, the Greek electricity market and the methodological approach were presented in the previous chapters. This chapter presents the empirical results.

The analysis focuses on the relationship between the Market Clearing Price and the selected explanatory variables. Natural gas prices, transition-related variables and balancing conditions are among the factors examined. The results are presented and discussed from both a statistical and an economic point of view.

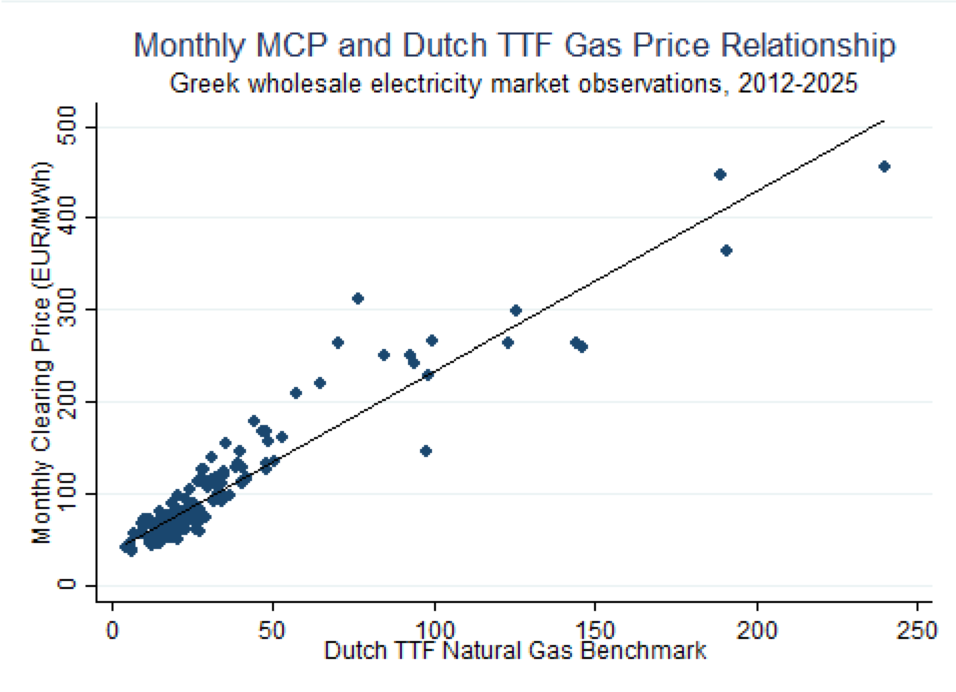
The chapter begins with a visual examination of the main patterns in the data. It then presents the results of the econometric model, followed by diagnostic checks and forecasting analysis. The chapter examines the behavior of electricity prices during the period under study and the variables that may help explain the observed patterns.

5.2 Preliminary Graphical Evidence

Before presenting the econometric results, it is useful to look at the data graphically. The figures presented in this section compare monthly Market Clearing Prices with Dutch TTF natural gas prices, the share of renewable energy and the share of natural gas generation. These figures do not show causal relationships, but they provide an initial picture of the patterns observed in the data.

Figure 5.1 compares monthly Market Clearing Prices with Dutch TTF natural gas prices. A general upward pattern can be observed in the figure. Higher electricity prices are often observed when gas prices are higher. This provides an initial indication that changes in gas prices were linked to changes in the Market Clearing Price during the period under study.

Figure 5.1 Relationship between Monthly MCP and Dutch TTF Gas Benchmark

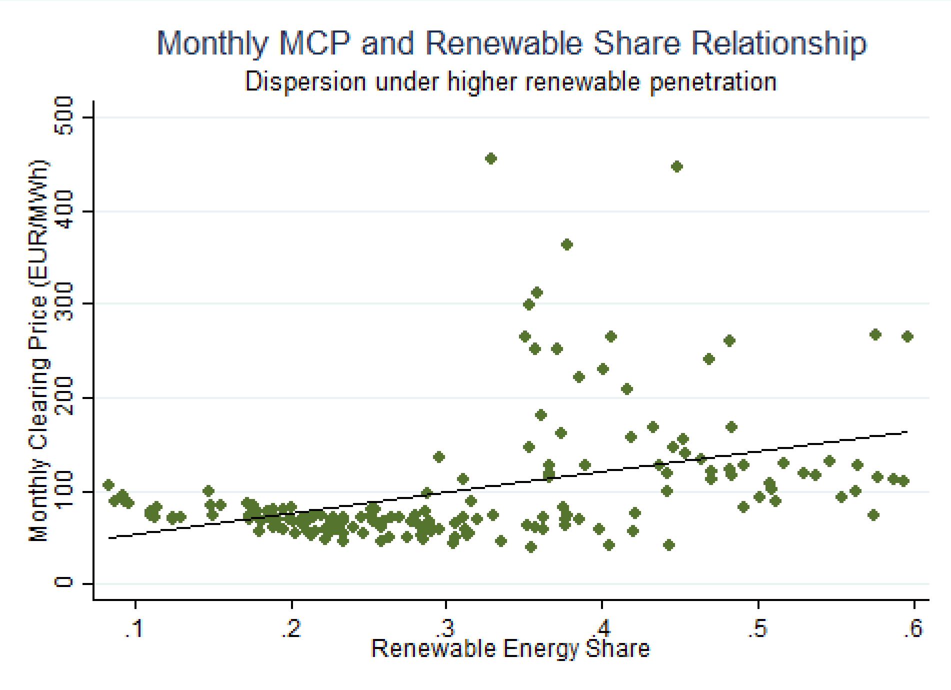


Source: Author's calculations based on monthly Greek electricity market dataset, 2012–2025.

The figure is consistent with the discussion presented earlier in the study. While the figure does not explain the reasons behind this relationship, it suggests that natural gas prices remained an important factor for electricity prices during the period under study.

Figure 5.2 compares monthly Market Clearing Prices with the renewable energy share. No clear pattern can be observed in the figure. Similar renewable shares are associated with different electricity price levels. This is particularly visible at medium and higher renewable shares, where the observations are more widely dispersed.

Figure 5.2 Relationship between Monthly MCP and Renewable Energy Share



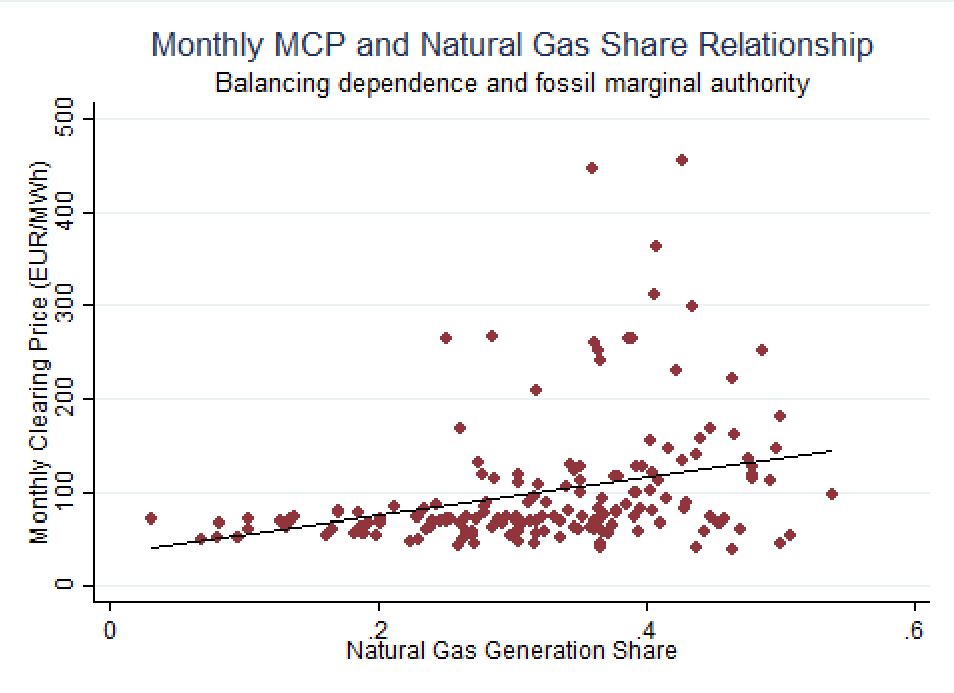
Source: Author's calculations based on monthly Greek electricity market dataset, 2012–2025.

The figure suggests that renewable energy share is only one of the factors associated with electricity prices. The wide spread of observations indicates that other factors may also influence price movements.

Figure 5.3 compares monthly Market Clearing Prices with the natural gas generation share. A general upward pattern can be observed in the figure. Higher natural gas shares are often associated with higher electricity prices. Some of the highest electricity prices are observed when the share of natural gas generation is relatively high.

The figure suggests that natural gas generation continued to play an important role in the operation of the electricity system during the period under study.

Figure 5.3 Relationship between Monthly MCP and Natural Gas Generation Share



Source: Author's calculations based on monthly Greek electricity market dataset, 2012–2025.

The figures offer a first look at the patterns observed in the data. By themselves, they cannot explain these patterns, but they help identify issues that are examined further in the econometric analysis.

5.3 Final Robust Dynamic Regression Estimation

The graphical results are followed by the estimation of the final model using robust standard errors. The model includes lagged MCP, Dutch TTF natural gas prices, balancing-related variables and the ETP Index. These variables were selected in order to examine the factors associated with monthly Market Clearing Prices during the period under study. The model also takes into account the effect of past price movements through the inclusion of the lagged dependent variable.

Table 5.1 presents the results of the final robust dynamic estimation.

Table 5.1 Final Robust Dynamic Regression Results (STATA Output)

```
. reg mcp L_mcp ttf res_sh_d hydro_sh_d imports_sh_d demand crisis etp_index etp2, robust

Linear regression                               Number of obs     =        167
                                                F(9, 157)         =     247.74
                                                Prob > F          =     0.0000
                                                R-squared         =     0.9554
                                                Root MSE          =     15.347
```

mcp	Coef.	Robust Std. Err.	t	P>|t|	[95% Conf.	Interval]
L_mcp	.5498716	.1154901	4.76	0.000	.3217569	.7779864
ttf	.5099563	.1823586	2.80	0.006	.1497635	.8701491
res_sh_d	-.9036337	28.45009	-0.03	0.975	-57.09795	55.29068
hydro_sh_d	9.496506	26.74957	0.36	0.723	-43.33896	62.33198
imports_sh_d	-22.65541	25.56143	-0.89	0.377	-73.14406	27.83325
demand	-5.86e-06	4.69e-06	-1.25	0.214	-.0000151	3.41e-06
crisis	11.19298	14.14583	0.79	0.430	-16.7477	39.13367
etp_index	24.11012	6.696709	3.60	0.000	10.88285	37.33738
etp2	11.53555	4.351635	2.65	0.009	2.940252	20.13086
_cons	49.16835	26.1614	1.88	0.062	-2.505364	100.8421

Source: Author's robust econometric estimation.

The results show that monthly Market Clearing Prices were associated with both conventional market variables and transition-related variables during the period under study.

Table 5.1 presents the results of the final model. The estimation uses robust standard errors in order to account for the high levels of price volatility observed during the period under study.

The coefficient of L_MCP is positive and statistically significant ($\beta = 0.5499$, $p < 0.001$). This result suggests that previous price levels remain relevant for current electricity prices. In other words, price movements in one month appear to be linked to price movements in earlier months.

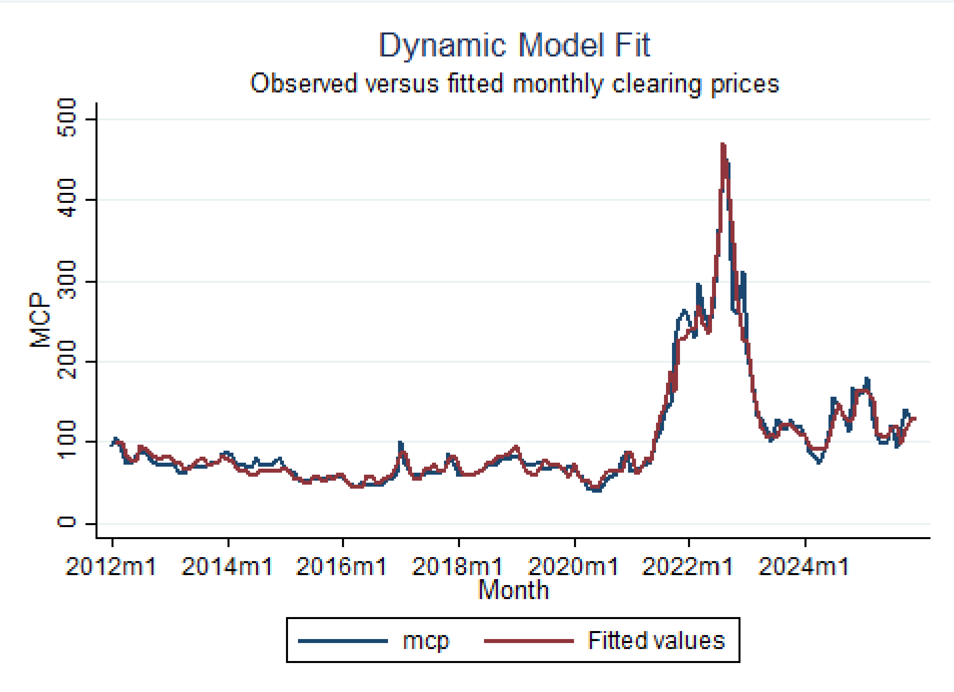
The Dutch TTF gas price variable is positive and statistically significant ($\beta = 0.5100$, $p = 0.006$). This result suggests that natural gas prices remained an important factor for wholesale electricity prices during the period under study.

The coefficients of ETP_INDEX and ETP2 are statistically significant. Both ETP_INDEX ($\beta = 24.1101$, $p < 0.001$) and ETP2 ($\beta = 11.5355$, $p = 0.009$) have positive coefficients. This suggests that the relationship between the energy transition and electricity prices may not be the same across all levels of renewable generation. The relationship does not appear to remain the same across all stages of the transition.

An R^2 value of 0.9554 is obtained for the final model. This indicates that the model explains a large share of the variation in monthly Market Clearing Prices during the sample period. However, the results depend on the variables included in the analysis and should not be interpreted as evidence of causal relationships.

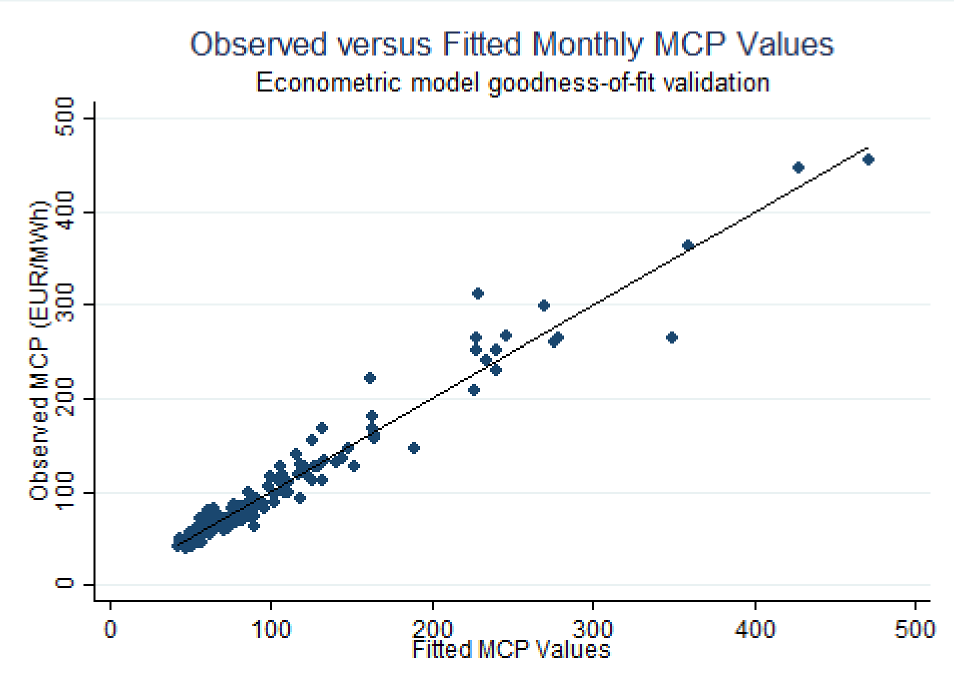
5.4 Model Fit and Diagnostic Validation

Figure 5.4 Dynamic Observed versus Fitted MCP Series



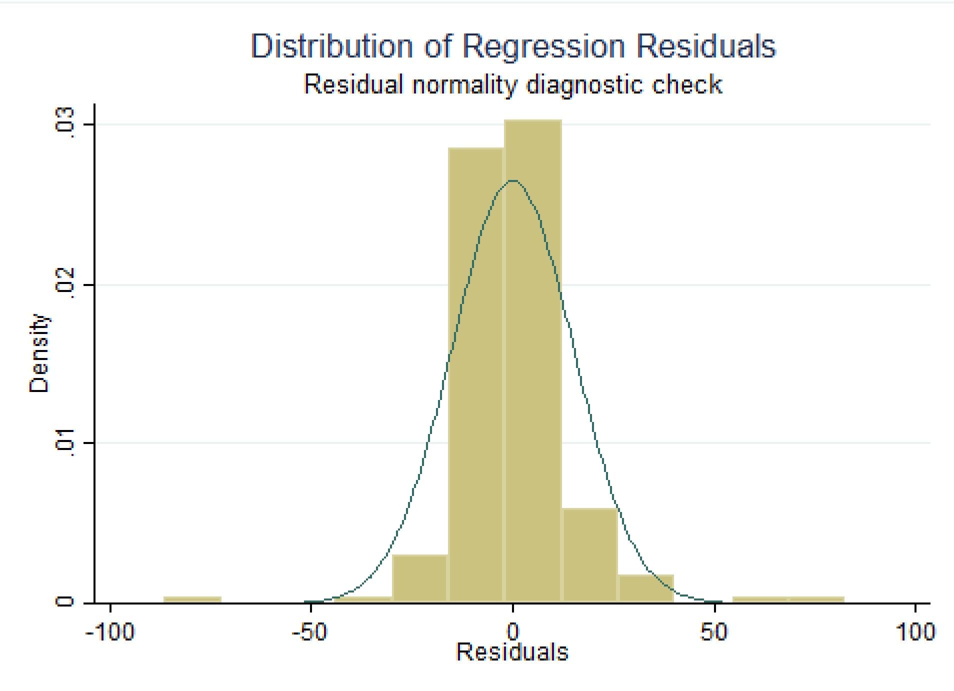
Source: Author’s STATA estimations.

Figure 5.5 Observed versus Fitted MCP Values



Source: Author's STATA estimations.

Figure 5.6 Distribution of Regression Residuals



Source: Author's STATA residual diagnostics.

The estimated coefficients do not provide the only basis for evaluating the model. Model fit and residual behavior are also examined. Figures 5.4–5.6 are used to compare observed and estimated values and to examine the distribution of the residuals.

Figure 5.4 compares observed and fitted MCP values over the sample period. The fitted series follows the main pattern of the observed series across most of the period examined. Similar movements can be seen in both series, including periods of lower and higher electricity prices. The figure does not show large and persistent differences between observed and fitted values.

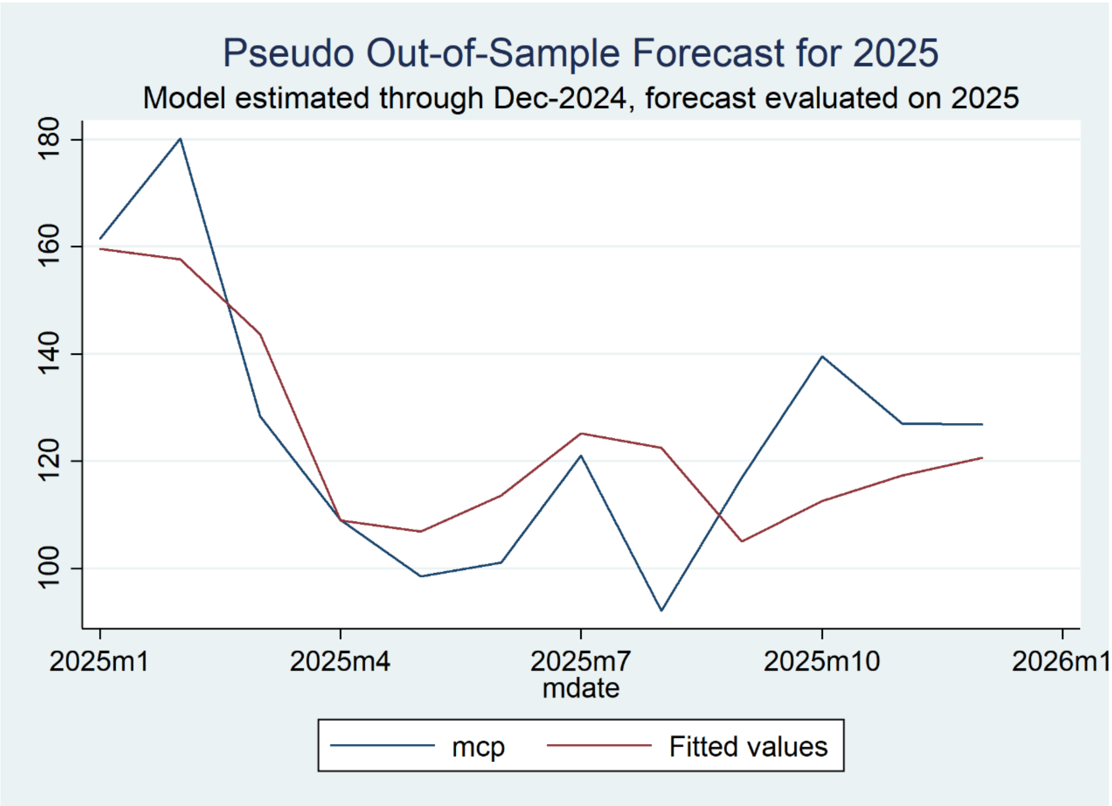
Figure 5.5 presents the relationship between observed and fitted MCP values. A large number of observations appear close to the fitted line. This suggests that the model is able to reproduce much of the variation observed in the data.

Figure 5.6 presents the distribution of the regression residuals. Most observations are located close to zero, while positive and negative residuals appear on both sides of the distribution. A small number of larger residuals can also be observed.

The results presented in Figures 5.4–5.6 suggest that the model performs reasonably well within the sample period. Even so, the findings should not be interpreted as a guarantee of future forecasting performance.

5.5 Pseudo Out-of-Sample Forecast Validation

Figure 5.7. Pseudo Out-of-Sample Forecast Validation: Observed and Predicted Monthly MCP Values for 2025.



Source: Author's STATA forecasting validation.

The forecasting exercise provides an additional way of evaluating the model. For this purpose, the model is estimated using data up to December 2024 and then compared with the observed monthly MCP values for 2025.

Figure 5.7 shows that the forecast follows the general pattern of the observed 2025 series. Similar movements can be seen during both the decline at the beginning of the year and the recovery that followed. Differences between forecasted and observed values are still visible, but the forecasts do not appear to be consistently above or below the observed values.

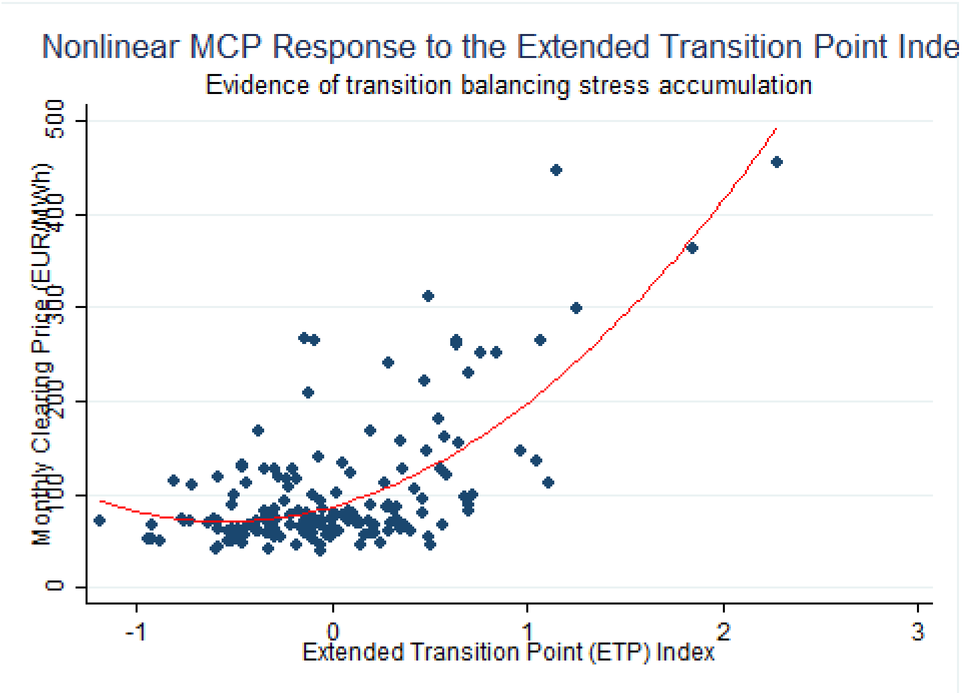
Table 5.2. Forecast Accuracy Measures for the Pseudo Out-of-Sample Validation

Forecast Accuracy Measure	Value
RMSE	15.59
MAE	12.51
MAPE	10.42%

The forecast accuracy measures were calculated using the pseudo out-of-sample observations reserved for model validation. The RMSE, MAE and MAPE results suggest that the model performs satisfactorily on this validation sample. Even so, these results should be interpreted with caution, as they are based on the available data and do not guarantee the same level of forecasting performance in future periods.

5.6 Nonlinear Sustainable Transition Response through the ETP Mechanism

Figure 5.8. Relationship between the Extended Transition Point (ETP) Index and Monthly Market Clearing Prices, including the estimated nonlinear fitted curve.



Source: Author's quadratic fitted estimations.

Figure 5.8 shows the relationship between the ETP Index and monthly Market Clearing Prices. Lower values of the index are often accompanied by lower MCP values. Higher MCP values become more common at higher levels of the ETP Index. The fitted curve also moves upward as the index increases.

The figure does not imply that renewable energy development increases electricity prices. It suggests that renewable expansion is only one of the factors related to electricity prices. Other factors related to system operation may also influence price movements during the period under study.

The ETP Index was developed to examine the relationship between the energy transition and electricity prices. Under this interpretation, electricity prices may be influenced not only by renewable generation but also by factors such as storage, hydroelectric generation, system flexibility and interconnections. The figure provides a visual illustration of this relationship.

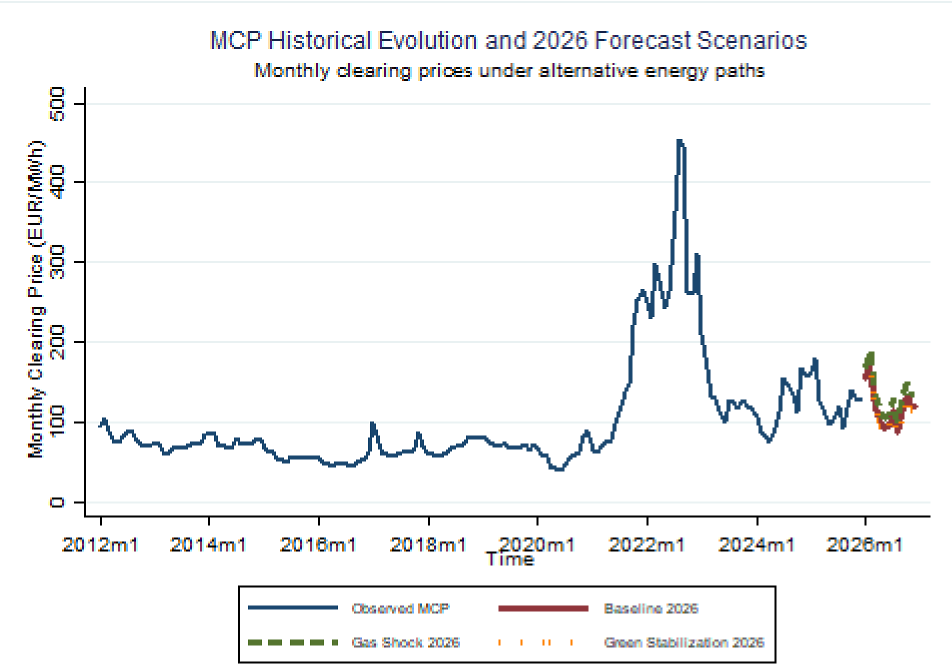
Table 5.3. Summary of the Robustness Check Based on an Alternative Model Specification.

Measure	Baseline Model	Alternative Specification
Quadratic ETP term (ETP2)	Included	Excluded
R^2	0.9545	0.9521
Root MSE	15.459	15.803
ETP_INDEX statistically significant	Yes	Yes
Main conclusions	Unchanged	Unchanged

Using an alternative specification did not materially change the main findings. This provides further support for the ETP framework and suggests that the main conclusions are not tied to a single model specification.

5.7 Monthly Forecast Scenarios for Greek MCP in 2026

Figure 5.9 Historical MCP Evolution and Alternative Forecast Scenarios for 2026



Source: Author's econometric scenario simulations.

Three alternative paths are examined for 2026. One scenario assumes no major changes in market conditions compared with the end of the sample period. Another scenario examines the effect of higher natural gas prices. The third reflects a situation with greater renewable participation, lower gas dependence and improved balancing conditions.

Figure 5.9 shows the three projected paths for 2026. The figure shows that prices remain below the levels reached during the 2022 energy crisis in all three scenarios. At the same time, prices do not fall back to the lower levels that were common before 2021.

The first scenario suggests a more stable market than the one observed during the energy crisis. The second produces higher prices as a result of higher natural gas prices. The third produces the lowest prices among the three scenarios. Even in this case, however, prices do not return immediately to earlier levels.

The three scenarios are consistent with the results presented earlier in this chapter. The scenarios show that electricity prices may remain lower than during the energy crisis. Future price levels may change as market conditions change. The results also suggest that renewable expansion is only one of the factors related to electricity prices. Other factors, including balancing conditions and system flexibility, might also play a role. The scenarios are included to show how prices may evolve under different conditions. They are not intended to predict actual future prices.

5.8 Synthesis of Empirical Findings

The results presented in this chapter suggest that several factors are related to monthly Market Clearing Prices in Greece. Natural gas prices remain an important factor, while previous MCP values continue to be linked to current price levels. The results also suggest that the relationship between the energy transition and electricity prices may not remain the same across all stages of the transition.

The results suggest that the Greek electricity market has not followed a simple pattern during the transition period. Renewable generation has increased substantially, but other factors remain important for electricity prices. Natural gas prices, balancing conditions and system flexibility are among these factors.

The model provides results that are broadly consistent with the observed data. Its high explanatory power, close observed-versus-fitted tracking, acceptable residual behavior and pseudo out-of-sample validation collectively provide support for its potential use in medium-term forecasting applications.

The ETP results are among the main findings of this study. The analysis suggests that the relationship between the energy transition and electricity prices does not remain the same across all stages of the transition. They also suggest that other factors, including storage and system flexibility, may be related to electricity prices.

The results suggest that the Greek electricity market has changed during the period under study. Renewable generation has increased, although electricity prices do not appear to respond in the same way under all conditions. The findings reflect the data and methods used in this study.

5.9 Chapter Recapitulation

The results presented in this chapter suggest that several factors were related to Greek wholesale electricity prices during the period under study. Natural gas prices, previous MCP values and the ETP variables are among the factors examined in the analysis.

The findings are consistent with the main argument of this dissertation. Renewable generation has increased, but electricity prices do not appear to respond in the same way under all conditions. The results also suggest that balancing conditions and system flexibility may remain important factors for electricity prices.

CHAPTER 6: POLICY IMPLICATIONS, STRUCTURAL LIMITATIONS AND TRANSITION CHALLENGES

6.1 Introduction

Chapter 5 presented the empirical results of the analysis. This chapter discusses what these results may suggest about the Greek electricity market and the energy transition.

The discussion focuses on how the observed relationships may be connected with market conditions and electricity price behavior. The aim is not to propose specific policy measures, but to consider what the results may suggest about the operation of the market during the period under study.

One of the findings of this study is that a higher share of renewable generation is not always associated with lower electricity price volatility. The results also suggest that balancing conditions and system flexibility remain important factors for the operation of the electricity system.

6.2 Policy Implications for the Greek Electricity Market

The results of this study may be relevant for discussions about the future development of the Greek electricity market. The analysis suggests that a greener electricity system does not always result in lower electricity prices. This is important because renewable expansion alone may not be sufficient to explain changes in electricity prices.

The results presented in Chapter 5 suggest that several factors were related to electricity prices during the period under study. Renewable generation increased and dependence on lignite declined, but natural gas prices and balancing conditions remained important factors. The results also suggest that natural gas continued to play an important role in the electricity market under certain conditions.

These findings may be relevant for future energy policy. The results suggest that changes in electricity prices cannot be explained by renewable expansion alone. Other factors, including storage and system flexibility, may also be important. The evidence indicates that the future development of the Greek electricity system is likely to depend not only on renewable expansion but also on the ability of the system to respond to changing conditions and balancing needs.

The results also highlight the possible importance of electricity storage. The findings suggest that balancing conditions may play a larger role at higher levels of renewable generation. Without sufficient storage and system flexibility, higher renewable participation may not always be associated with lower electricity prices.

This issue might become more important during periods of uncertainty in international energy markets. The empirical analysis indicates that Dutch TTF gas prices remained an important factor for Greek electricity prices during the period under study. This suggests that changes in international natural gas prices are likely to continue to affect electricity prices in Greece. The findings also suggest that reducing exposure to natural gas price fluctuations may depend not only on cleaner electricity generation but also on stronger balancing conditions within the electricity system.

The findings demonstrate different priorities for the short, medium and long term. In the short term, one of the main priorities is to reduce reliance on volatile natural gas prices while improving balancing mechanisms. Over the medium term, greater investment in storage, demand response and grid modernization can help support the continued expansion of renewable energy. In the longer term, the challenge is to ensure that renewable growth is supported by sufficient flexibility, stronger interconnections and adequate reserve capacity.

Consistent with these observations, several areas may be important for the future development of the electricity system. These include:

- large-scale electricity storage infrastructure,
- hydroelectric development,
- smart grid modernization,
- electricity interconnections,
- demand response measures,
- and flexible reserve capacity.

The results also suggest that balancing conditions and system flexibility are likely remain important as renewable generation increases.

6.3 Storage, Flexibility and the Question of Balancing Sovereignty

One of the observations of this study is that electricity systems with higher levels of renewable generation may face additional balancing challenges. Solar and wind generation have low production costs, but their output can vary over time. When balancing needs continue to be covered by fossil fuel generation, electricity prices may remain sensitive to changes in market conditions.

The Greek case provides an example of this situation. Renewable generation increased during the period under study, while the role of lignite became smaller. At the same time, electricity prices continued to be affected by natural gas prices and balancing conditions. This suggests that different parts of the energy transition may develop at different speeds.

The concept of balancing sovereignty is also relevant to this discussion. In this study, it refers to the ability of an electricity system to meet its balancing needs without a high level of dependence on imported fossil fuels or external support.

The findings suggest that balancing flexibility plays an important role at higher levels of renewable generation. They also suggest that renewable expansion alone may not always be associated with lower electricity prices. Other factors, including storage and system flexibility, may also be important.

The findings also suggest that electricity storage may play an important role in the operation of the electricity system. Batteries, pumped hydro systems and other balancing technologies may help the system operate with higher levels of renewable generation. They may also contribute to more stable electricity prices under certain conditions.

The same idea could apply to hydroelectric flexibility and electricity interconnections. Interconnections may help the electricity system during periods of market pressure. However, they may also transmit price pressures from other electricity markets under certain conditions. The findings suggest that both domestic flexibility and electricity interconnections may be important for the operation of the electricity system.

Within the framework of this study, it appears that the future development of electricity systems may depend not only on renewable generation but also on system flexibility.

6.4 Structural Limitations of the Present Econometric Framework

The results of this study should be interpreted in light of several limitations. Electricity prices are affected by many factors, including technological, economic, political and environmental developments. As a result, no single econometric model can capture every aspect of electricity market behavior.

The first limitation concerns the use of monthly data. Monthly observations were used in order to examine longer-term price movements. However, daily or hourly data might provide additional information about short-term changes in electricity prices and balancing conditions.

A second limitation relates to storage and balancing technologies. Storage variables were not included in the model because there is not yet enough historical information available. For this reason, the ETP Index was used as an indirect measure.

A third limitation relates to the forecasting scenarios presented in Chapter 5. Each scenario is based on a different set of assumptions. They should not be interpreted as forecasts of actual future prices. Future market conditions may differ from those assumed in the scenarios.

Another limitation relates to the ETP Index. The index was developed for this study and should not be viewed as a standard transition indicator. The index could be examined further in future studies using additional variables.

Finally, the analysis is limited to the Greek electricity market. Some findings may also be relevant in other countries. However, electricity systems can differ considerably from one market to another. This is why the results should be applied cautiously to other cases.

Despite these limitations, the findings provide useful information about the relationship between the energy transition and electricity prices. The results suggest that this relationship may be more complex than a simple link between renewable expansion and lower electricity prices. This relationship could be examined further in future studies.

6.5 Broader Implications for the European Energy Transition

The findings of this study may also be relevant beyond the Greek electricity market. The recent energy crisis highlighted that renewable generation alone may not always be sufficient to reduce the influence of natural gas prices on electricity markets.

These observations raise a broader question for European energy policy: to what extent can electricity systems remain simultaneously liberalized, highly renewable and structurally stable without additional development of balancing institutions?

The findings from the Greek case may indicate that the answer depends partly on flexibility capacity. An electricity market may increase renewable generation while electricity prices continue to be influenced by natural gas prices. Under these conditions, electricity systems may become greener while price volatility remains relatively high.

The findings suggest that the energy transition involves more than renewable generation or changes in generation technologies alone. Storage, balancing conditions, interconnections, market conditions and system flexibility may also play an important role in the operation of electricity systems. These observations are based on the framework used in this study and should not be viewed as general conclusions for all electricity markets.

6.6 Chapter Recapitulation

The discussion presented in this chapter suggests that the energy transition cannot be understood through renewable generation alone. The findings suggest that electricity prices may also be related to balancing conditions, storage and system flexibility.

The discussion also suggests that a sustainable electricity system involves more than cleaner electricity generation. System flexibility and the operation of the electricity system may also be important.

These observations provide the basis for the final chapter, which summarizes the main findings of the dissertation and discusses possible directions for future research.

CHAPTER 7: CONCLUSIONS AND FUTURE RESEARCH

7.1 General Conclusions

This dissertation examined whether, and to what extent, conventional forecasting approaches can be used to analyze the Greek wholesale electricity market during a period of rapid energy transition, volatility of imported fossil fuels, and institutional market restructuring.

The findings suggest that electricity price behavior cannot be explained by a single factor. Natural gas prices, balancing conditions and renewable energy generation all appear to be related to price movements. The results also suggest that these relationships may not always follow a simple linear pattern.

The generation mix of the Greek electricity market changed significantly. The Greek electricity market became more integrated with the European Target Model. During the same period, renewable energy participation increased and lignite use decreased. Although progress toward decarbonization is evident, wholesale electricity prices do not appear to be moving toward greater stability. The market continued to experience periods of high price volatility, especially when balancing needs increased and fuel prices were higher.

The econometric analysis suggests that Greek Market Clearing Prices (MCP) are related to several factors. These include previous MCP values, natural gas prices and balancing conditions. The results also suggest that the Greek electricity market remains influenced by both past price movements and developments in European natural gas markets.

At the same time, through the proposed ETP framework, there is an indication that the evolution of the sustainable transition may not follow a purely linear path. The findings lead to the consideration that the expansion of renewable energy sources is not sufficient to ensure proportionally lower wholesale electricity prices, particularly when the pace of transition is not accompanied by corresponding development in balancing capabilities and electricity storage. Put simply, renewable energy integration has advanced more rapidly than the development of the necessary flexibility.

This distinction constitutes one of the main interpretations of the present study. Sustainable transition should not be interpreted solely as the replacement of fossil fuels with renewable energy technologies. This interpretation should also include the restructuring of balancing and flexibility mechanisms, as market stability appears to be associated with them as well. The findings suggest that the energy transition involves more than decarbonization alone. System stability and flexibility may also play an important role.

The findings of this study suggest that renewable expansion alone is unlikely to be sufficient to ensure lower and more stable electricity prices. Electricity storage, hydro flexibility, reserve adequacy and balancing conditions may also play an important role. The results also suggest that renewable generation is only one of the factors related to electricity prices. These observations should not be interpreted as general rules for all electricity markets. They reflect the data and methods used in this study and should be interpreted accordingly.

7.2 Main Empirical Contributions of the Dissertation

The present dissertation seeks to contribute to the existing literature in several distinct ways. First, through the proposal of a dynamically multivariate forecasting framework. Its design has been based on the characteristics that govern the Greek electricity market during the post-lignite era. The model combines the behavior of previous prices, the influence of international fuel prices, and variables related to the transition toward renewable energy sources. In this way, a more modern and dynamic approach to electricity price forecasting is attempted.

Following this, a synthetic framework has been developed for the purposes of the present research in order to capture the nonlinear interaction between renewable energy expansion and dependence on balancing mechanisms. This framework is named the “Extended Transition Point (ETP) Index”. The empirical significance of both the ETP term and its quadratic component may indicate that the dynamics of the sustainable transition cannot be fully captured solely through renewable energy participation indicators.

Furthermore, the dissertation suggests that decarbonization and electricity affordability may depend on broader system conditions rather than follow a mechanically linear relationship. This finding highlights the distinction between generation decarbonization and system flexibility. A finding that may contribute to the broader discussions surrounding the economic dimension of the energy transition.

Additionally, the selected specification demonstrates strong explanatory performance within the examined sample. This is indicated through the forecasting and diagnostic exercises. The model not only captures a significant share of the observed variation in MCP values, but is also generally considered consistent in its forecasting behavior during pseudo out-of-sample validation exercises.

Finally, the Greek case provides an example of how renewable energy expansion, natural gas prices and balancing conditions may influence electricity prices during the energy transition. Although the analysis focuses on Greece, some of the findings may also be relevant in a broader context. These observations are based on the framework used in this study and should be interpreted accordingly.

7.3 Future Research Directions

The present dissertation could serve as a starting point for further research in several areas. Future studies may use more detailed data. Such data may be hourly or intraday, with the aim of examining in greater detail how balancing requirements and electricity market volatility at the short-term level are affected by renewable energy sources.

Furthermore, as storage technologies continue to develop in Greece, it becomes easier to study their impact on wholesale electricity prices. Variables directly related to electricity storage, such as battery energy storage systems, could be incorporated more explicitly into future analyses.

Moreover, by comparing the Greek case study with other European electricity markets, it could be determined whether the Greek case is uniquely distinctive or whether there are other countries that exhibit similar energy transition dynamics.

At the same time, the addition of new variables could contribute to the further development of the ETP mechanism. Such variables may include:

- reserve adequacy,
- storage adequacy,
- renewable energy curtailment,
- balancing costs,
- or smart-grid flexibility variables.

Finally, electricity markets are affected by a range of economic, political and regulatory factors. Future research could examine how these factors interact with electricity demand and market behavior.

The findings of this study suggest that technological progress alone may not be sufficient. Stability, flexibility and balancing conditions may also be important for the future development of electricity systems.

7.4 Final Concluding Remarks

The transition toward sustainable electricity systems is one of the major changes taking place in the energy sector. The findings of this study suggest that its progress cannot be assessed only through renewable energy expansion or reductions in carbon emissions.

The operation of electricity systems depends on more than electricity generation. Stability and balancing conditions may also play an important role. The Greek electricity market provides an example of this, as cleaner electricity generation is not always associated with greater market stability.

As the present dissertation is examined, it becomes evident that its findings suggest a broader interpretation of the sustainable transition, as an issue that concerns not only decarbonization, but also institutional flexibility, system flexibility, and the effective coordination of its individual mechanisms. In many respects, it appears that the future challenge of electricity economics is likely to focus increasingly on managing complexity within ever more interconnected electricity systems.

This interpretation is also consistent with the findings of this study. The results suggest that electricity markets are influenced by more than generation technologies alone. Infrastructure, system flexibility and balancing conditions may also play an important role.

Cleaner electricity generation expanded during the period covered by this study. A cleaner electricity mix did not necessarily translate into a more stable market. The findings suggest that renewable energy expansion on its own is unlikely to be sufficient. The availability of storage, system flexibility, balancing resources and broader system resilience also appears to be important for the effective functioning of electricity markets.

APPENDIX

Table A.1. Augmented Dickey–Fuller (ADF) Unit Root Test Results

Variable	Test Statistic	p-value	Decision
MCP	-2.454	0.127	Non-stationary
TTF	-2.785	0.061	Non-stationary
gas_sh_d	-0.812	0.816	Non-stationary
res_sh_d	-1.054	0.733	Non-stationary
Demand	-2.957	0.039	Stationary
Etp_index	-1.872	0.346	Non-stationary

Table A.2. Phillips–Perron (PP) Unit Root Test Results

Variable	Test Statistic	p-value	Decision
MCP	-2.349	0.160	Non-stationary
TTF	-2.725	0.072	Non-stationary
gas_sh_d	-3.554	0.008	Stationary
res_sh_d	-2.624	0.098	Non-stationary
Demand	-7.738	0.000	Stationary
Etp_index	-7.842	0.000	Stationary

Table A.3. KPSS Stationarity Test Results

Variable	Test Statistic	p-value	Decision
MCP	0.091	N/A	Trend-stationary
TTF	0.084	N/A	Trend-stationary
gas_sh_d	0.136	N/A	Mixed evidence
res_sh_d	0.133	N/A	Mixed evidence
Demand	0.045	N/A	Stationary
Etp_index	0.092	N/A	Trend-stationary

Notes: For the KPSS test, failure to reject the null hypothesis indicates stationarity.

Table A.4. Lag Selection Criteria (VARSOC)

Lag	AIC	HQIC	SBIC
0	44.596	44.635	44.691
1	38.457	38.687	39.024
2	37.774	38.196	**38.814***
3	**37.579***	**38.193***	39.091
4	37.605	38.411	39.590

Notes: Optimal lag length is selected based on information criteria. Lower values indicate preferred lag specification.

Table A.5. Johansen Cointegration Test Results

Null Hypothesis	Trace Statistic (lag=2)	Trace Statistic (lag=3)	5% Critical Value	Decision
r = 0	210.938	208.246	68.52	Reject
r ≤ 1	80.863	73.919	47.21	Reject
r ≤ 2	32.510	30.561	29.68	Reject
r ≤ 3	8.649	9.441	15.41	Do not reject

Notes: Johansen trace statistics indicate cointegration rank equal to 3 under both lag specifications.

Table A.6. Engle–Granger Cointegration Test Results

Test	Test Statistic	p-value	Decision
Residual-based ADF (Engle-Granger)	-2.840	0.053	Weak evidence of cointegration (10% level)

Notes: Residual stationarity is rejected at the 10% significance level but not at the 5% level. Accordingly, the Engle–Granger procedure provides weak evidence of cointegration.

Table A.7. Newey-West Robustness Estimation

Variable	Coef.	Std. Err.	t	p>|t|	|95% Conf. Interval|
L_MCP	0.5112	0.0834	6.13	0.000	[0.347, 0.677]
TTF	1.0411	0.111	9.37	0.000	[0.822, 1.260]
DEMAND	8.18E−06	2.64E−06	3.09	0.002	[2.96E−06, 0.000]
ETPI	−11.531	6.140	-1.88	0.062	[−23.658, 0.594]
$ETPI^2$	1.959	1.503	1.30	0.194	[−1.010, 4.928]
Constant	−10.988	13.194	−0.83	0.406	[−37.045, 15.068]

Note: Newey–West standard errors (lag = 3) were applied as a robustness check for autocorrelation and heteroskedasticity.

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