

Article

Toward a Sustainable Electricity Market: Dynamic Interactions Across Day-Ahead, Intraday, and Balancing Markets in Greece

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Abstract

This paper investigates the interaction and price discovery mechanisms among the day-ahead, intraday, and balancing segments of the Greek wholesale electricity market under the European Target Model, emphasizing their contribution to a sustainable and flexible energy transition. Using a Vector Error Correction Model with exogenous variables (VECMX), hourly data from 2023 to September 2025 are analyzed, incorporating key system fundamentals and regime-dependent dynamics. The results reveal a hierarchical market structure in which the day-ahead market dominates long-run price discovery, the intraday market acts as a short-run adjustment mechanism, and the balancing market reflects real-time system conditions associated with renewable energy variability and system reliability. Forecast Error Variance Decomposition shows that day-ahead shocks explain most long-run price variation, while balancing market effects are mainly transitory. Cointegration analysis confirms stable long-run relationships among market segments, with imbalance prices anchored to forward market outcomes and moderated by intraday adjustments. *Robustness tests* based on *alternative recursive orderings* and *Generalized Impulse Response Functions* (GIRFs) confirm the stability of the results and the dominant role of the day-ahead market in price discovery. The findings have important policy implications for market design and sustainability, highlighting the role of integrated day-ahead, intraday, and balancing markets in supporting renewable energy integration, system flexibility, and the transition toward a resilient low-carbon electricity system. The Greek electricity market is gradually evolving toward a mature and resilient Target Model structure capable of supporting higher renewable energy penetration, improved operational flexibility, and enhanced market efficiency within the European decarbonization framework.

Keywords: sustainable electricity market; target model; day-ahead; intraday; balancing; imbalance price; VECM; cointegration; IRF; FEVD; market integration

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1. Introduction

The transition to the European Target Model has fundamentally reshaped price formation in wholesale electricity markets by introducing a sequence of forward and real-time trading stages designed to support market integration, operational efficiency, and

the *sustainable energy* transition. In this framework, the day-ahead market determines financially binding schedules, the intraday market allows market participants to update positions closer to delivery, and the balancing mechanism resolves residual system imbalances in real time. These market layers play an increasingly important role in facilitating the integration of variable renewable energy sources (RES), enhancing system flexibility, and supporting the decarbonization objectives of the European electricity sector. Understanding how information is transmitted across these market stages is therefore essential not only for assessing market efficiency and balancing costs, but also for evaluating the ability of electricity markets to *support a reliable and sustainable low-carbon energy system*. While a growing literature examines price formation in European electricity markets, most studies focus on individual trading stages or on cross-border integration, *with comparatively limited evidence on the dynamic interaction among day-ahead, intraday, and balancing prices within a unified empirical framework*. This issue is particularly relevant for markets that have recently completed the transition to the Target Model, where liquidity, forecasting accuracy, renewable energy penetration, and participant behavior are still evolving. The Greek wholesale electricity market provides a natural laboratory for such an analysis. Since the implementation of the Target Model, the market has developed a sequential trading structure with distinct yet interrelated price signals, while simultaneously experiencing rapid growth in renewable generation, increased cross-border exchanges, and changing balancing needs associated with the energy transition. These features raise important questions about the *locus of price discovery, the role of intraday trading as a flexibility and adjustment mechanism, and the extent to which balancing prices reflect real-time scarcity conditions or forward scheduling decisions*.

This paper investigates the dynamic transmission of price signals across the Greek day-ahead, intraday, and balancing markets. We employ a cointegrated Vector Error Correction Model with exogenous system fundamentals (VECMX), which allows us to jointly capture long-run equilibrium relations, short-run adjustment dynamics, and the conditioning role of physical system variables such as demand, net imports, activated balancing energy, and scarcity indicators. The econometric framework is consistent with the institutional sequencing of the Target Model and enables a structural interpretation of shocks through a recursive identification based on market timing.

The results reveal a strongly hierarchical and increasingly forward-oriented price discovery process. The three price series are linked by stable cointegrating relationships, confirming a high degree of structural integration and effective arbitrage across market stages. In the long run, innovations in the day-ahead market account for the dominant share of the variance of both intraday and imbalance prices, while intraday innovations have only a limited independent role. This indicates that the day-ahead market functions as the primary platform for information aggregation, with the intraday market acting mainly as a short-run flexibility and adjustment mechanism. The imbalance price is largely anchored to day-ahead market outcomes after very short horizons, suggesting that real-time balancing costs primarily reflect prior scheduling decisions rather than autonomous real-time price formation.

A comparison across years shows a strengthening of this hierarchy over time. The increasing importance of day-ahead innovations and the declining role of real-time shocks are consistent with improving renewable generation forecasts, enhanced intraday liquidity, and greater market participant adaptation to the Target Model environment. Moreover, regime analysis based on balancing activation levels indicates that price discovery becomes even more forward-driven during system stress, while the long-run integration among the three markets remains robust.

These findings have important implications for both market design and *sustainable energy policy*. First, they highlight the central role of forward markets in supporting effi-

cient system operation, reducing balancing costs, and facilitating renewable energy integration through improved forecasting and risk allocation. Second, the limited independent contribution of imbalance price innovations suggests that high balancing costs are primarily symptomatic of inefficiencies in forward scheduling rather than failures in the real-time mechanism itself. Third, the persistence of long-run integration across regimes indicates that the Target Model is functioning effectively in aligning price signals across trading horizons and enhancing system resilience under increasing renewable penetration.

This paper contributes to the literature in several ways. First, it provides new empirical evidence on price discovery across electricity market stages under the European Target Model using high-frequency data from a recently restructured market undergoing rapid energy transition. Second, it applies a VECMX framework that incorporates both fundamental drivers and regime-dependent dynamics, allowing for a comprehensive analysis of long-run integration and short-run adjustments. Third, it documents a non-linear process of market maturation, showing a transition from strong forward market dominance toward a more interactive structure in which real-time balancing conditions increasingly influence price formation. Finally, it offers new insights into the role of intraday trading and balancing markets in enhancing system flexibility, mitigating imbalances associated with renewable intermittency, and supporting the development of a *more sustainable and resilient electricity market*. To assess the *robustness of the results*, the study complements the baseline identification scheme with *alternative recursive orderings and Generalized Impulse Response Functions (GIRFs)*. These additional analyses allow the stability of the estimated price discovery relationships to be evaluated under different identification assumptions.

Research Hypotheses

The preceding discussion highlights the central role of market integration, price discovery, and system flexibility within the European Target Model. Building upon the theoretical framework of sequential electricity markets and the institutional characteristics of the Greek wholesale electricity market, this study formulates four testable hypotheses regarding the interaction among the Day-Ahead Market (DAM), Intraday Market (IDM), and Balancing Market (represented by the Imbalance Price, IP).

H1. *Long-run Market Integration Hypothesis.*

The day-ahead, intraday, and imbalance prices are cointegrated and share stable long-run equilibrium relationships. This hypothesis reflects the expectation that the three market stages operate as interconnected components of a unified electricity market, linked through arbitrage mechanisms and sequential trading decisions.

H2. *Day-Ahead Price Discovery Hypothesis.*

The day-ahead market constitutes the dominant venue for price discovery and represents the primary source of long-run information for subsequent market stages. Given its role as the principal scheduling mechanism within the Target Model, DAM prices are expected to incorporate most available market information (an efficient market requirement) and therefore exert a dominant influence on IDM and IP dynamics.

H3. *Market Maturation Hypothesis.*

The contribution of intraday and balancing markets to price discovery increases over time as the market matures and renewable energy penetration expands. As forecasting technologies improve, market liquidity increases, and renewable generation becomes

more prominent, intraday and balancing markets are expected to play a progressively larger role in the transmission and incorporation of information.

H4. Regime-Dependent Price Discovery Hypothesis.

The price discovery process differs between normal and stress conditions characterized by elevated balancing activation requirements. Periods of system stress may alter the relative importance of the three market stages, potentially increasing the influence of real-time balancing conditions and modifying the transmission of information across markets.

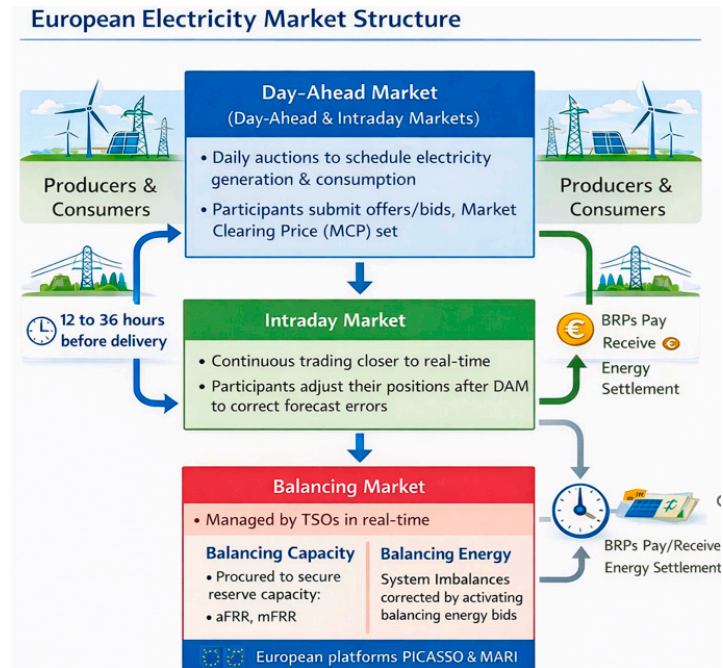
The empirical analysis conducted in the following sections evaluates these hypotheses using a Vector Error Correction Model with exogenous variables (VECMX), impulse response analysis, forecast error variance decomposition, and regime-dependent comparisons. Together, these methods allow the investigation of both long-run equilibrium relationships and short-run information transmission mechanisms within the Greek wholesale electricity market.

2. The Greek Wholesale Electricity Market (GEM) Under the Target Model

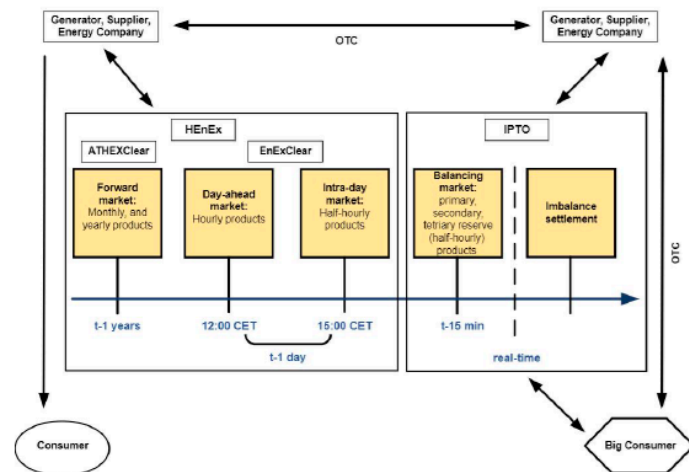
An ‘exhaustive’ literature review on the Greek wholesale electricity market is given by [1], with an extensive literature that captures the historical stages of its evolution. However, for completeness of this work, we provide here a short description of the market’s components. GEM transitioned to the European Target Model in November 2020, in accordance with Regulation (EU) 2019/943 (EU 2019/943) [2]. The reform replaced the former mandatory pool model with a sequential market structure composed of a Forward Market (FM), a Day-Ahead Market (DAM), an Intraday Market (IDM), and a Balancing Market (BM).

The DAM and IDM are operated by the *Hellenic Energy Exchange (HEX)*, while the *Balancing Market* and imbalance settlement are operated by the *Independent Power Transmission Operator (IPTO/ADMIE)*. The Target Model establishes a chronological adjustment mechanism in which market participants progressively refine their positions from forward contracting to real-time balancing. This *sequential structure induces structural interdependence* across DAM, IDM, and imbalance prices. In Figures 1 and 2 we depict the sequential structure of GEM and its applied auction time frames.

The sequential structure of the Greek Target Model (Figures 1 and 2 and Table 1) implies structural co-movement across DAM, IDM, and imbalance prices. The imbalance price provides a real-time scarcity signal, which feeds back into intraday and day-ahead bidding strategies. Therefore, a multivariate framework (e.g., VECM) is particularly appropriate to capture long-run equilibrium relationships and short-run spillovers. *The present study contributes to the Greek electricity market literature* by providing the first joint econometric analysis of DAM, IDM (CRIDA auctions), and imbalance prices, explicitly modeling the sequential adjustment mechanism, examining regime dependence linked to balancing activation volumes, and finally identifying evolving market leadership patterns following Target Model implementation.



(a)



(b)

Figure 1. (a) A typical view of the European Electricity market structure, (b) The sequential structure of the Greek electricity market constituents and their interactions (adopted from [1]).

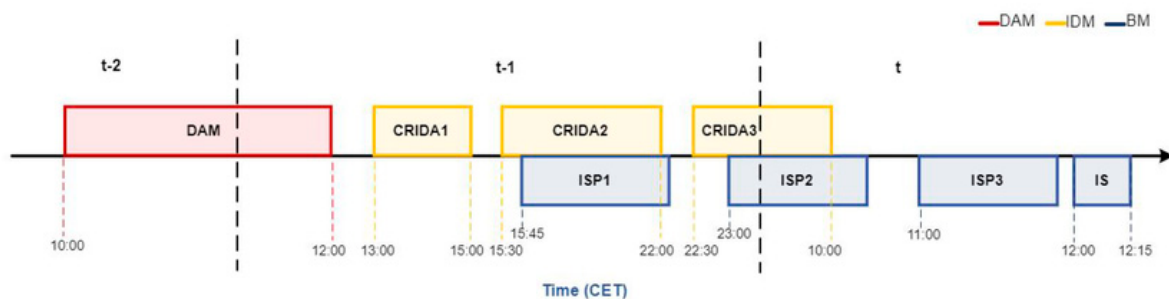


Figure 2. Applied auctions time frames in the sequence of GEM's submarkets ([1]). Dashed vertical lines indicate the separation of periods $t-2$, $t-1$, and t .

Table 1. Greek market sequence and key features.

Market	Timing	Product	Price Output	Key Participant Behavior	Link to Next Market
Forward Market	Months–Years ahead	Bilateral forward contracts	Forward contract price	Hedge long-term exposure	Defines hedging baseline
Day-Ahead Market (DAM)	D-1 auction	24-hour energy contracts	DAM MCP	Main price discovery; schedule baseline	Creates binding schedules
Intraday Market (IDM—CRIDA1/2/3)	D-1 (15:00, 22:00) & D (10:00); three auctions	Hourly adjustment contracts	IDM MCPs	Correct forecast errors; reduce imbalance exposure	Updates final scheduled position
Balancing Market (BM)	Real time	Balancing energy & capacity	Activation price; Imbalance price	Activated by TSO; deviations settled	Final financial settlement

2.1. Day-Ahead Market (DAM)

The Day-Ahead Market is the primary price discovery platform in Greece. It operates as a uniform-price auction clearing once per day for 24-hour contracts and is coupled with European markets through the Single Day-Ahead Coupling (SDAC). DAM determines hourly Market Clearing Prices (MCPs), cleared quantities, and net positions per market participant.

Existing literature on the Greek market [1] prior to and during the transition to the Target Model has largely focused on price volatility, market power, market integration with neighboring systems, and renewable penetration effects. Earlier studies under the pre-Target Model pool regime documented structural characteristics such as high price volatility, regulatory intervention effects, and the role of Public Power Corporation dominance. Subsequent research following market reform emphasized European integration and the evolving role of cross-border coupling. However, most of these studies concentrate either on DAM price formation or on overall volatility patterns, without explicitly modeling the sequential DAM–IDM–BM interaction introduced by the Target Model.

2.2. Intraday Market (IDM): The CRIDA Auctions

The Greek Intraday Market operates through *three Complementary Regional Intraday Auctions* (CRIDA1, CRIDA2, CRIDA3), aligned with the European Single Intraday Coupling (SIDC) framework. Each CRIDA auction clears hourly contracts, updates scheduled positions and produces intraday market clearing prices. CRIDA3 occurs closest to physical delivery and therefore represents the final opportunity for schedule correction before real-time balancing.

The literature on Greek electricity markets has only recently begun addressing intraday trading dynamics [1]. Most empirical work remains concentrated on DAM pricing behavior or system marginal price dynamics under the old pool model. Studies focusing on renewable integration highlight the growing importance of intraday corrections in systems with high-RES penetration [3], in which DAM and IDM are associated with Greek power system flexibility. But *a formal econometric analysis of CRIDA interactions with DAM and imbalance prices remains limited*. In contrast, broader European studies [4,5] show that intraday markets increasingly serve as forecast-correction platforms, reducing imbalance

exposure and smoothing system operations. This European evidence suggests strong economic linkages between day-ahead commitments, intraday corrections, and balancing outcomes—an interaction that remains underexplored for Greece. In the context of CRIDAs, only contracts requiring physical delivery are traded, each representing a one-hour time unit. The primary order type across the three CRIDAs is the hourly hybrid order, with participants submitting buy or sell orders during each session. More specifically (see Figure 2), CRIDA 1 opens at 13:00 CET and closes at 15:00 CET on the day before delivery, covering all IDM time units. CRIDA 2 runs from 15:30 CET to 22:00 CET on the day before delivery, also covering all IDM time units and finally CRIDA 3 opens at 22:30 CET on the day before delivery and closes at 10:00 CET on the delivery day, applying only to the second half of IDM time units (see Figure 2). During each CRIDA, order matching between coupled borders is paused until results are published, and all orders are verified and validated. The results include: (i) the acceptance status of each order, (ii) a single net position for each bidding zone and market time unit, and (iii) the CRIDA clearing price per bidding zone and market time unit. In Conclusion, this structured approach to CRIDA sessions ensures transparency, efficient order processing, and clear outcomes for all market participants, supporting the integrity and reliability of the market framework. In Section 4 (Methodology), we explain why we have adopted CRIDA3 as one of the three dependent variables of the VECMX model. In Appendix A.5, we provide extra information on the related topics to this paper, the European context and integration of balancing markets.

2.3. Link of Greek BM to the Econometric Framework

Based on the above, the institutional structure of the Greek electricity market implies strong dynamic interactions between prices across market stages. In particular, the *day-ahead market provides the primary price signal, the intraday market allows participants to adjust positions as new information becomes available, and the balancing market reflects real-time system conditions and operational constraints*. Because these markets are sequentially cleared and connected through arbitrage and portfolio adjustments, their prices are expected to exhibit *long-run equilibrium relationships and short-run adjustment dynamics*. This motivates the use of a *Vector Error Correction Model with exogenous variables (VECMX)* to analyze price interactions across the three market stages. In this framework, cointegration relationships capture the *long-run integration of prices across markets*, while *short-run dynamics* reflect the *transmission of shocks arising from demand fluctuations, cross-border flows, and balancing needs*. By combining impulse response analysis and variance decomposition, the model allows us to *identify the relative contribution of each market stage to price discovery and volatility transmission*. Additionally, more detailed information on the features of all the above prices is provided in Appendix A (see A1, A2, A3 and A4 sub-appendices).

2.4. Literature Review, Research Gap and Contribution

Table 2 synthesizes the principal strands of the literature on the Greek wholesale electricity market and highlights a structural gap that remains unaddressed. Although substantial progress has been made in understanding institutional reform, price formation, and forecasting in individual market segments, the dynamic interdependence implied by the Target Model's sequential architecture has not been systematically quantified.

Table 2. Literature map: Greek electricity market studies.

Paper	Market Period /Data	Methodology	Market Segment(s)	Main Focus/Findings	Limitation	How This Study Extends
Makrygiorgou et al. (2023) [1]	Post-Target Model (after Nov 2020)	Legislative review + case study efficiency analysis	FM, DAM, IDM, BM	Provides detailed description of Greek Target Model opera-	Primarily descriptive; lacks econometric	

				tion; finds improved efficiency, lower balancing prices, increased IDM liquidity; highlights remaining challenges	modeling of co-move	
European Commission (2019) [2]	EU-wide	Policy analysis	Intraday markets	Discusses future intraday market design & flexibility needs	Not Greece-specific; no empirical modeling	Applies concepts to Greek CRIDA auction dynamics
Metaxas et al. (2019) [6]	Pre-Target Model transition period	Institutional/regulatory analysis	DAM (structural design)	Discusses implementation challenges of the Target Model in Greece and regulatory alignment with EU market coupling	No high-frequency empirical price modeling	Adds post-Target Model empirical analysis of DAM-IDM-BM price interaction
Biskas et al. (2016) [7]	Pre-Target Model	Market design framework	DAM (architecture compliance)	Proposes system-level design for Target Model implementation	Focus on architecture, not price dynamics	Tests empirically whether Target Model structure induces long-run price integration
Koltsaklis & Dagoumas (2018) [8]	DAM scheduling context	Optimization/scheduling modeling	DAM	Studies EUPHEMIA-based market product design and scheduling implications	Does not analyze intraday or imbalance prices jointly	Examines dynamic spillovers between DAM and IDM prices
Ioannidis et al. (2019) [9]	Pre- and early Target Model	Exchange design analysis	DAM/Exchange structure	Examines energy exchange design and product definition in Greece	No intraday-balancing interaction analysis	Incorporates IDM (CRIDA) and imbalance pricing in unified econometric framework
Papaioannou et al. (2015) [10]	Pre-Target Model; Greece–Italy DAM prices	Wavelet time-frequency analysis	Cross-border DAM	Identifies time-varying co-movement and multi-scale integration between Greek and Italian markets	Focus on cross-border DAM only; no intraday or balancing layers	Shifts focus from cross-border integration to intra-market DAM-IDM-BM co-evolution under Target Model
Papaioannou et al. (2020) [11]	Greece–Italy–Bulgaria cross-border prices	Granger causality network analysis	Cross-border wholesale markets	Maps directional information flows and market leadership in regional trading	Focus on cross-border links, not intra-market structure	Applies dynamic causality tools to internal Target Model sequence (DAM→IDM→BM)
Papaioannou et al. (2018) [12]	Greek spot price & fundamentals	Rolling VECM	Greek spot market (DAM)	Finds long-run cointegration between electricity prices and fundamentals; time-varying short-run dynamics	Does not model intraday corrections or imbalance pricing	Extends VECM framework to sequential DAM-IDM-IP interaction and stress regime analysis
O’Conor et al. (2025) [13]	Multi-market electricity datasets (DA, ID, Balancing)	Comparative review of forecasting models (statistical, ML, hybrid, ensemble)	DAM, IDM, BM	Reviews electricity price forecasting models across market layers; finds hybrid/ensemble models strongest in DAM, RNNs in IDM, simpler models effective in balancing markets	Focus on forecasting accuracy; not on structural co-movement across markets	Complements forecasting literature by modeling structural interdependence and equilibrium relationships between DAM-IDM-IP
Plakas et al. (2023) [14]	Greek balancing market; imbalance volumes	Algorithm comparison; predictive modeling	BM/Imbalance volumes	Evaluates imbalance volume forecasting in Greece; shows increasing complexity due to RES integration	Focus on imbalance volume prediction, not price interaction across markets	Extends balancing analysis by linking imbalance price to DAM and IDM through multivariate dynamic modeling
Ioannidis et al. (2021/Target Model assessment) [15]	Pre- and post-November 2020 comparison	Institutional and performance assessment	All segments (FM, DAM, IDM, BM)	Reviews effects of Target Model implementation; identifies transitional distortions, especially in balancing market	Descriptive; does not quantify price transmission mechanisms	Empirically tests how transitional distortions translate into dynamic price interactions

Greek RAE Market Reform Plan (2017) [16]	Regulatory planning phase	Policy/institutional documentation	All segments	Roadmap for transition to T target Model	Descriptive, not econometric	Quantifies dynamic interactions implied by reform
HEnEx Spot Rulebook [17]	Post-2020	Legal/operational framework	DAM & IDM (CRIDA)	Defines clearing rules, product structure, auction timing	No empirical evaluation	Uses rulebook definitions to construct econometric variables
IPTO Balancing Market Documentation [18]	Post-2020	Operational rules	BM/Imbalance	Defines balancing activation and imbalance settlement mechanism	No dynamic analysis of imbalance price behavior	Models imbalance price jointly with DAM and IDM
EFET (2020) [19]	EU-wide	Market design recommendations	Intraday	Emphasizes importance of intraday corrections in RES-dominated systems	Not empirically tested in Greek context	Empirically tests intraday correction role via VECM

A first body of work examines the institutional transition of the Greek market to the European Target Model [1,6,7]. These contributions provide detailed analyses of regulatory alignment, market coupling, and the operational restructuring of forward, day-ahead, intraday, and balancing markets. They document the structural transformation from a centralized pool to a multi-layered market system and assess performance during and after the transition. However, their focus is primarily institutional and descriptive. While they explain how DAM, IDM, and BM are organized and how they are intended to interact, they do not empirically evaluate whether this sequential design generates measurable long-run integration or short-run transmission across price series.

A second strand concentrates on day-ahead market design and clearing mechanisms [8,9]. These studies investigate auction algorithms, product definitions, and scheduling optimization under the EUPHEMIA framework. Their contributions are essential for understanding price formation in the DAM and the operational constraints embedded in the clearing process. Nevertheless, the analysis remains largely confined to the day-ahead layer and does not incorporate intraday corrections or balancing settlement within a unified empirical framework.

A third stream employs advanced econometric techniques to study electricity price dynamics. Reference [10] documents a co-movement analysis of Italian and Greek electricity market a wholesale price using wavelet approach, while a time-varying cross-border integration between Greece and Italy using Granger Causality network methods is presented in [11], while Reference [12] applies a *rolling VECM* to uncover cointegration between Greek spot prices and fundamental determinants. These studies significantly advance methodological rigor and demonstrate that electricity prices exhibit evolving long-run and short-run relationships. Yet their scope is either cross-border or limited to price–fundamental interactions within a single market layer, typically the day-ahead market.

More recent contributions focus on forecasting and balancing market behavior. Reference [13] provides a comprehensive review of price forecasting techniques across day-ahead, intraday, and balancing markets, highlighting heterogeneity in model performance across trading layers. Reference [14] examines imbalance volume forecasting in the Greek balancing market, emphasizing the growing complexity introduced by renewable penetration. While these studies deepen predictive insights, they are primarily concerned with forecasting accuracy rather than structural interdependence across markets. An assessment of the Target Model implementation in Greece is described in [15].

Taken together, the literature summarized in Table 2 demonstrates that the Greek electricity market has been extensively analyzed from institutional, algorithmic, cross-border, and forecasting perspectives. However, a central implication of the Target Model re-

mains empirically underexplored: the dynamic co-evolution of prices across its sequential trading layers. The DAM establishes baseline commitments; the IDM refines these positions through CRIDA auctions; and the Balancing Market settles residual deviations through imbalance pricing. This structure implies potential long-run equilibrium relationships and short-run feedback mechanisms linking day-ahead, intraday, and imbalance prices. Yet no existing study jointly models these layers within the post-2020 Target Model framework. The present study addresses this gap by providing the first integrated multivariate analysis of DAM, IDM (CRIDA auctions), and imbalance prices in Greece under the fully implemented Target Model. Using a Vector Error Correction Model (VECM) framework complemented by impulse response functions (IRFs) and forecast error variance decomposition (FEVD), the paper quantifies both long-run integration and short-run transmission mechanisms across market layers. Furthermore, by incorporating regime-dependent analysis based on balancing activation volumes, it evaluates how system stress conditions alter price leadership and spillover dynamics. By bridging institutional analysis and dynamic econometric modeling, this study advances the literature beyond descriptive reform assessments and isolated price analyses. It offers empirical validation of the sequential adjustment mechanism embedded in the Target Model and provides new insights into the internal hierarchy and co-movement structure of the Greek wholesale electricity market.

3. Data of DAM, IDM, BM, Their Variable Construction and Descriptive Statistics

3.1. Data Construction and Variable Definition

The empirical analysis uses hourly observations from the Greek wholesale electricity market following the implementation of the European Target Model. The *endogenous price vector* is defined as:

$$Y_t = (P_t^{DAM}, P_t^{IDM}, P_t^{IP})' \quad (1)$$

where, *Day-ahead price* P_t^{DAM} is the day-ahead price is the hourly Market Clearing Price (MCP) of the Day-Ahead Market (DAM). This price results from the EUPHEMIA-based single day-ahead market coupling and represents the financially binding forward schedule for each delivery hour. It reflects participants' expectations, cross-zonal capacity allocation, and the merit order of generation and imports. *Intraday price* P_t^{IDM} is the intraday price is constructed from the three daily CRIDA auctions. For each delivery hour, we use the latest available CRIDA auction price, i.e.:

$$P_t^{IDM} = \begin{cases} CRIDA3_t, & \text{if available} \\ CRIDA2_t, & \text{otherwise} \\ CRIDA1_t, & \text{otherwise} \end{cases} \quad (2)$$

This definition captures the *final tradable market position before real-time balancing*, which is the relevant price for portfolio rebalancing, renewable forecast updates, and imbalance risk management. Using the last CRIDA (CRIDA3) (our adoption in this work) rather than an average is consistent with the sequential nature of the Target Model and with the economic role of the intraday market as the final adjustment stage before delivery (Figure A1 in Appendix A shows CRIDA3 times series and all its parameters, for 2023–2024). *Imbalance price* P_t^{IP} , in the balancing market is represented by the *imbalance settlement price*. This price is calculated by the Greek TSO (IPTO, ADMIE) based on *activated balancing energy*, reflects real-time system scarcity, and determines the financial settlement of deviations from scheduled positions. It therefore constitutes the economically relevant price signal linking market schedules to physical system operation. *Exogenous fundamentals* X_t : to isolate the *endogenous interaction between DAM, IDM, and IP imbalance prices*, we condition

the model on system variables that are determined outside the wholesale price formation mechanism. The exogenous vector includes (1) *Demand*, the total system load represents the primary driver of the supply–demand balance and determines the marginal technology in the merit order. (2) *Net imports*, the net cross-border flows that capture market coupling outcomes, interconnection constraints, and external price signals. These flows are scheduled before real time and therefore act as predetermined fundamentals at the hourly frequency. (3) The *Activated balancing energy*, which measures the real-time system imbalance and constitutes a direct indicator of *system stress* and *scarcity*. It is determined by the Greek TSO according to balancing activation rules and is therefore treated as weakly exogenous to wholesale price innovations. (4) *Production* as a generation availability proxy. A proxy for available generation capacity captures short-term supply conditions, including outages and renewable availability. (5) *Balancing energy price signals (mFRR up/down)*, which when included, provide an additional *scarcity signal* reflecting the marginal cost of balancing energy. All variables are aligned at the *hourly frequency*. Observations with missing values are removed to ensure a balanced estimation sample. Exogenous variables may be *standardized* to improve numerical stability without affecting the economic interpretation of the impulse responses.

In figure3, we show the evolution of DAM, IDM and IP, as well as their correlations and the rolling volatility. Vertical red dotted lines indicate major market and regulatory milestones (see also table) relevant to the interpretation of DAM–IDM–BM interactions: the transition toward a high renewable penetration regime in 2024 (over 51%) thus stronger balancing needs, the introduction in Greek market of power bill subsidies after wholesale price pressure (6 December 2024), reflecting renewed stress in the Greek and SEE electricity market, the operational integration of IPTO into the European PICASSO balancing platform on 18 March 2025, an event directly relevant to BM/IP dynamics and finally the 15- minute SDAC go-live on trading day 30 September 2025. These markers help relate changes in price volatility, rolling correlations, and cross-market dynamics to structural developments in the Greek and European electricity market.

Figure 3 presents the evolution of the Day-Ahead Market (DAM), Intraday Market (IDM), and Imbalance Price (IP) over the period January 2023–September 2025, together with four major market and regulatory milestones. Several important observations emerge.

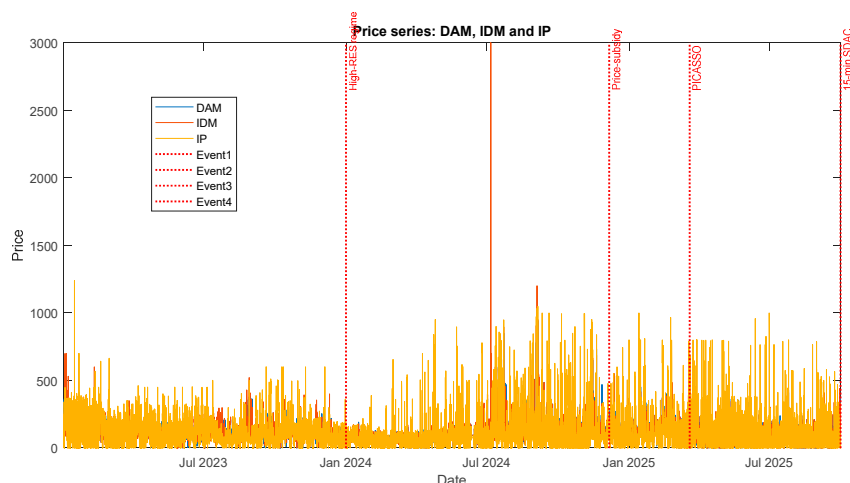


Figure 3. Evolution of day-ahead market (DAM), intraday market (IDM), and imbalance price (IP) prices in the Greek wholesale electricity market (January 2023–September 2025). Red dotted lines indicate major market and regulatory milestones relevant to market integration and renewable energy transition (High-RES regime, Price subsidy, PICASSO, and 15-min SDAC policy adoption).

First, the three price series exhibit a common long-run movement, consistent with the cointegration results reported later in the paper. Although imbalance prices display substantially larger short-term fluctuations and occasional extreme spikes, their overall evolution remains broadly aligned with DAM and IDM prices. This visual evidence supports the existence of strong integration among the three market segments.

Second, the beginning of 2024, marked as the **High-RES regime**, coincides with a gradual increase in the frequency and magnitude of imbalance price excursions. This behavior is consistent with the growing penetration of renewable energy sources and the associated increase in balancing requirements and forecast uncertainty.

Third, during the period surrounding the **price-subsidy intervention** (December 2024), price volatility remains elevated, reflecting the persistence of wholesale market pressures across Greece and the wider Southeast European region. The intervention appears to have mitigated retail price impacts without fundamentally altering the underlying market dynamics.

Fourth, following the integration of IPTO into the **PICASSO balancing platform** in March 2025, the imbalance price series appears to become somewhat less erratic, suggesting improved balancing-market coordination and more efficient access to balancing resources at the European level. While this observation is descriptive, it is consistent with the increasing integration of balancing markets under the Target Model framework.

Overall, Figure 3 suggests that despite substantial short-run volatility and several important market developments, DAM, IDM, and IP continue to evolve within a common market structure characterized by strong cross-market linkages.

Figure 4 presents the *rolling correlations among DAM, IDM, and IP* using a 168-hour (one week) moving window. The most striking result is the persistently high correlation between DAM and IDM prices throughout the sample. After 2024, the DAM–IDM correlation remains close to unity for extended periods, frequently exceeding 0.9. This finding confirms the increasing integration of forward and intraday trading and supports the interpretation of the intraday market as a short-run adjustment mechanism rather than an independent source of price discovery.

The correlations involving imbalance prices are considerably more variable. Both the DAM–IP and IDM–IP correlations fluctuate substantially over time, occasionally becoming negative during periods of market stress. This behavior reflects the inherently corrective role of balancing markets, which react to forecast errors, renewable intermittency, and unexpected system conditions.

The event markers provide additional insight. Following the transition to the High-RES regime in 2024, the correlations involving IP become more volatile, suggesting that increased renewable penetration introduces additional balancing requirements and short-run deviations from scheduled market positions. Around the price-subsidy intervention and during the months preceding PICASSO integration, the DAM–IP and IDM–IP correlations exhibit notable fluctuations, reflecting heightened balancing-market activity and changing system conditions.

After the implementation of PICASSO, the DAM–IDM correlation remains exceptionally strong, while the correlations involving IP gradually stabilize. This pattern is consistent with improved balancing-market coordination and more efficient management of balancing resources. The figure therefore provides visual evidence of the progressive maturation and integration of the Greek electricity market.

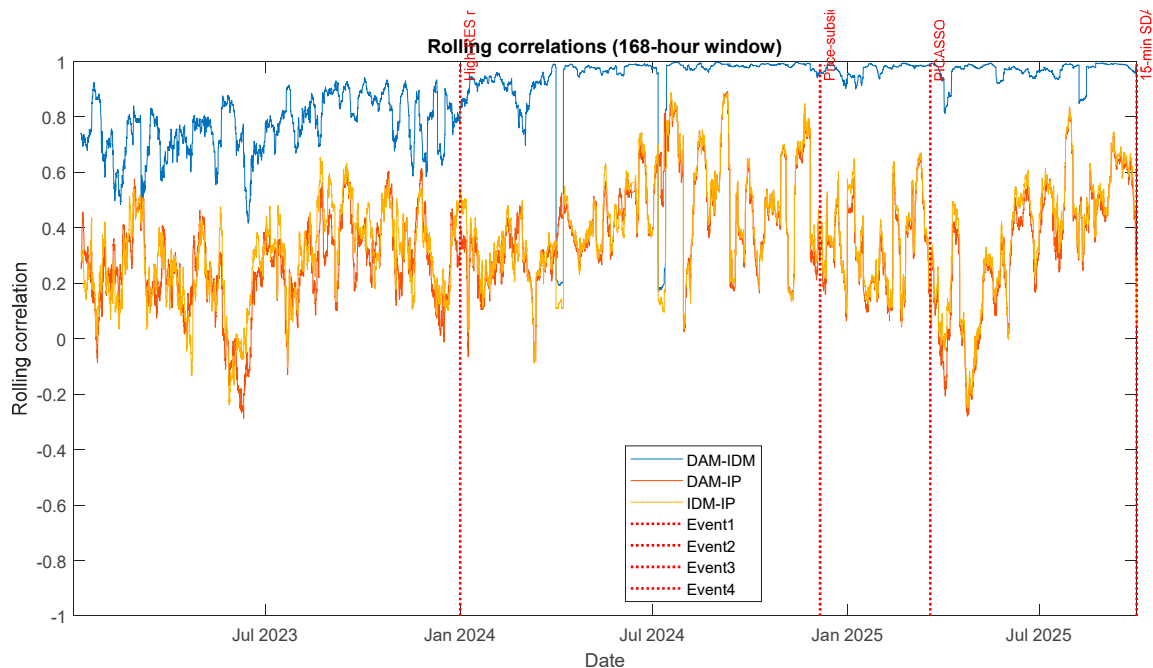


Figure 4. Rolling correlations (168-hour window) among DAM, IDM, and IP prices. Red dotted lines denote major regulatory and market events affecting cross-market interactions and price discovery.

Figure 5 reports the rolling volatility of DAM, IDM, and IP prices, measured as the rolling standard deviation over a 168-hour window. Several distinct phases can be identified. During most of 2023, volatility remains relatively moderate and stable across all three markets. Beginning in 2024, however, volatility increases noticeably, particularly for imbalance prices. This period coincides with the transition to a higher renewable penetration regime and reflects the growing operational challenges associated with balancing variable renewable generation.

The most pronounced volatility spikes occur during 2024 and early 2025. In particular, the imbalance price series exhibits substantially higher volatility than both DAM and IDM, confirming that balancing markets remain the primary channel through which short-run system stress and forecast errors are absorbed. The significantly larger fluctuations of IP compared with DAM and IDM are consistent with the balancing market's role as the final mechanism for maintaining real-time system equilibrium.

Following the PICASSO integration milestone, volatility remains elevated but becomes less episodic and more clustered, suggesting a gradual transition toward a more coordinated balancing framework. Although volatility does not disappear, the absence of extreme persistent spikes after this period may indicate increasing market efficiency and enhanced access to balancing resources.

Taken together, the rolling volatility results suggest that the Greek electricity market has become more exposed to short-run operational variability as renewable penetration increases. At the same time, the persistence of moderate DAM and IDM volatility relative to IP indicates that the forward market continues to absorb a large share of information and uncertainty before delivery. This finding is fully consistent with the FEVD and impulse response results, which identify the day-ahead market as the dominant source of long-run price discovery.

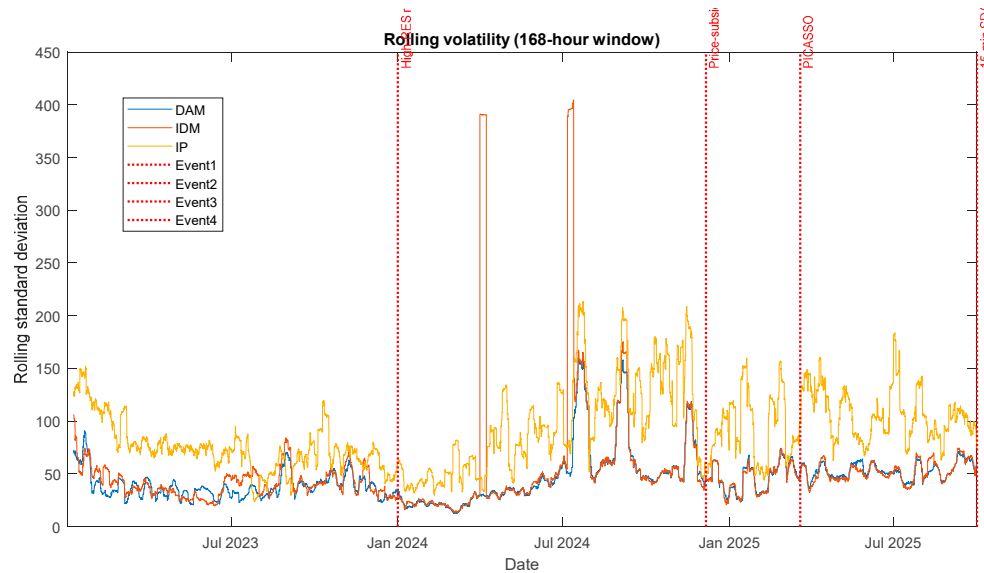


Figure 5. Rolling volatility (168-hour window) of DAM, IDM, and IP prices. Red dotted lines mark key developments in the Greek and European electricity markets associated with market integration, balancing mechanisms, and renewable energy penetration.

3.1.1. Economic Interpretation of Chosen Variables

With this construction, P_t^{DAM} represents forward (day-ahead) scheduling and expectations, P_t^{IDM} represents portfolio correction close to delivery, and P_t^{IP} represents real-time system balancing and scarcity. This layered structure mirrors the sequential clearing of the Target Model and allows the econometric model to identify the transmission of shocks across forward, adjustment, and real-time market stages. This data construction directly reflects the sequential flow from forward commitment to real-time balancing in the Target Model and provides the basis for the VECMX specification described in the following section. We also describe below shortly the ‘Stylized Facts’ information tailored to our exact dataset structure, variables, and the VECMX framework presented before. It matches our summary statistics and spreads tables.

3.1.2. Stylized Facts

Table 3 is an overview of all variables in the dataset available for this work, with their symbol, sampling frequency, description and the sources providing them. The variables included in the model are given in Table 4.

Table 3. Overview of all variables in the dataset considered in this work. The variables included in the model are given in Table 4.

Variable, Unit	Symbol	Frequency	Description	Data Source
<i>Dependent Variables</i>				
Day-ahead spot price, Euro/Mwh	P_t^{DA}	Hourly	DAM spot sum. (SELL) MCP	HeNeX or ENTSO-E transparency
Intra-Day spot price, Euro/Mwh	P_t^{IDM}	Hourly	IDM CRIDA1 spot sum. (SELL) MCP	HeNex
Imbalance price, Euro/Mwh	P_t^{IP}	Hourly	BM, Imbalance price	IPTO (ADMIE)
<i>Independent Variables</i>				
DAM Generation (Production), Mwh	G_t	Hourly	DAM spot sum. (Sell) production	HeNex

DAM Imports, Mwh	Imp_t	Hourly	DAM spot sum. (SELL) Imports	HeNex
DAM Demand, Mwh	D_t	Hourly	DAM spot sum. (BUY) Demand	HeNex
DAM Exports, Mwh	Exp_t	Hourly	DAM spot sum. (BUY) Imports	HeNex
BE IDEV, Mwh	$BEIDEV_t$	Hourly	Balancing Energy To- tal Deviation	IPTO
BE UDEV, Mwh	$BEUDEV_t$	Hourly	Balancing Energy UP/Down Deviation	IPTO
BE TotActEn, Mwh	$totBE_t$	Hourly	Total Activated Bal- ancing Energy	IPTO
mFRR price UP, Euro/Mwh	$mFRR_t^{UP}$	Hourly	Manual Frequency Restoration Re- serve,UP	IPTO
mFRR price UP, Euro/Mwh	$mFRR_t^{Down}$	Hourly	Manual Frequency Restoration Reserve, Down	IPTO

Notes: DAM: Day-ahead market, IDM: Intra-day market, BM: Balancing market administered by IPTO (ADMIE).

Table 4. Descriptive statistics of dependent variables and independent variables included in VECMX model (2023–2025).

Time	Variable	Min	Max	Mean	St. Dev	Skewness	Kurtosis
Series Symbol	Name						
P_t^{DA}	DAM price	−50	942	107.7	59.26	2.25	19.50
P_t^{IDM}	IDM CRIDA 3	−4999	1200	114.12	86.2	−15.7	1044
P_t^{IP}	BM Imbalance price	−50	1238	107.8	103.8	2.89	17.77
D_t	Demand (Load)	3192	11315	5982	1369	0.656	3.218
G_t	Total Generation (Production)	1747	12987	5794	1861	0.260	2.61
$mFRR_t^{UP}$	Manual Frequ. Restoration Up	0.00	1309.7	150	119.5	2.48	13.72
$mFRR_t^{Down}$	Manual Frequ. Restoration Down	−50	224.9	49.8	37.9	−0.172	2.67
$NImp_t$	Net Imports (Imports-Exports)	−2219	2675	191.7	974.4	−0.184	2.29
$totBE_t$	Total activated Balancing Energy	−2000	1830	−80.0	385.7	0.063	3.83

Table 4 reports the *descriptive statistics* of the endogenous price variables and the exogenous system fundamentals used in the VECMX specification. The sample consists of hourly observations covering the period January 2023 to December 2024. The *imbalance price* exhibits the *highest volatility and pronounced positive skewness*, reflecting the occurrence of *scarcity episodes and real-time system stress*. In contrast, the *day-ahead price* displays lower dispersion, consistent with its role as the main forward scheduling and price discovery venue. The *intraday price* lies between the two, capturing continuous portfolio adjustments

as updated information becomes available. Among the exogenous variables, *balancing activation* and *cross-border exchanges* show substantial variability, indicating the importance of real-time system conditions for price formation. *These stylized facts provide strong support for a cointegration-based framework with exogenous drivers.*

Prices Spread (Differences)

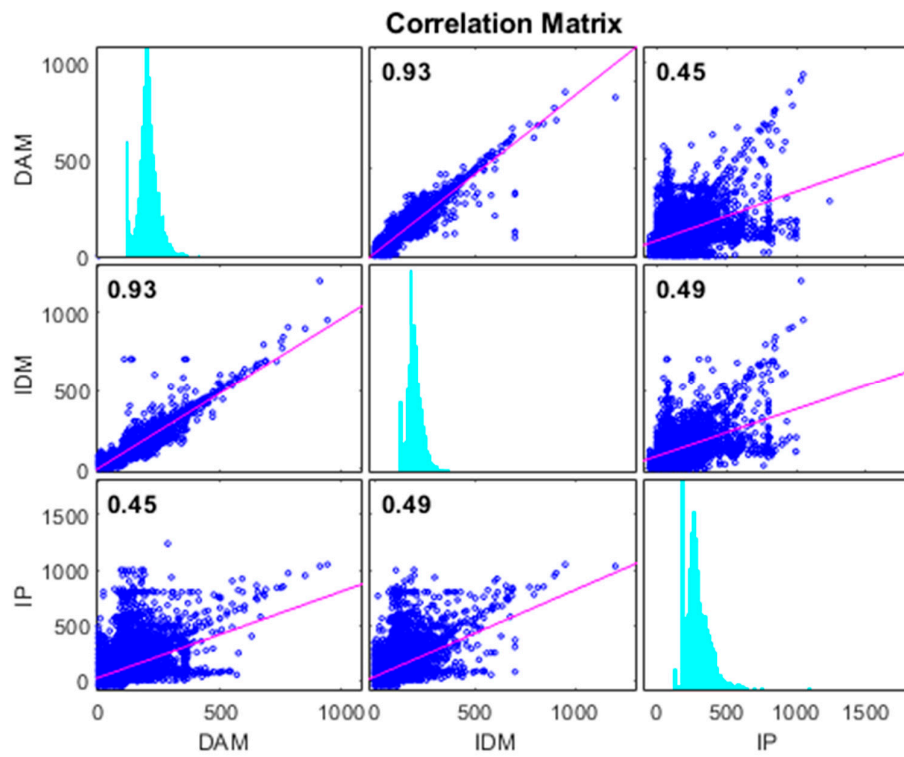
The behavior of inter-market spreads provides further evidence of long-run integration. As shown in Table 5, the *price differentials are between DAM, IDM, and imbalance settlement*. Table reports the descriptive statistics of the cross-market price spreads. The *DAM–IDM spread exhibits the lowest standard deviation, indicating the strongest integration between forward scheduling and intraday adjustments*. Its positive mean value suggests *systematic downward corrections in the intraday market as updated information becomes available*, while the pronounced *negative skewness and extreme kurtosis* reflect the occurrence of *rare but large upward intraday price movements during system stress*. The *DAM–imbalance spread has a mean close to zero, providing evidence that balancing outcomes are increasingly anticipated in the day-ahead market, which is consistent with the progressive maturation of the Target Model*. In contrast, the *IDM–imbalance spread displays the highest volatility and a negative mean, implying that intraday trading reduces but does not eliminate real-time balancing costs*. The strong excess kurtosis across all spreads highlights the importance of scarcity episodes and justifies the use of a regime-dependent dynamic framework.

Table 5. Descriptive statistics of differences of prices, 2023–25.

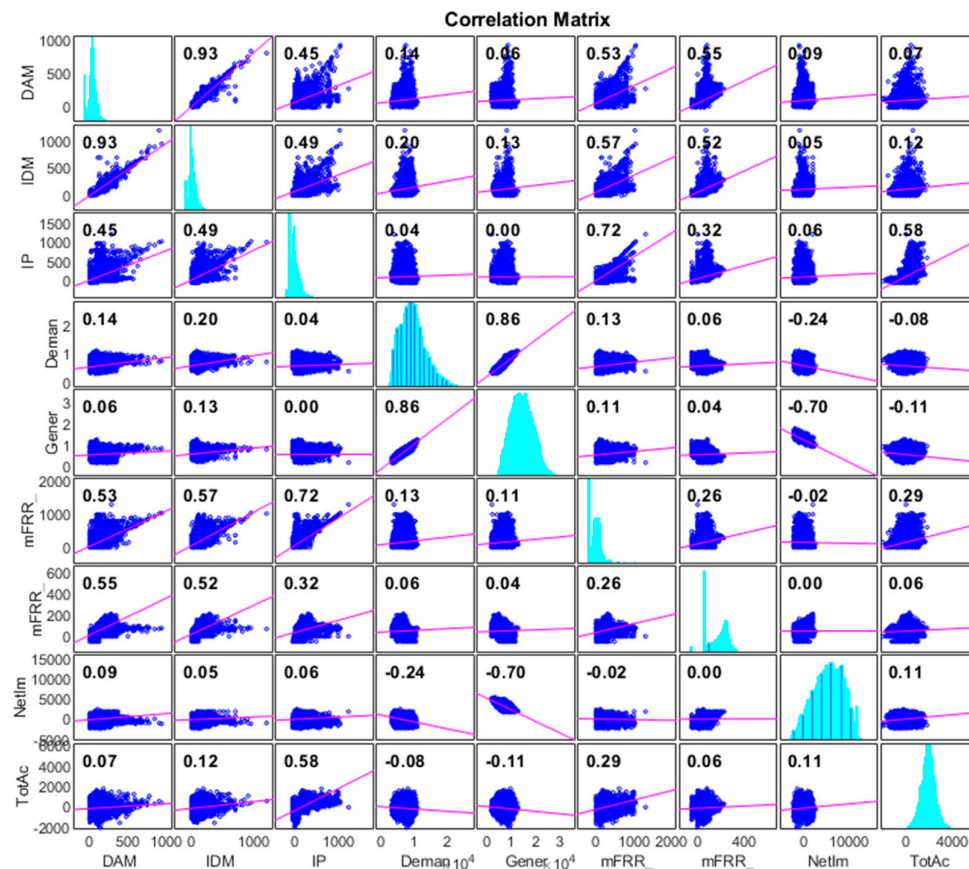
Time	Variable	Min	Max	Mean	St. Dev	Skewness	Kurtosis
Series Symbol	Name						
$P_t^{DA} - P_t^{IDM}$	DAM–IDM price	−594	4999	4.39	52.7	70.63	6735
$P_t^{DAM} - P_t^{IP}$	DAM–IP price	−953.4	520.4	−0.124	93.7	−2.41	17.36
$P_t^{IDM} - P_t^{IP}$	IDM–IP price	−4.999	632.2	−7.92	112.77	−8.72	330.46

Correlations of VECMX Model’s Variables

The strong contemporaneous co-movement between the markets is confirmed by the *correlation matrix in Figure 6a*. The *day-ahead and intraday prices are highly correlated (corr. 0.93)*, reflecting the role of the intraday market as an adjustment stage to previously established DAM forward positions. The *imbalance price shows a lower unconditional correlation with the forward markets (0.45 and 0.49)*, which is expected given its real-time formation, but its association with the other two prices *increases during periods of high balancing activation, indicating a tighter linkage under system stress*.



(a)



(b)

Figure 6. (a) Correlation matrix with histograms and scatter plots of DAM, IDM and IP prices, 2023–2025. (b) Correlation matrix with histograms and scatter plots of all variables in VECMX model, 2023–2025.

The correlation matrix for the full sample (2023–September 2025) confirms a strong integration between the day-ahead and intraday markets, with a correlation of 0.93, indicating that the intraday market closely follows the price signal established in the day-ahead market. In contrast, demand exhibits only weak correlations with all price variables (0.14 for DAM, 0.20 for IDM, and 0.04 for the imbalance price), suggesting that *price formation is not directly driven by aggregate demand levels but rather by marginal conditions and system constraints*. Similarly, net imports show negligible correlations with prices, indicating a *limited direct role of cross-border flows in price determination during the sample period*. By contrast, the imbalance price is strongly correlated with balancing market variables, including mFRR prices and total activated balancing energy, highlighting the dominant role of real-time system conditions in balancing price formation. Importantly, total activated balancing energy remains only weakly correlated with forward market prices, supporting its use as an exogenous indicator of system stress in the empirical analysis. Correlation matrix with histograms and scatter plots, of all variables in the VECMX model, 2023–2025, is shown in Figure 6b.

To examine how the interaction of the three markets is developing over the period 2023–September 2025, i.e., during each stage, we have presented Pearson’s correlation co-

efficient in Table 6a,b, separately for 2023–2024 and 2023–2025 market stages. The correlation analysis indicates a high level of integration between the day-ahead and intraday markets, with the correlation between DAM and IDM prices increasing slightly from 0.92 in the 2023–2024 sample to 0.93 in the extended 2023–2025 sample. This suggests improved information transmission between the two trading stages as the market matures. In contrast, the correlations between the imbalance price and both the day-ahead and intraday prices decrease slightly over the same period.

Table 6. (a) Correlations between all variables in the VECMX model, for 2023–2024 data. (b) Correlations between all variables in the VECMX model 2023–2025 data.

Table 6(a)

	P_t^{DA}	P_t^{IDM}	P_t^{IP}	D_t	G_t	$mFRR_t^{UP}$	$mFRR_t^{Down}$	$NImp_t$	$totBE_t$
P_t^{DA}	1								
P_t^{IDM}	0.92	1							
P_t^{IP}	0.49	0.53	1						
D_t	0.11	0.09	0.01	1					
G_t	0.10	0.16	0.03	−0.59	1				
$mFRR_t^{UP}$	0.54	0.58	0.72	−0.03	0.13	1			
$mFRR_t^{Down}$	0.49	0.45	0.30	−0.00	0.14	0.24	1		
$NImp_t$	0.11	0.07	0.05	0.92	−0.67	−0.02	−0.01	1	
$totBE_t$	0.13	0.18	0.60	0.03	−0.16	0.32	0.06	0.12	1

Table 6(b)

P_t^{DA}	1								
P_t^{IDM}	0.93	1							
P_t^{IP}	0.45	0.49	1						
D_t	0.14	0.20	0.04	1					
G_t	0.06	0.13	0.00	0.86	1				
$mFRR_t^{UP}$	0.53	0.57	0.72	0.13	0.11	1			
$mFRR_t^{Down}$	0.55	0.52	0.32	0.06	0.04	0.26	1		
$NImp_t$	0.09	0.05	0.06	−0.24	−0.70	−0.02	0.00	1	
$totBE_t$	0.07	0.12	0.58	−0.08	−0.11	0.29	0.06	0.11	1

This pattern indicates that balancing prices increasingly reflect real-time system conditions rather than expectations embedded in earlier market stages. Overall, the results are consistent with the sequential structure of the European Target Model, where the day-ahead market acts as the primary price discovery venue while the balancing market reflects short-term operational imbalances. The extended sample confirms several structural patterns in the Greek electricity market. First, the strong correlation between day-ahead and intraday prices persists and slightly increases, indicating a high level of integration between the two forward trading stages. Second, balancing energy activation becomes more strongly correlated with forward market prices, suggesting that expectations of system stress increasingly influence bidding behavior in earlier markets. Finally, balancing prices remain strongly linked to balancing energy prices (mFRR) but show slightly weaker correlations with day-ahead and intraday prices, indicating that the balancing market increasingly reflects real-time operational conditions rather than forward market expectations.

These results are further enhanced by computing the *rolling correlation*, as follows. Figure 7 presents the 720-hour rolling Pearson correlations between the day-ahead, intraday and imbalance prices. The rolling volatility analysis for the period 2023–September 2025 reveals a clear hierarchy across market stages, with *imbalance prices exhibiting the highest volatility*, followed by intraday and day-ahead prices.

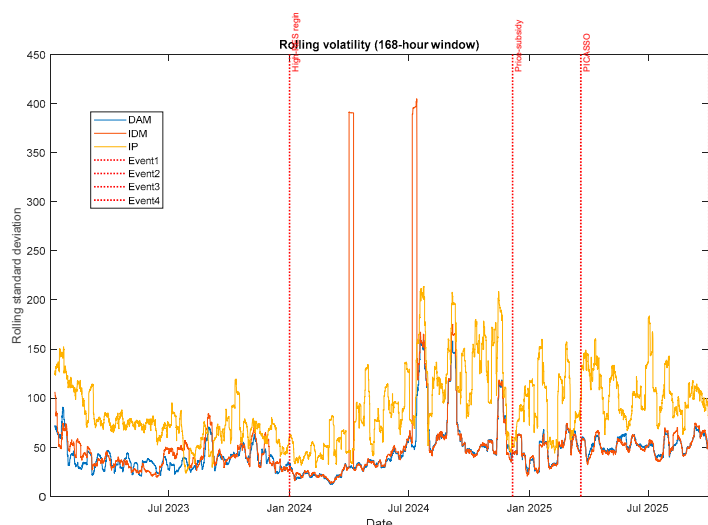


Figure 7. Rolling monthly volatility of DAM, IDM, and imbalance prices (2023–September 2025). The figure shows a persistent volatility ordering ($IP > IDM > DAM$), a decline during 2023, a low-volatility regime in early 2024, and a sharp increase in mid-2024 associated with system stress. Volatility remains elevated in 2025 relative to earlier periods.

During 2023, volatility declines across all markets, reflecting a normalization phase following the energy crisis. Early 2024 is characterized by a low-volatility regime, indicating relatively stable system conditions and limited balancing needs. In contrast, *the second half of 2024 exhibits a pronounced increase in volatility across all markets, with particularly sharp spikes in the imbalance price*. This period reflects elevated system stress, likely driven by *increased balancing activation and real-time imbalances*. Importantly, volatility shocks during this period appear to propagate across all market stages, suggesting that forward markets (DAM and IDM) increasingly internalize real-time system conditions. In 2025, volatility decreases from its peak but remains persistently higher than in earlier periods, indicating *a transition to a new equilibrium characterized by more frequent system fluctuations*. Overall, *the*

results highlight the increasing importance of balancing conditions in shaping price dynamics across electricity market stages.

4. Methodology

4.1. Unit Root Tests

Before proceeding to VECM modeling, we performed several stationarity tests to justify such an approach: (1) ADF (augmented Dickey-Fuller) H_0 : unit root (non-stationary), (2) KPSS H_0 : (trend/level) stationary, and (3) PP Phillips-Perron) H_0 : unit root (non-stationary, and followed the following Classification (practical rule-of-thumb): “Stationary ($I(0)$, level)”: ADF rejects unit root AND KPSS does NOT reject stationarity (level), “Trend-stationary”: ADF rejects unit root (with trend) AND KPSS does NOT reject (trend), “Unit root/ $I(1)$ likely”: ADF fails to reject AND KPSS rejects, “Inconclusive/mixed”: other combinations. Also tests first differences to suggest $I(1)$ if levels are nonstationary and diffs are stationary.

All price series were found to be *non-stationary in levels but stationary in first differences*, indicating that they are *integrated of order one, $I(1)$* . This result is supported by the joint interpretation of the ADF, PP and KPSS tests. The KPSS rejection of level stationarity is consistent with the presence of strong deterministic and seasonal components typical of hourly electricity prices. *Since the variables are $I(1)$, the VECM framework is appropriate for modeling their long-run equilibrium relationships*. Our empirical strategy builds on the established literature that models electricity market interactions within a cointegrated framework. Several studies demonstrate that day-ahead and intraday prices exhibit long-run equilibrium relationships with short-run adjustments driven by updated information, renewable forecast errors, and demand shocks (e.g., [20,21]). Error correction representations have been shown to effectively capture the anchoring role of day-ahead prices and the corrective dynamics of intraday markets, particularly in systems with high renewable penetration [22]. More recent work extends this framework to include balancing prices, highlighting the interdependence between forward scheduling, intraday corrections, and real-time scarcity signals (e.g., [23]). Consistent with this literature, we adopt a Vector Error Correction Model with exogenous fundamentals (VECX), allowing for (i) long-run equilibrium relationships among day-ahead (DAM), intraday (IDM), and imbalance prices (IP), and (ii) short-run adjustments driven by renewable generation, load, and system conditions. This specification is particularly suited to the Greek Target Model, whose sequential structure ($DAM \rightarrow IDM \rightarrow BM$) implies both equilibrium anchoring and dynamic feedback mechanisms across trading layers.

4.2. Cointegration and Error Correction Analysis

4.2.1. Integration and Cointegration

A *univariate* time series y_t is called *integrated* if it can be stationary via differencing, and the number of differences required to achieve stationarity is called the *order of integration*. Time series of order d are denoted $I(d)$ while a *stationary* series is denoted $I(0)$.

An n -dimensional time series y_t is *cointegrated* if some linear combination $\beta_1 y_{1t} + \dots + \beta_n y_{nt}$ of the component variables is stationary. Such a combination is called a *cointegrating relation*, and the coefficients $(\beta_1, \dots, \beta_n)'$ form a *cointegrating vector*. Cointegration is usually linked to systems of $I(1)$ variables, because any $I(0)$ variables are trivially cointegrated with other variables using a vector with coefficient 1 on the $I(0)$ component and coefficient 0 on the other components. Cointegration can be generalized to systems of higher-order variables, in the case that a linear combination of variables reduces their common order of integration.

Cointegration is distinguished from traditional *economic equilibrium*, in which a balance of forces produces *stable long-term levels* in the variables. Cointegrated variables are generally *unstable* in their levels, but exhibit *mean-reverting “spreads”* (generalized by the cointegrating relation) that force the variables to move around common *stochastic trends*. Cointegration is also distinguished from the *short-term synchronies of positive covariance*, which only measures the tendency to *co-move at each time step*. If we modify a VAR model to include cointegrated variables, this has the effect of balancing the short-term dynamics of the system with long-term tendencies.

4.2.2. Cointegration and Error Correction [24]

Cointegrated variables have the tendency to revert to *common stochastic trends* (called *mean reverting or persistent variables*), and it is expressed in terms of *error correction*. If y_t represents an n -dimensional time series and β is a cointegrating vector, then the combination $\beta' y_{t-1}$ measures the “error” in the data (the deviation from the stationary mean) at time $t-1$. The ‘speed’ at which series “correct” from disequilibrium is expressed by a vector α of *adjustment speeds*, which are incorporated into the VAR model at time t through a multiplicative error correction term $\alpha \beta' y_{t-1}$.

Generally, in n -dimensional time series y_t there may be multiple cointegrating relations among its variables, so the vectors α and β become matrices A and B , with each column of B representing a specific relation. Thus, the error correction term becomes $AB' y_{t-1} = C y_{t-1}$, where $AB' = C$, and C is called the *impact matrix*. Now, if we add the error correction term to a VAR model expressed in differences of variables, we generate the *vector error correction (VEC) model*:

$$\Delta y_t = C y_{t-1} + \sum_{i=1}^q B_i \Delta y_{t-i} + \varepsilon_t \quad (3)$$

In case the variables in y_t are all $I(1)$ (order $d=1$), the terms involving differences are *stationary*, thus only the error correction term can introduce long-term stochastic trends which are determined by the rank of the *impact matrix* C . Thus, long-term dynamics are C -dependent, i.e., if C has *full rank*, the system y_t is *stationary in levels* (not in changes, differences), while if C has rank 0, the error correction term vanishes, so the system is stationary in differences. The full and zero ranks of C extremes correspond to typical univariate modeling. However, in the multivariate case, there are intermediate rank choices, corresponding to *reduced ranks* between 0 and n : if C is restricted to reduced rank r , then C is decomposed (factors) into (nonunique) n -by- r matrices A and B with $C = AB'$, and there are r independent cointegrating relations among the variables in y_t .

We can convert a $VEC(q)$ model to a $VAR(p)$ model in levels, with $p = q + 1$, by collecting differences, as follows:

$$y_t = A_1 y_{t-1} + \dots + A_p y_{t-p} + \varepsilon_t = \sum_{i=1}^p A_i y_{t-i} + \varepsilon_t \quad (4)$$

In this work, using MATLAB (version 2018b), the conversion between $VEC(q)$ and $VAR(p)$ representations of an n -dimensional system are carried out by the functions `vec2var` and `var2vec`. Because of the equivalence of the two representations, a VEC model with a reduced rank error correction coefficient is often called a *cointegrated VAR model*, and cointegrated VAR models can be simulated and forecast using standard VAR techniques.

4.2.3. The Role of Deterministic Terms

The cointegrated VAR model is often augmented with *exogenous terms* Dx :

$$\Delta y_t = AB'y_{t-1} + \sum_{i=1}^q B_i \Delta y_{t-i} + Dx + \varepsilon_t \quad (5)$$

Array x may include variables as seasonal or interventional dummies, or terms representing deterministic trends in the levels of the data. Because (5) is in differences Δy_t , constant terms in x represent *deterministic linear trends* in the *levels* of y_t and linear terms represent deterministic quadratic trends. Constant and linear terms in the cointegrated series, however, reflect intercepts and linear trends, although restricted to the stationary variable formed by the cointegrating relation. Reference [24] considers five cases for $AB'y_{t-1} + Dx$ and in this work we have adopted case 'H1' $A(B'y_{t-1} + c_0) + c_1$, i.e., we assume that there are intercepts in the cointegrated series and there are deterministic linear trends in the levels of the data.

4.3. Econometric Framework for Analyzing the Greek Spot Market

4.3.1. Model Specification

We analyze the dynamic interaction among the Greek day-ahead (DAM), intraday (IDM), and balancing settlement prices using a cointegrated Vector Error Correction Model with exogenous fundamentals (VECMX), as described before. Let

$$y_t = (P_t^{DAM}, P_t^{IDM}, P_t^{IP})' \quad (6)$$

denote the vector of hourly prices, where P_t^{IP} is the imbalance price. The model is specified as in Equation (5).

4.3.2. Exogenous Fundamentals and Weak Exogeneity

The vector $\mathbf{x}_t$ includes system fundamentals that are determined outside the short-run price formation mechanism of the spot sub-markets: *total load (demand)* $\mathbf{D}_t$, net imports $\mathbf{NImp}_t$, total activated balancing energy, $\mathbf{totBE}_t$, generation/production $\mathbf{G}_t$, and, when included, balancing reserve price signals $\mathbf{mFRR}_t^{up}$, or $\mathbf{mFRR}_t^{down}$. These variables are treated as *weakly exogenous* with respect to the long-run price relations because they are primarily driven by physical system conditions, cross-border schedules, and TSO balancing needs rather than by contemporaneous wholesale price innovations. At the hourly frequency, feedback from price shocks to load or scheduled interconnector flows is negligible, while the opposite effect is economically meaningful. Under weak exogeneity, $\mathbf{x}_t$ affects short-run dynamics and equilibrium adjustment but does not alter the cointegration space. Lagged exogenous terms are optionally included to capture delayed transmission from system conditions.

4.3.3. Lag Order Selection and Cointegration Rank

The lag order p of the underlying VAR in levels is selected using the Bayesian Information Criterion (BIC). Conditional on the selected lag length, the cointegration rank r is determined using the *Johansen trace test* [24] under a restricted-constant specification, which allows for equilibrium price spreads without imposing deterministic trends in levels.

4.3.4. Short-Run Predictability

Short-run directional predictability is assessed through *Granger-style joint significance tests* in the differenced system. Specifically, we test whether lagged price changes are jointly significant in each equation, conditional on the error correction term(s) and the exogenous fundamentals.

4.3.5. Impulse Response Functions and Variance Decomposition

To quantify dynamic transmission across market layers, the estimated VECMX is converted into its implied VAR representation and expressed in moving-average form. *Structural shocks* are identified using a *recursive (Cholesky) decomposition* of the covariance matrix Σ with the ordering $P_t^{DAM} \rightarrow P_t^{IDM} \rightarrow P_t^{IP}$. This ordering reflects the sequential clearing of the Greek Target Model: the day-ahead market closes first, intraday trading updates positions afterward, and the imbalance price is formed in real time based on activated balancing energy and system imbalance. Orthogonalized *impulse responses* and *forecast error variance decompositions (FEVD)* are reported for a horizon of 168 h.

4.3.6. Parameter Stability and Regime Dependence

To examine structural changes in the transmission mechanism, the model is re-estimated for yearly sub-samples and for system regimes. Stress periods are defined using high levels of activated balancing energy $\mathbf{totBE}_t$, allowing the dynamics to differ between normal and scarcity conditions.

4.4. Identification and Variable Construction

4.4.1. Justification of the Recursive Ordering

The identification scheme is grounded in institutional timing rather than statistical ordering. At the hourly frequency, the DAM price is determined before intraday trading begins and therefore *cannot react contemporaneously to intraday or balancing shocks*. Intraday prices can respond contemporaneously to DAM innovations but precede real-time balancing. The imbalance price is formed by the Greek TSO in real time and can therefore

react contemporaneously to both forward DAM deviations. This timing structure justifies the ordering $P_t^{DAM} \rightarrow P_t^{IDM} \rightarrow P_t^{IP}$ and is consistent with the operational sequence of the European Target Model.

Robustness Analysis

The structural interpretation of shocks in the VECMX framework requires an identification scheme for the innovation covariance matrix. In the baseline specification, orthogonalized impulse response functions (IRFs) and forecast error variance decompositions (FEVDs) are obtained using a recursive Cholesky decomposition with the ordering DAM–IDM–IP. This ordering is motivated by the institutional sequence of the European Target Model, where the Day-Ahead Market (DAM) clears first and establishes financially binding schedules, the Intraday Market (IDM) subsequently allows market participants to update positions closer to delivery, and the Imbalance Price (IP) is determined ex post through the balancing market settlement process.

Because Cholesky-based decompositions may be sensitive to variable ordering, particularly in systems characterized by strong contemporaneous interactions, additional robustness tests were performed. Specifically, alternative recursive orderings (DAM–IP–IDM and IP–IDM–DAM) were examined and compared with the baseline specification. Furthermore, Generalized Impulse Response Functions (GIRFs) were computed. Unlike orthogonalized IRFs, GIRFs are invariant to variable ordering and therefore provide an ordering-independent benchmark for assessing the stability of the estimated transmission mechanisms.

The results of these robustness tests are described in results Section 5.7, and their tables and plots are reported in Appendix C (Tables A1, A2 and figures A7, A8). The analysis shows that although alternative recursive orderings affect the numerical allocation of contemporaneous variance, the principal conclusions regarding market integration, price discovery, and the dominant role of the day-ahead market remain qualitatively unchanged across all specifications.

4.4.2. Construction of the Intraday Price

As already mentioned, the Greek intraday market comprises three daily CRIDA auctions. Two alternative constructions are typically used in empirical studies: an average across sessions, representing a general intraday level, or the latest available intraday price, representing the final correction before delivery. Because the objective of this study is to analyze the interaction between DAM forward scheduling and real-time balancing, the intraday price is defined as *the latest available CRIDA price* for each delivery hour. Specifically, CRIDA3 is used where available; otherwise, CRIDA2 (and CRIDA1 where necessary). This approach produces a single 24-hour intraday series aligned with the transition from scheduled to actual system operation and corresponds to the closest-to-delivery intraday signal commonly used in European market analyses. Continuous intraday (XBID) prices are not considered.

4.4.3. Interpretation of Structural Shocks

Under this identification scheme, a DAM shock represents unexpected changes in DAM market expectations and scheduling decisions, an IDM shock captures intraday revisions closer to delivery (e.g., updated renewable forecasts or portfolio rebalancing), and an imbalance price shock reflects real-time system scarcity and balancing activation. Robustness to the recursive identification can be assessed using alternative orderings or generalized impulse responses.

4.4.4. Regime Definition and Stress Identification

To analyze how price transmission changes under stressed system conditions, we split the sample into *normal and stress regimes* based on the level of balancing energy activation. In particular, stress periods are defined as observations in which *Total Activated Balancing Energy (TotBE)* lies in the upper quantile of its empirical distribution. Formally, the stress regime is defined as $TotBE_t \geq Q_{0.80}(TotBE)$, where $Q_{0.80}$ denotes the 80th percentile of the Total Activated Balancing Energy series.

The use of TotBE as the regime indicator is motivated by both operational and econometric considerations. From a system perspective, TotBE measures the *realized quantity of balancing energy deployed by the transmission system operator* and therefore provides a direct proxy for *system imbalance and operational stress*. Periods with high balancing activation correspond to situations in which forecast errors, unexpected demand fluctuations, renewable variability, or network constraints require significant real-time corrective actions.

This quantity-based measure captures system stress more comprehensively than price-based balancing indicators. In particular, balancing price variables such as mFRR upward and downward prices primarily reflect *scarcity conditions in specific reserve segments*, while TotBE reflects *the actual volume of balancing interventions required to maintain system balance*.

In the VECMX specification, mFRR upward and downward prices are included as *exogenous control variables* in the model. These variables capture scarcity signals in the balancing market and influence the formation of the *Imbalance Price (IP)*, which is calculated as the weighted average price of activated balancing energy in the predominant direction (upward or downward) for manual and automatic FRR products during each imbalance settlement period.

Using mFRR prices directly to define the stress regime would therefore introduce a more mechanical relationship between the regime definition and the endogenous balancing price dynamics. Since the imbalance price is partly derived from balancing energy prices, such a specification could blur the distinction between *regime classification and model conditioning variables*. For this reason, we adopt *TotBE as the baseline regime indicator*, while retaining mFRR price variables in the exogenous block of the VECMX model to control for balancing-market scarcity effects.

An alternative regime definition based on high mFRR prices would instead capture *price-scarcity episodes* rather than *activation-volume stress*. While both concepts are related, they reflect different aspects of balancing market dynamics. For completeness, we therefore examine this alternative definition as a *robustness exercise*.

4.4.5. Interpretation for the VECMX Results

The regime classification affects the estimation of impulse responses and variance decompositions because the VECMX model is re-estimated separately for the two subsamples. Consequently, the impulse response functions (IRFs) and forecast error variance decompositions (FEVDs) reflect the dynamic structure of price interactions under different system conditions. Under high balancing activation regimes, stronger interactions between balancing prices and earlier market stages may emerge, reflecting the increasing role of real-time system constraints in price formation. By contrast, under normal operating conditions, price discovery is expected to be driven primarily by the day-ahead and intraday markets.

4.4.6. Expected Dynamic Price Transmission Across Market Stages

Because electricity markets clear sequentially, price discovery is expected to follow a hierarchical structure across market stages. Under normal conditions, the day-ahead market should act as the primary source of price discovery, with shocks propagating to the

intraday and balancing markets through portfolio adjustments and real-time balancing actions. Intraday trading updates positions as new information becomes available, while the balancing market mainly reflects real-time operational conditions. However, during periods of high balancing activation, real-time system constraints may play a stronger role in price formation, potentially strengthening the influence of balancing prices on earlier market stages. Comparing impulse responses across regimes therefore allows us to assess how system stress modifies the transmission of shocks across electricity market stages.

4.4.7. Interpretation of Forecast Error Variance Decomposition (FEVD)

Forecast error variance decomposition (FEVD) quantifies the contribution of shocks originating in each market stage to the variability of electricity prices over different horizons. In an efficient sequential market structure, a large share of the variance of intraday and balancing prices should be explained by day-ahead shocks, reflecting the role of the day-ahead market as the primary price discovery venue. Deviations from this pattern, particularly during periods of high balancing activation, may indicate that real-time system conditions and balancing needs play a stronger role in price formation. FEVD therefore provides a complementary measure to impulse responses for assessing how price discovery and volatility transmission evolve across market stages and system conditions.

5. Results and Discussion

The results that are presented in this section can be grouped into the following four groups, in an effort to link them to the research hypothesis stated in the introduction: *Cointegration results*: the findings support H1, *FEVD results*: the dominance of DAM innovations supports H2, *year-by-year comparison*: the increasing role of IDM and IP provides evidence in favor of H3 and *Normal vs. stress regime analysis*: the observed differences across regimes support H4.

Table 7 reports the main results of the VECMX model estimated for the full sample (2023–September 2025). Panel A presents normalized cointegration relationships, Panel B adjustment coefficients, and Panel C forecast error variance decomposition at short-run (1-hour) and long-run (168-hour) horizons. The results highlight a clear transition from short-run dominance of balancing market shocks (92.9% of IP's response to self-shocks at $h = 1$ h) and to long-run dominance of day-ahead market shocks 87.0% and 85.6% of IDM and IP responses to DAM shocks at $h = 168$ h), consistent with the sequential structure of electricity markets.

Table 7. VECMX main results: A – long-run relationships, B – adjustment coefficients, C-FEVD and D-key Economic Interpretation (sample 2023–September 2025).

A: Long-run Cointegration Relationships (β , Normalized)			
Relation	Equation		
CI1 (IDM)	$IDM = 0.867\,DAM + 0.057\,IP + 4.309$		
CI2 (IP)	$IP = 1.012\,DAM - 0.095\,IDM + 8.329$		
B: Adjustment Coefficients (α)			
Variable	CI1	CI2	Interpretation
DAM	0.633	6.53	Moderate adjustment (price anchor)
IDM	24.476	3.841	Strong adjustment (main error-correcting market)
IP	-1.468	-31.91	Strong adjustment (real-time correction)

C: Forecast Error Variance Decomposition (FEVD) (values only for $h = 1$ and $h = 168$ h, for other h values see Section 5.2).

Response DAM		
Source	$h = 1$	$h = 168$
DAM	98.80%	88.70%
IDM	0.00%	0.02%
IP	1.20%	11.30%
Response IDM		
Source	$h = 1$	$h = 168$
DAM	39.00%	87.00%
IDM	60.40%	1.90%
IP	0.50%	11.10%
Response IP		
Source	$h = 1$	$h = 168$
DAM	7.10%	85.60%
IDM	0.00%	0.02%
IP	92.90%	14.30%
D: Key Economic Interpretation		
Finding	Interpretation	
Short-run: IP dominates (92.9%)	Real-time system shocks drive balancing prices	
Long-run: DAM dominates (~85–89%)	Day-ahead market anchors price formation	
IDM shifts from own shocks → DAM	Intraday transmits information over time	
Strong α (IDM)	Intraday market restores equilibrium	
Strong α (IP)	Balancing market corrects deviations quickly	

5.1. Forecast Error Variance Decomposition (FEVD): Price Discovery and Shock Transmission

5.1.1. FEVD in DAM

The forecast error variance decomposition (FEVD) reveals a clear hierarchical structure in price formation. The *day-ahead price* (response variable) is almost entirely *self-driven on all horizons*, with more than 88% of its variance explained by its own innovations even after one week ($h = 168$), as Table 8 and Figure 8 depict. This confirms its role as the *primary price discovery stage*, reflecting forward expectations, cross-zonal coupling, and portfolio optimization.

Table 8. FEVD: Response of DAM price, on its own shocks and from IDM and IP market prices.

Horizon		Response Variable: DAM		
Hours		DAM_Shock	IDM_Shock	IP_Shock
$h1$		0.987	1.970e-05	0.012
$h6$		0.933	0.00012	0.067
$h24$		0.898	0.000204	0.101
$h72$		0.889	0.000223	0.110
$h168$		0.886	0.00022	0.113

Figure 8 presents the forecast error variance decomposition (FEVD) of day-ahead (DAM) prices over different horizons. The results show that DAM shocks dominate price variability at all horizons, explaining approximately 99% of the variance in the short run and around 89% in the long run (after a week). *The contribution of imbalance price (IP) shocks increases gradually over time, reaching about 11–12%, indicating that real-time system conditions are incorporated into day-ahead price formation with a delay. Thus, there is a feedback with a delay between DAM and BM.* In contrast, intraday (IDM) shocks have a negligible impact on all horizons. Overall, the results confirm the dominant role of the day-ahead market in price discovery.

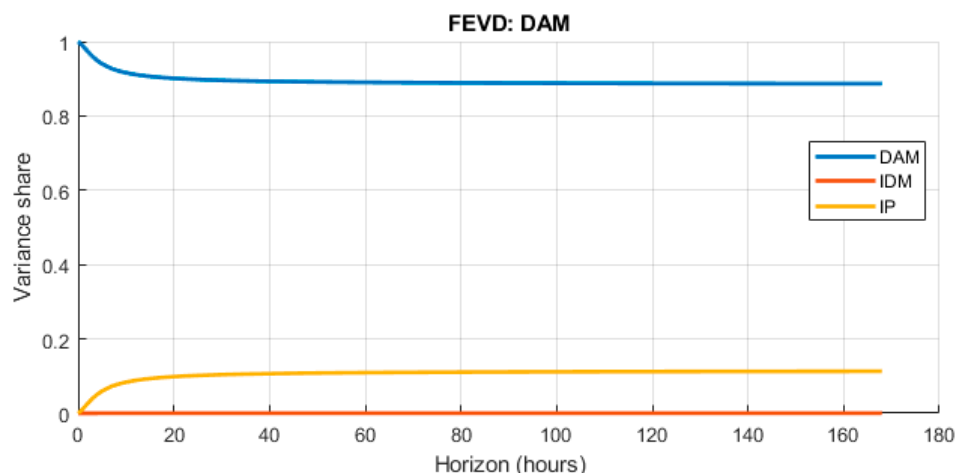


Figure 8. FEVD in DAM. How DAM price (response) is affected by self-driven shocks and IDM and IP shocks in prices, for the 2023–September 2025 period.

The variance decomposition results confirm that the *day-ahead market is the primary source of price discovery*, with balancing market shocks playing a *secondary but increasing role* over longer horizons, while intraday shocks have negligible explanatory power. In the context of the Target Model, this is the expected and desirable outcome, as it indicates that *forward markets (as DAM) internalize system fundamentals and that the balancing mechanism primarily settles deviations rather than forming independent price signals.*

In conclusion, the FEVD for the day-ahead price confirms its dominant role in price discovery, with more than 88% of its variance explained by its own innovations at the weekly horizon, while intraday shocks are almost zero and imbalance shocks affect the forward DAM only gradually through persistent system scarcity signals.

Implications of DAM's FEVD Results: Market Efficiency, Renewable Integration, and System Design Implications

The fact that more than 88% of the day-ahead forecast error variance is explained by its own innovations even at the weekly horizon ($h = 168$) indicates that the DAM market is the dominant platform for information aggregation. This is a *key indicator of market efficiency* in a *sequentially cleared system*, as it implies that expectations about demand, renewable generation, cross-border flows, and system constraints are *incorporated primarily at the day-ahead stage rather than being deferred to real time.*

The negligible contribution of intraday shocks confirms the role of the intraday market as an *adjustment mechanism rather than an independent price discovery venue.* Intraday trading allows market participants to rebalance their positions in response to updated forecasts, but *it does not generate new long-run information* capable of influencing forward prices. This finding is fully consistent with the economic function of CRIDA auctions in the Eu-

European Target Model and suggests that *intraday liquidity* is being used mainly for *portfolio optimization* rather than for *speculative price formation*.

By contrast, the gradual, not negligible increase in the contribution of *imbalance price shocks*, reaching 11.3% at longer horizons, indicates that *persistent real-time scarcity* conditions are eventually transmitted back to the DAM forward market. This *feedback mechanism* is economically intuitive. When *balancing activation remains structurally high*, market participants internalize the associated imbalance risk into their *day-ahead bids*, leading to a *delayed but measurable impact on DAM forward prices*. In a system with *increasing renewable penetration*, such as the Greek power system, this channel reflects *the cost of forecast errors and flexibility scarcity being priced ex ante*. Thus, in the Greek system, due to *high-RES share*, the efficiency of the DAM market depends on its ability to anticipate real-time balancing needs. The dominance of day-ahead innovations in explaining its own variance suggests that *renewable forecast information* is effectively incorporated at the *day-ahead stage*, that intraday trading successfully corrects short-term deviations without generating persistent price distortions, and finally that *the balancing market primarily settles residual imbalances as well as partially affects the formation of DAM's price*.

At the same time, the *non-zero long-run influence of imbalance shocks* indicates that structural *flexibility scarcity*, for example, limited ramping capability or insufficient balancing resources, is gradually priced into the DAM forward market. This is a desirable feature from a system perspective, as it provides investment signals for *flexible generation, storage, and demand response*.

The observed hierarchical structure—DAM → IDM → BM—is the intended outcome of the European Target Model. A forward market that *dominates long-run price formation* while intraday and balancing markets handle *short-run deviations* is typically interpreted as a sign of increasing market liquidity, improved forecasting, more efficient portfolio management, and reduced reliance on real-time corrective actions.

In other words, Figure 8 provides empirical evidence that *the Greek market is moving toward the standard Target Model equilibrium*, in which *balancing costs* are largely determined by DAM forward scheduling decisions rather than by purely real-time shocks. A relevant discussion is given in Section 5.9, connecting strategic behavior, balancing price formation and market power.

From a *regulatory* perspective, the results have several implications. First, *strengthening the day-ahead market*—through improved cross-zonal capacity allocation, better participation of flexible resources, and enhanced liquidity—is likely to yield the largest efficiency gains, as this is the main platform for price discovery. Second, the *intraday market* should be evaluated primarily in terms of its *ability to reduce imbalance volumes rather than to generate independent price signals*. Measures that increase intraday liquidity and access for renewable producers can further reduce balancing costs. Third, *the transmission of persistent imbalance conditions to the forward DAM market highlights the importance of adequate flexibility procurement*. Structural scarcity in balancing resources will eventually be reflected in higher forward prices, providing long-run investment signals.

5.1.2. FEVD in IDM

The response of IDM price (via FEVD) to shocks from its own shocks and from IDM and IP market prices is shown in Table 9 and Figure 9.

Table 9. Response of IDM price to shocks from its own shocks and from IDM and IP market prices.

Horizon	Response Variable: IDM		
	DAM_Shock	IDM_Shock	IP_Shock

<i>h1</i>	0.390	0.604	0.005
<i>h6</i>	0.644	0.307	0.048
<i>h24</i>	0.797	0.112	0.090
<i>h72</i>	0.852	0.041	0.105
<i>h168</i>	0.870	0.018	0.111

The intraday price becomes increasingly dominated by day-ahead shocks as the horizon increases, with the contribution of DAM innovations rising 87% in the long run ($h = 168$ h). IDM is significantly influenced by its own shocks at $h = 1$ and $h = 6$, indicating that the intraday market does generate an independent short-run price signal. However, no influence is observed on the long run by its own and IP shocks.

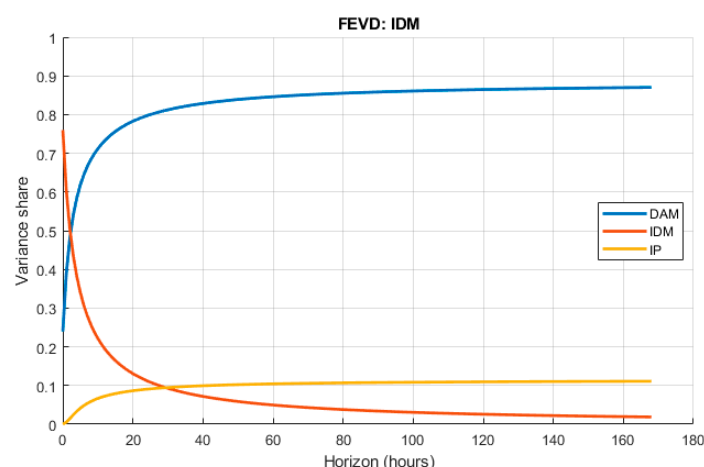


Figure 9. Forecast error variance decomposition of *intraday prices*. Intraday prices are initially driven by their own dynamics but rapidly converge to the day-ahead price signal, with a secondary influence from balancing market conditions.

Figure 9 presents the forecast error variance decomposition (FEVD) of intraday (IDM) prices across different horizons. In the short run, IDM prices are largely driven by their own shocks, accounting for approximately 60% of the variance. However, this contribution declines rapidly, and day-ahead (DAM) shocks become dominant, explaining around 85–87% of the variance at longer horizons. The contribution of imbalance price (IP) shocks increases gradually to approximately 10–11%, indicating that *balancing market conditions are incorporated into intraday price formation over time*. Overall, the results confirm that *the intraday market acts primarily as a transmission mechanism for information from both forward DAM and real-time markets*. As a conclusion, the variance decomposition of intraday prices shows a rapid decline in the importance of own shocks and a corresponding increase in the contribution of day-ahead shocks, *confirming the dominant role of the day-ahead market in price discovery and the adjustment role of the intraday market*.

Implications of IDM's FEVD Results

The dynamic shown in Figure 9 is fully consistent with the sequential architecture of the European Target Model, i.e., that the *day-ahead market* acts as the main platform for price discovery, the *intraday market* operates as a short-run correction mechanism, and the

balancing market provides real-time scarcity signals that are gradually priced into earlier stages.

The rapid decline of the intraday market's own variance share indicates that intraday innovations are largely transitory and do not alter the long-run equilibrium. This is an important sign of the Greek market's maturity: intraday trading is being used to fine-tune positions rather than to form independent price expectations.

In systems with high renewable penetration, such as the Greek one, intraday markets are expected to play a key role in absorbing forecast errors. Figure 9 shows that this adjustment occurs primarily in the short run, while the long-run price level remains anchored in the day-ahead market. This implies that renewable forecast updates are efficiently incorporated without creating persistent price distortions, balancing risk is increasingly anticipated at the forward stage, and the system relies less on real-time corrective pricing.

5.1.3. FEVD in BM (IP)

Table 10 depicts the response of IP price to self-driven shocks and from shocks in IDM and IP market prices, shown also in Figure 10.

Table 10. Response of IP price to self-driven shocks and from IDM and IP market price shocks.

<i>Horizon</i>		Response Variable: IP		
<i>Hours</i>	<i>DAM_Shock</i>	<i>IDM_Shock</i>	<i>IP_Shock</i>	
<i>h1</i>	0.070	0.0001	0.929	
<i>h6</i>	0.391	0.0001	0.608	
<i>h24</i>	0.709	0.0001	0.290	
<i>h72</i>	0.820	0.0002	0.179	
<i>h168</i>	0.856	0.0002	0.143	

The imbalance price is initially strongly driven by its own innovations (0.92 at $h = 1$), reflecting real-time system conditions, and gradually decreases after $h = 6$. However, the influence of day-ahead shocks increases rapidly and exceeds 85% at longer horizons ($h = 168$ h), while that of IDM is almost zero. This result implies that real-time balancing costs are largely determined by DAM forward market outcomes, while purely real-time shocks are transitory. This is very important in realizing which factor drives balancing costs, which in 2024 reach very high levels.

As Figure 10 depicts, balancing prices are driven by real-time shocks in the short run (93% at $h = 1$) but converge to day-ahead market fundamentals in the long run, a clear shift from real-time autonomy to forward market dominance. In the short run, IP is almost entirely driven by its own shocks, reflecting real-time system imbalances.

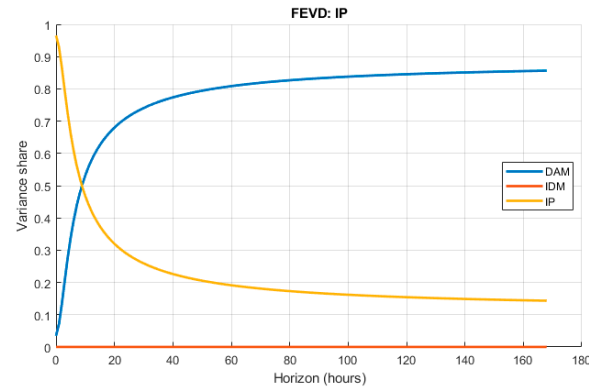


Figure 10. Forecast error variance decomposition of imbalance prices.

However, the contribution of own shocks declines rapidly, while the influence of day-ahead (DAM) shocks increase and becomes dominant, explaining approximately 85% of the variance at longer horizons. Intraday (IDM) shocks have a negligible impact on all horizons. These results indicate that balancing prices are driven by transient system conditions in the short run but are anchored to forward DAM market fundamentals in the long run. *The variance decomposition of imbalance prices reveals a clear transition from short-run dominance of own shocks to long-run dominance of day-ahead shocks, indicating that real-time imbalances are temporary and that price formation ultimately converges to forward market fundamentals.* This result is economically intuitive: the imbalance price is formed in real time by the Greek TSO (ADMIE) based on *activated balancing energy* and system conditions, and therefore reflects *contemporaneous scarcity, unexpected renewable forecast errors, and operational constraints*. However, this dominance declines rapidly as the horizon increases. The contribution of day-ahead shocks rises steeply and becomes the primary source of imbalance price variability, exceeding 85% on longer horizons. This indicates that real-time balancing costs are not independent in the long run but are largely determined by DAM forward market outcomes. In economic terms, persistent imbalances originate from scheduling decisions and expectation errors made in the day-ahead stage. By contrast, intraday shocks remain negligible at all horizons. This confirms that intraday trading, although crucial for short-term portfolio adjustments, does not generate an independent long-run source of uncertainty for real-time system balancing. This dynamic reflects the intended logic of the Target Model, i.e., that the *balancing market* absorbs short-run forecast errors and system shocks, and when these shocks are persistent, they are *internalized ex-ante in the day-ahead market* through *revised bidding strategies* and *imbalance risk premia*. As a result, *the long-run behavior of the imbalance price is anchored in forward scheduling*. In other words, the imbalance price acts primarily as the *real-time financial settlement of the DAM's market deviations*, not as an independent price discovery platform.

Implications of IP's FEVD Results for System Operation and Flexibility

Additionally, Figure 10 has a clear interpretation in terms of *system efficiency* and *renewable integration*. The rapid decline in the own-shock contribution indicates that real-time scarcity events are largely transitory. This suggests effective intraday rebalancing, improving renewable forecasting, and increasing the ability of market participants to anticipate balancing needs. At the same time, the strong long-run influence of day-ahead shocks implies that *structural flexibility scarcity is priced in the forward DAM market* [3]. This is a desirable outcome because it provides efficient investment signals for flexible generation and storage, incentives for demand response, and improved risk management for renewable producers.

In conclusion, the FEVD for the *imbalance price* shows that real-time system conditions dominate only at very short horizons, with own shocks explaining most of the one-hour forecast error variance. Their importance declines rapidly thereafter, and day-ahead innovations become the main driver of imbalance price variability, accounting for more than 80% at the weekly horizon. Intraday shocks remain negligible throughout. This pattern indicates that persistent balancing costs are largely determined by forward scheduling decisions, while real-time scarcity shocks are transitory and are progressively internalized in day-ahead bidding.

FEVD for alternative and reverse Cholesky, as a robustness test of the impact of ordering (DAM-IDM-IP vs. IP-DAM-IP, etc.), is presented in Appendix C.

5.2. Yearly Comparison: Evolution of Maturation Stages of the Greek Target Model

Tables 11–13 show the FEVD over the period 2023–September 2025. The results suggest a transition from strong DAM forward-market dominance toward a more balanced system where real-time conditions increasingly contribute to price formation.

Table 11. Responses of DAM, IDM and PI prices in shocks, for the year 2023.

<i>Horizon</i>		Response Variable: DAM, 2023		
<i>Hours</i>		<i>DAM_Shock</i>	<i>IDM_Shock</i>	<i>IP_Shock</i>
<i>h1</i>		0.992	0.0035	0.0038
<i>h6</i>		0.961	0.0055	0.0332
<i>h24</i>		0.943	0.0053	0.050
<i>h72</i>		0.939	0.0052	0.055
<i>h168</i>		0.938	0.0052	0.056
<i>Horizon</i>		Response variable: IDM, 2023		
<i>hours</i>		<i>DAM_shock</i>	<i>IDM_shock</i>	<i>IP_Shock</i>
<i>h1</i>		0.524	0.473	0.0021
<i>h6</i>		0.744	0.229	0.026
<i>h24</i>		0.874	0.077	0.047
<i>h72</i>		0.914	0.031	0.054
<i>h168</i>		0.927	0.016	0.056
<i>Horizon</i>		Response variable: IP, 2023		
<i>hours</i>		<i>DAM_shock</i>	<i>IDM_shock</i>	<i>IP_Shock</i>
<i>h1</i>		0.113	0.033	0.883
<i>h6</i>		0.487	0.033	0.508

<i>h24</i>	0.782	0.004	0.212
<i>h72</i>	0.881	0.004	0.113
<i>h168</i>	0.912	0.005	0.082

The comparison of FEVD results across 2023, 2024, and up to September 2025 reveals a clear evolution in the structure of price formation in the Greek electricity market. In 2023, the day-ahead market already dominates price discovery, explaining approximately 94% of its own variance at longer horizons, while the intraday and balancing markets play secondary roles. In 2024, this dominance becomes even more pronounced, with day-ahead shocks explaining more than 99% of the variance, indicating a highly centralized price formation mechanism and strong consolidation of the forward market.

Table 12. Responses of DAM, IDM and PI prices in shocks, for the year 2024.

Response Variable: DAM, 2024			
Horizon	DAM_Shock	IDM_Shock	IP_Shock
Hours			
h1	0.997	1.543e-08	0.002
h6	0.994	1.093e-06	0.0055
h24	0.993	1.582e-06	0.006
h72	0.993	1.704e-06	0.006
h168	0.993	1.740e-06	0.006
Response variable: IDM, 2024			
Horizon	DAM_shock	IDM_shock	IP_Shock
hours			
h1	0.367	0.631	0.001
h6	0.696	0.299	0.003
h24	0.891	0.102	0.005
h72	0.956	0.037	0.006
h168	0.977	0.016	0.006
Response variable: IP, 2024			
Horizon	DAM_shock	IDM_shock	IP_Shock
hours			
h1	0.286	9.632e-05	0.713
h6	0.684	4.198e-05	0.315
h24	0.895	1.447e-05	0.104

<i>h</i> 72	0.958	6.266e-06	0.041
<i>h</i> 168	0.978	3.73e-06	0.021

Table 13. Responses of DAM, IDM and PI prices in shocks, for the year Sept 2025.

Response variable: DAM, Sep2025			
<i>Horizon</i>	<i>DAM_Shock</i>	<i>IDM_Shock</i>	<i>IP_Shock</i>
<i>Hours</i>			
<i>h</i> 1	0.999	7.95e-06	0.0003
<i>h</i> 6	0.979	0.020	0.0001
<i>h</i> 24	0.950	0.049	0.0001
<i>h</i> 72	0.942	0.057	0.0001
<i>h</i> 168	0.940	0.059	0.0001
Response variable: IDM, Sep2025			
<i>Horizon</i>	<i>DAM_shock</i>	<i>IDM_shock</i>	<i>IP_Shock</i>
<i>hours</i>			
<i>h</i> 1	0.922	0.077	0.0004
<i>h</i> 6	0.968	0.031	0.0002
<i>h</i> 24	0.948	0.051	0.0001
<i>h</i> 72	0.941	0.058	0.0001
<i>h</i> 168	0.939	0.059	0.001
Response variable: IP, Sep2025			
<i>Horizon</i>	<i>DAM_shock</i>	<i>IDM_shock</i>	<i>IP_Shock</i>
<i>hours</i>			
<i>h</i> 1	0.065	0.011	0.923
<i>h</i> 6	0.231	0.011	0.756
<i>h</i> 24	0.497	0.029	0.472
<i>h</i> 72	0.717	0.045	0.236
<i>h</i> 168	0.828	0.053	0.118

However, by 2025, a *partial rebalancing emerges*. While the day-ahead market remains dominant, its share declines slightly, and both intraday and balancing market contributions increase. In particular, the intraday market exhibits a more persistent role, and the balancing market shows increased long-run variance contributions, indicating a growing

influence of real-time system conditions. This suggests a transition of the Greek market from a rigid hierarchical structure toward a more interactive system.

Overall, the results indicate that the Greek electricity market is moving toward a more mature Target Model configuration. While maintaining a clear hierarchy with the day-ahead market as the primary price discovery venue, the system increasingly incorporates real-time balancing signals and intraday adjustments, reflecting improved market integration and more efficient transmission of information across market stages.

5.3. FEVD in Normal vs. Stress Regimes: Transmission Under Scarcity

To perform a regime analysis, we used the top quantile value of the *total activated balancing energy* variable (totBE) as a *stress split* ($\text{stressQuantile} = 0.80$) to set the regimes. The regime analysis, presented in Tables 14 and 15, highlights a *striking asymmetry*. More specifically, in *normal conditions* during normal system operation (i.e., when $\text{totBE} < \text{threshold} = 0.80 \times \text{totBE}$), the *transmission* of impact from DAM's shocks to IDM and IP is gradual and *strong*, i.e., *the shock explains IDM's variance from 34.8% to 95.1%, while real-time shocks remain relevant for both short and weakly horizons, ranging from 10.5% to 94%*. The intraday and balancing markets retain a non-negligible autonomous role (large responses to self-shocks) up to $h = 6$ h (FEVD ranges from 65% to 35.8%, and from 89.3% to 54.6%, respectively).

Table 14. Responses of DAM, IDM and PI prices to shocks during *normal conditions*.

Horizon		Response Variable: DAM, Normal Regime		
hours		DAM_Shock	IDM_Shock	IP_Shock
h1		0.997	1.1587e-06	0.0031
h6		0.982	0.0009	0.016
h24		0.976	0.0015	0.022
h72		0.974	0.0016	0.024
h168		0.973	0.0017	0.024
Horizon		Response variable: IDM, Normal Regime		
hours		DAM_shock	IDM_shock	IP_Shock
h1		0.348	0.650	0.0009
h6		0.631	0.358	0.0098
h24		0.842	0.138	0.019
h72		0.923	0.053	0.022
h168		0.951	0.0248	0.023
Horizon		Response variable: IP, Normal Regime		
hours		DAM_shock	IDM_shock	IP_Shock

<i>h1</i>	0.105	0.0001	0.893
<i>h6</i>	0.452	0.0004	0.546
<i>h24</i>	0.775	0.0012	0.223
<i>h72</i>	0.898	0.0015	0.099
<i>h168</i>	0.940	0.0016	0.058

Table 15. Responses of DAM, IDM and PI prices in shocks during *stress conditions*.

Response Variable: DAM, Stress Regime			
Horizon			
Hours	DAM_Shock	IDM_Shock	IP_Shock
h1	0.999	5.098e-05	0.00011
h6	0.997	0.0022	0.0003
h24	0.994	0.0047	0.0004
h72	0.994	0.0055	0.0004
h168	0.993	0.005	0.0004
Response variable: IDM, Stress Regime			
Horizon			
hours	DAM_shock	IDM_shock	IP_Shock
h1	0.882	0.117	0.000
h6	0.953	0.0466	0.000
h24	0.981	0.018	0.000
h72	0.989	0.010	0.000
h168	0.991	0.0078	0.000
Response variable: IP, Stress Regime			
Horizon			
hours	DAM_shock	IDM_shock	IP_Shock
h1	0.363	0.001	0.634
h6	0.767	0.004	0.227
h24	0.927	0.005	0.060
h72	0.970	0.005	0.023
h168	0.983	0.005	0.010

In stress conditions, under high balancing energy activation ($\text{totBE} > \text{threshold}$), shocks in DAM explain the variances of IDM and IP in the range 88.2% to 99.1%, and 36.3% to 98.3%, respectively, i.e., with a gradual increase from $h = 1$ to $h = 168$. Thus, in stress conditions, the dominance of day-ahead shocks becomes overwhelming, the intraday market loses its independent role almost completely (its responses to self-shocks are negligible) and finally the imbalance price is driven almost entirely by forward (DAM) market outcomes at medium and long horizons, since shocks in IDM have almost zero impact on IP's variance.

This indicates that *when the system is under stress, forward (DAM) scheduling errors determine the cost of balancing, and the intraday market has limited ability to correct them*. Economically, this means that *scarcity episodes are not purely real-time phenomena but are largely rooted in forward DAM market expectations and scheduling decisions*.

The comparison between normal and stress regimes reveals a significant change in the structure of price formation. Under normal conditions, the market exhibits a multi-layered structure, with the intraday and balancing markets playing meaningful roles in price adjustment and short-run dynamics. In contrast, under stress conditions, the system becomes highly centralized, with the day-ahead market overwhelmingly dominating price formation across all horizons. The contribution of balancing market shocks declines sharply, particularly in the long run, while the intraday market loses its independent role and becomes a pure transmission channel. *These findings suggest that during periods of system stress, market participants rely more heavily on DAM forward price signals, and real-time imbalances are rapidly absorbed into the dominant day-ahead pricing mechanism*. This behavior indicates that stress conditions enhance market integration by aligning all market stages with forward expectations, but at the cost of reduced informational diversity from real-time signals. System stress leads to a tightening of the price formation process, with all market stages converging toward the day-ahead price as the dominant signal.

The combined cointegration and FEVD results point to a hierarchical price formation mechanism in the Greek Target Model. The day-ahead market is the dominant source of price discovery, while the intraday market operates primarily as a short-run correction platform and the balancing price reflects the real-time settlement of forward DAM scheduling errors. This structure becomes more pronounced over time and under system stress, indicating increasing forward integration and reduced reliance on real-time price formation as the market matures.

As a robustness check, we also define stress regimes using high mFRR prices instead of using the total activated balancing energy (totBE_t) variable. The qualitative conclusions regarding price transmission and market leadership remain unchanged (see also 5.9 limitations).

5.4. Impulse Response Analysis to a DAM Price Shock

Figure 11 presents orthogonalized impulse response functions following a one-standard-deviation shock to the day-ahead market (DAM) price. The responses reveal a fast and economically intuitive propagation of forward market information across the subsequent trading stages. The DAM exhibits a strong immediate response that gradually converges to equilibrium, indicating persistent but mean-reverting dynamics. More specifically, DAM's price *own response* ($\text{DAM} \rightarrow \text{DAM}$) is immediate and strongly positive, followed by an almost rapid (after 6 to 8 h) convergence to a new equilibrium level. The absence of oscillatory behavior and the very fast stabilization indicate a *highly efficient* forward DAM market in which new information is quickly incorporated into prices and *does not generate persistent internal dynamics*. This behavior is consistent with the role of the day-ahead market as the primary price discovery platform and with the high degree of liquidity provided by market coupling and portfolio optimization.

The *intraday price* reacts instantaneously and in the same direction as the day-ahead shock, with a magnitude comparable to the own response of the forward market. The ad-

justment is completed within a few hours ($h = 6$ to 8 in the figure), after which the response remains stable. This pattern confirms that: intraday trading immediately internalizes forward price signals, there is no delayed or gradual transmission from DAM to IDM, and the intraday market does not generate an independent dynamic path.

Economically, IDM price's response reflects the fact that market participants rebalance their positions immediately after the publication of the day-ahead results, aligning intraday bids with the new forward price level. The *imbalance price* also responds positively and very rapidly to the day-ahead shock. The effect builds up within the first 6 to 8 h and then stabilizes at a higher level without subsequent reversal. This dynamic indicates that: forward scheduling decisions determine the expected cost of real-time balancing, balancing prices adjust to the new forward equilibrium rather than generating an independent trajectory, and the transmission from DAM to BM is both strong and fast.

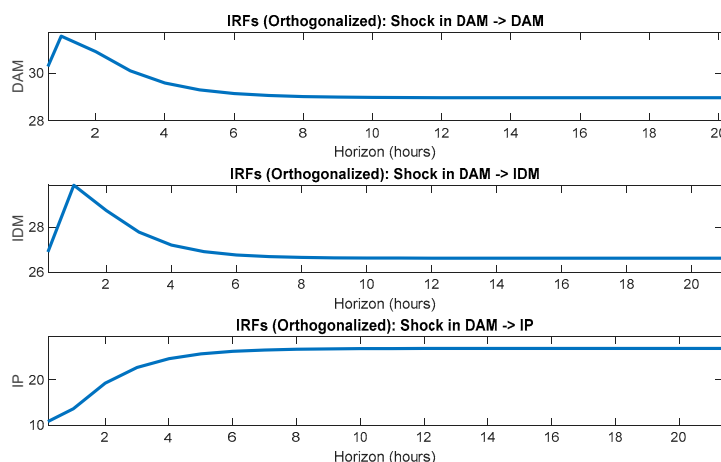


Figure 11. Orthogonalized impulse response functions to a positive innovation in the DAM price. A day-ahead shock propagates instantaneously and proportionally to intraday and imbalance prices, with rapid convergence and no oscillatory dynamics, confirming the forward-centered price formation of the Target Model.

Taking all the above together, the IRFs provide direct dynamic evidence of the hierarchical structure already identified by the FEVD:

1. *The day-ahead market leads the system:* a forward shock propagates contemporaneously and almost proportionally to the intraday and balancing prices.
2. *The intraday market acts as a transmission channel:* it does not amplify or dampen the shock but rapidly aligns with the forward equilibrium.

The balancing market settles forward deviations: its response is strong but not autonomous, indicating that real-time prices are anchored in forward expectations.

The absence of delayed or hump-shaped responses suggests that information flows efficiently across market stages and that there are no significant frictions in the adjustment process. From a market design perspective, the speed and stability of the transmission mechanism indicate:

high informational efficiency of the day-ahead market,
effective intraday rebalancing,
limited persistence of real-time disequilibria.

In a system with increasing renewable penetration, such as the Greek one, such a fast adjustment is particularly desirable because it implies that forecast updates and flexibility

scarcity are incorporated early in the trading sequence rather than being deferred to the balancing stage.

5.5. Impulse Response Analysis to an IDM Price Shock

Figure 12 presents the orthogonalized impulse responses to a positive innovation, i.e., following a one-standard-deviation shock to the intraday market (IDM) price. The intraday price exhibits a strong but short-lived response, dissipating rapidly within a few hours ($h = 4$), indicating that *intraday shocks are transitory*. The response of the day-ahead price (DAM) is limited and reverses quickly (after $h = 1$), suggesting that intraday deviations do not significantly influence forward DAM market expectations. Similarly, the imbalance price (IP) shows a temporary response that converges toward equilibrium, indicating that intraday shocks do not generate persistent system imbalances. Overall, the results confirm the role of the intraday market as an *adjustment mechanism rather than a primary driver of price discovery*, and do not drive long-run price formation or system imbalance.

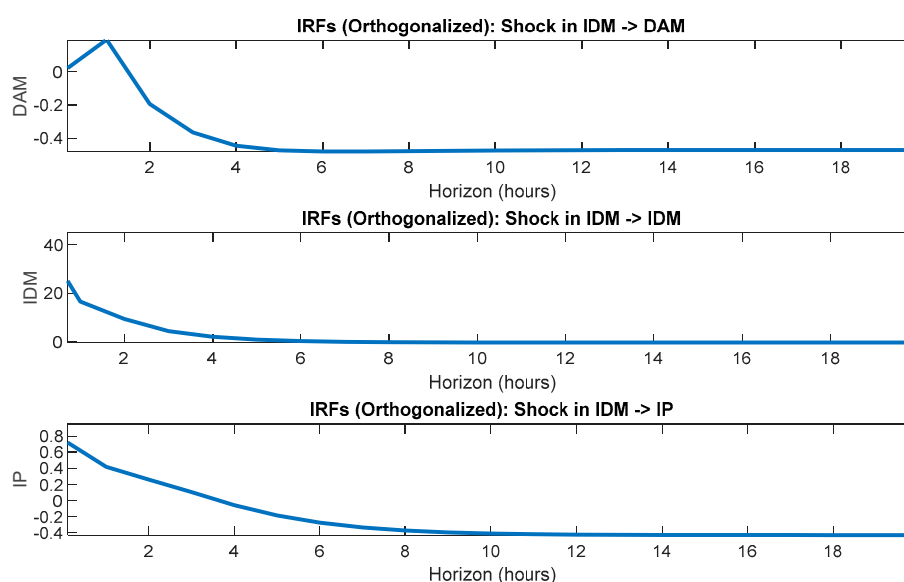


Figure 12. Impulse response functions to an *intraday price shock*.

The response dynamics shown in Figure 12 reflect the *temporal sequencing of the markets*: once the day-ahead market has cleared, its price cannot adjust to intraday information for the same delivery period. The near-zero long-run response indicates that intraday innovations do not contain new information capable of altering forward price expectations.

Economically, this confirms that *causality runs from DAM to IDM and not in the opposite direction*. The *own response of the intraday price* is large on impact but decays extremely rapidly, vanishing within the first four hours. This indicates that intraday shocks are *purely transitory* and do not generate persistent deviations from the long-run equilibrium. Such behavior is consistent with continuous updating of bids as new information arrives, high short-term liquidity, and efficient arbitrage against the day-ahead price. In other words, intraday innovations are quickly absorbed through trading and portfolio rebalancing. The *imbalance price* reacts positively on impact, but the effect dissipates almost immediately and converges to zero. This shows that intraday shocks do not generate lasting changes in real-time system balancing costs. This result is economically intuitive: the intraday market *reduces imbalance volumes*, so its shocks are associated with short-run corrections rather than with structural system scarcity. From Figure 11, we also conclude that the intraday market stage of the Greek Target model functions as a *flexibility and error correction platform*.

[3], not as an independent pricing layer. This dynamic pattern is a hallmark of a *well-functioning sequential electricity market*, i.e., forward prices are determined in the day-ahead stage, intraday trading corrects forecast errors, and balancing prices settle residual deviations.

Also, the rapid decay of all responses to an intraday shock indicates an *efficient arbitrage between DAM and IDM*, an effective incorporation of updated renewable forecasts, and a limited propagation of short-term disturbances to real time. For the Greek-TM market, this is a strong empirical sign of its *increasing maturity and liquidity*. The impulse responses to an intraday shock are large on impact but vanish within a few hours for all three prices. The day-ahead price exhibits no permanent response, while the imbalance price reacts only temporarily. This confirms that intraday innovations are purely transitory and that the intraday market operates as a short-run adjustment mechanism without an independent role in long-run price discovery.

5.6. Impulse Response Analysis to an IP Price Shock

Figure 13 presents orthogonalized impulse response functions following a one-standard-deviation shock to the imbalance price (IP). The imbalance price exhibits a strong initial response that decays rapidly (IP → IP), indicating that balancing market shocks are short-lived (after $h = 5$, it becomes stable at a very low level) and reflect *temporary system imbalances*. In contrast, both day-ahead (IP → DAM) and intraday (IP → IDM) prices respond positively and persistently, suggesting that *real-time system conditions are incorporated into forward market expectations*. More specifically, the stronger and faster response of the *intraday market* reflects its role as an *adjustment mechanism*, while the gradual response of the day-ahead market indicates *the incorporation of balancing information into future DAM price formation*.

In summary, in Sections 5.4–5.6, we have analyzed orthogonalized impulse response functions (IRFs) derived from the estimated VECMX model to examine the dynamic transmission of shocks across electricity market stages. The results reveal a clear and economically intuitive structure of price interactions across the day-ahead (DAM), intraday (IDM), and balancing (imbalance price, IP) markets. Taken together, the impulse response analysis reveals a *dual transmission structure* in the Greek electricity markets, a feature shared also by other markets. First, in the long run, price discovery is driven by the day-ahead market, with shocks propagating forward to the intraday and balancing markets. Second, in the short run, balancing market shocks capture real-time system conditions and propagate upstream, influencing both intraday trading and, to a lesser extent, day-ahead price expectations. The intraday market plays an intermediate role, acting as a transmission channel that rapidly incorporates information from both forward expectations and real-time system conditions, while exhibiting limited persistence in its own shocks.

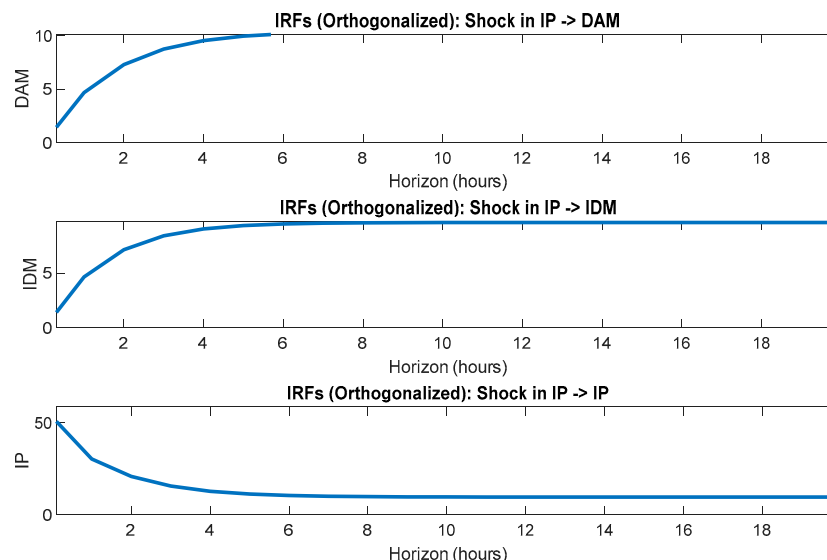


Figure 13. Impulse response functions to a balancing market (imbalance price) shock.

Overall, as a contribution-centered conclusion, the results indicate that price formation in the Greek electricity market is characterized by long-run dominance of day-ahead prices combined with short-run feedback effects from real-time balancing conditions.

5.7. Robustness Analysis: Alternative Recursive Orderings and Generalized Impulse Responses

Because the orthogonalized impulse response functions (IRFs) and forecast error variance decompositions (FEVDs) rely on a recursive Cholesky identification, an additional robustness analysis was conducted to assess the sensitivity of the results to alternative ordering assumptions. While the baseline specification follows the institutional sequence of the European Target Model (DAM–IDM–IP), two additional recursive structures were examined: DAM–IP–IDM and the reverse ordering IP–IDM–DAM. In addition, Generalized Impulse Response Functions (GIRFs), which are invariant to variable ordering, were computed following Pesaran and Shin [25]. Detailed numerical results are reported in Appendix C.

The robustness analysis indicates that *the main conclusions of the study remain unchanged across alternative identification schemes*. The two economically motivated orderings, DAM–IDM–IP and DAM–IP–IDM, generate almost identical FEVD results at all forecast horizons. For example, in the full sample at the one-week horizon (168 h), shocks originating in the day-ahead market explain approximately 87% of the variance of intraday prices and 86% of the variance of imbalance prices under both specifications (compare Table A1 in Appendix C with Tables 9 and 10). The differences between the two orderings are negligible and do not alter the interpretation of the results. A more demanding test is provided by the reverse ordering IP–IDM–DAM, which assigns contemporaneous priority to balancing-market information. As expected, the quantitative contribution of day-ahead shocks decreases under this specification because a larger share of contemporaneous variance is attributed to variables appearing earlier in the recursive structure. Nevertheless, the day-ahead market remains the dominant source of long-run variation. At the one-week horizon, day-ahead shocks continue to explain approximately 59% of DAM variance, 57% of IDM variance, and 56% of imbalance price variance, remaining the largest

single contributor across all market segments. The robustness of the hierarchical market structure is further confirmed by the regime analysis. During periods of elevated balancing activation, day-ahead market dominance becomes even more pronounced. In the stress regime, day-ahead shocks account for more than 98% of the long-run variance of imbalance prices, indicating that balancing-market outcomes remain strongly anchored to information incorporated in forward market schedules. This finding suggests that system stress reinforces rather than weakens the role of the day-ahead market in the price discovery process.

The GIRF analysis leads to the same qualitative conclusions (Figures A6–A8, Appendix C). Because generalized impulse responses do not depend on recursive ordering assumptions, their consistency with the orthogonalized IRFs provides additional evidence that the observed transmission mechanisms are not artifacts of the selected Cholesky decomposition. Across all robustness specifications, the Greek electricity market exhibits a strongly hierarchical price discovery structure in which the day-ahead market serves as the primary source of long-run information, the intraday market functions mainly as a short-run adjustment mechanism, and balancing-market shocks remain largely transitory.

Overall, the robustness analysis demonstrates that although alternative recursive orderings affect the numerical allocation of contemporaneous variance, they do not alter the central economic conclusions of the paper. The dominance of the day-ahead market, the adjustment role of the intraday market, and the transitory nature of balancing-market shocks are robust features of the Greek Target Model throughout the sample period.

5.8. Market Power and Strategic Behavior Implications

The strong linkage between forward DAM and balancing market (BM) has important implications for potential strategic behavior. The cointegration relationship (Equation (5)) linking imbalance prices to day-ahead and intraday prices implies that balancing outcomes are structurally anchored in forward market decisions. More specifically, (5) shows the strong linkage between imbalance prices and forward market outcomes:

$$P_t^{IP} = 1.012 P_t^{DAM} - 0.095 P_t^{IDM} + c \quad (6)$$

The dominant positive coefficient on the day-ahead price implies that *balancing costs are ultimately anchored in DAM forward market scheduling decisions*. This creates a potential channel through which participants active in both markets could influence balancing revenues indirectly via strategic bidding in the day-ahead market. In particular, under tight system conditions, higher day-ahead prices may translate into higher imbalance prices, potentially increasing incentives for cross-market strategies.

At the same time, the negative relationship between intraday prices and imbalance prices highlights the *mitigating role of intraday trading*. Efficient intraday adjustments reduce imbalance volumes and limit the profitability of imbalance-based strategies, acting as a *disciplining mechanism*.

The *dynamic results* further reinforce this interpretation. Impulse response functions (IRFs) show that balancing market shocks are short-lived and rapidly dissipate, while forecast error variance decomposition (FEVD) indicates that imbalance prices are dominated by their own shocks only in the short run and converge toward day-ahead fundamentals at longer horizons. These findings imply that attempts to exploit real-time imbalances are unlikely to generate persistent gains, as the system quickly reverts to its long-run equilibrium.

However, the *regime analysis* (FEVD in *normal* and *stress* conditions, Section 5.4) reveals that the structure of price formation changes under system stress. During stress periods, the dominance of the day-ahead market increases further, and the intraday market loses part of its independent role. While this strengthens price convergence, it may also

increase the sensitivity of the system to forward DAM market behavior. In such conditions, the potential impact of strategic bidding in the day-ahead market could be amplified, particularly in markets with limited competition or high concentration.

Overall, the findings indicate that while the integrated structure of the Greek Target Model constrains the scope for sustained market manipulation, *short-term strategic interactions cannot be entirely ruled out*, especially under stressed system conditions. Ensuring sufficient intraday liquidity, effective monitoring of bidding behavior, and competitive forward markets remains essential for preserving market efficiency.

The results have important economic and regulatory implications. First, *they confirm the central role of the DAM forward market* in allocating system costs and providing investment signals for *flexibility* resources. Persistent balancing needs are increasingly reflected in DAM's price expectations, thereby creating incentives for storage, demand response, flexible generation, and improved forecasting technologies. Second, they highlight the growing importance of intraday trading as a mechanism for integrating updated system information and reducing real-time imbalances. Third, they suggest that policies aimed at strengthening both DAM and IDM liquidity—including improved cross-zonal capacity allocation, enhanced transparency, and broader participation of flexible resources—are critical for maintaining efficient price formation.

5.9. Limitations

This study is subject to several limitations that open avenues for further research. First, the *recursive identification* is based on *institutional timing*; although economically well founded, alternative identification schemes or *generalized impulse responses* could provide additional robustness. Second, the imbalance price aggregates different activation products and system states; distinguishing between upward and downward balancing (i.e., via mFRR Up, mFRR Down) or between balancing technologies would allow a more granular analysis of real-time dynamics. As mentioned in 5.7, as a robustness check, we have also defined stress regimes using high mFRR prices instead of using the total activated balancing energy (totBE_t) variable, and found that the qualitative conclusions regarding price transmission and market leadership remain unchanged.

Third, the analysis focuses on the domestic market; extending the framework to a multi-country setting would allow a direct assessment of cross-border interactions within the Target Model. Finally, as intraday market liquidity continues to increase, incorporating higher-frequency intraday data would provide further insight into the interaction between forward scheduling and real-time balancing.

Overall, the results show that the Greek wholesale electricity market is evolving toward a *mature, DAM-anchored but increasingly interactive pricing system*, in which most uncertainty is resolved *ex ante*, real-time prices function primarily as a settlement mechanism, and balancing signals are progressively integrated into DAM forward market expectations. This *hybrid structure*—combining strong DAM price discovery with meaningful real-time feedback—constitutes a key condition for the efficient integration of variable renewable energy and the long-term cost efficiency of the Greek power system.

Several other limitations should also be acknowledged. First, the analysis focuses on the period January 2023–September 2025, which corresponds to a relatively mature stage of Greek Target Model development characterized by high renewable energy penetration and increasing balancing-market activity. Consequently, the results should not be interpreted as representative of all historical phases of the Greek electricity market. In particular, the market conditions prevailing during the initial Target Model implementation period and the European energy crisis of 2021–2022 differ substantially from those examined in this study.

Second, the paper focuses exclusively on the Greek market. Although the findings are broadly consistent with evidence reported for other European Target Model markets, a systematic cross-country comparison using a common econometric framework would provide valuable insights into the generalizability of the observed price discovery mechanisms.

Future research could therefore extend the analysis both temporally, by incorporating earlier market phases, and geographically, by conducting comparative investigations across European electricity markets operating under the Target Model.

6. Discussion and Conclusions

This paper analyzed the dynamic interaction and price discovery process across the day-ahead, intraday, and balancing segments of the Greek wholesale electricity market under the Target Model using a VECMX framework that conditions price dynamics on fundamental system drivers. The results provide robust evidence of a strongly hierarchical and forward-centered market structure in which the day-ahead market acts as the dominant source of permanent price innovations, the intraday market operates primarily as a short-run adjustment and flexibility mechanism, and imbalance prices in the balancing market reflect the real-time settlement of deviations from forward schedules. These findings are particularly relevant in the context of the *sustainable energy transition*, where efficient coordination across market stages is essential for *integrating increasing shares of variable renewable energy sources* while maintaining system reliability and operational efficiency.

The cointegration results confirm a high degree of structural integration across trading horizons. Two stable long-run equilibrium relationships link the three market segments, with the intraday price adjusting closely around the day-ahead benchmark and the imbalance price tied to both day-ahead and intraday market outcomes. In particular, the relationship linking imbalance prices to preceding market stages indicates that balancing outcomes are fundamentally anchored in forward scheduling decisions, while efficient intraday trading reduces real-time deviations and balancing needs. The stability of these relationships across yearly sub-samples and both normal and stress regimes indicates effective arbitrage and coherent cross-market adjustment even under adverse system conditions, reinforcing the resilience of the Target Model framework.

The forecast error variance decomposition (FEVD) confirms that day-ahead shocks explain the overwhelming share of long-run variance not only of intraday prices but also of imbalance prices, while shocks originating in the latter markets remain largely transitory. The regime analysis further shows that price discovery is state-dependent. During periods of high balancing activation, the system becomes more strongly forward-driven, with day-ahead innovations explaining almost all medium- and long-run variation. At the same time, the short-run influence of real-time shocks remains significant, indicating that stress conditions are partly anticipated but still materialize through balancing actions. Importantly, the long-run equilibrium structure remains stable even under stress, confirming the robustness of market integration and the ability of the market design to support system stability during periods of elevated operational uncertainty.

At the same time, the extended data sample (2023–September 2025) reveals a moderate increase in the contribution of intraday and balancing market shocks, particularly after 2024, indicating that real-time system conditions are increasingly incorporated into the price formation process. This suggests a gradual transition from a purely day-ahead-driven system toward a more interactive and information-rich market structure, without undermining the dominant role of the day-ahead market. More specifically, the temporal comparison between 2023, 2024, and 2025 reveals a non-linear process of market maturation. The transition from 2023 to 2024 is characterized by a strong consolidation of forward

market dominance, reflecting improved renewable generation forecasting, increased intraday participation, and more efficient portfolio optimization. However, the 2025 results indicate a partial rebalancing, with a modest increase in the role of intraday and balancing markets. This suggests that as the market matures further and renewable penetration increases, real-time conditions and intraday adjustments regain importance, contributing to a more flexible, adaptive, and resilient electricity system.

From a *sustainability perspective*, these findings highlight the importance of well-functioning forward and real-time electricity markets in supporting decarbonization objectives and the *efficient integration of renewable energy sources*. Improved coordination between day-ahead, intraday, and balancing stages reduces system inefficiencies, lowers balancing costs, enhances operational flexibility, and strengthens *system resilience* under variable generation conditions. Consequently, the Target Model appears capable of facilitating not only efficient price discovery but also the broader transition toward a sustainable and low-carbon electricity sector. The results therefore have important implications for electricity market design, renewable integration policy, balancing market development, and the *long-term sustainability* of European power systems.

6.1. Data Sample Representativeness and Scope of Inference

An important consideration when interpreting the results is the representativeness of the sample period examined in this study. The analysis covers the period from January 2023 to September 2025, which corresponds to a phase of rapid market maturation under the Greek Target Model, increasing renewable energy penetration, expanding balancing requirements, and progressive integration with European electricity market platforms. This period is also characterized by elevated balancing-market activity and increased operational complexity compared with earlier stages of market development.

Consequently, the results should be interpreted as characterizing the current phase of Greek Target Model operation rather than the entire historical evolution of the Greek electricity market. The primary objective of the study is to investigate the interaction among day-ahead, intraday, and balancing markets under contemporary market conditions, where renewable energy sources play an increasingly important role and market participants have largely adapted to the Target Model framework.

The period preceding 2023 differs substantially from the study sample. The Target Model was only introduced in late 2020, while the subsequent years were affected by significant implementation adjustments, lower intraday market liquidity, the COVID-19 recovery period, and the unprecedented European energy crisis of 2021–2022. These factors created structural conditions that are not directly comparable to those observed during the more mature market environment examined here. As a result, a direct comparison between the pre-2023 and post-2023 periods would involve fundamentally different institutional and economic regimes, potentially confounding the interpretation of price discovery and market integration mechanisms.

At the same time, several of the qualitative findings reported in this study—including the dominant role of the day-ahead market in price discovery, the adjustment function of intraday trading, and the increasing importance of balancing markets under higher renewable penetration—are consistent with evidence reported for other European Target Model markets. This suggests that while the quantitative magnitudes observed in Greece may be sample- and country-specific, the underlying mechanisms are likely to reflect broader trends associated with the evolution of European electricity markets toward greater flexibility, renewable integration, and cross-market coordination.

Therefore, the conclusions of this study should be viewed primarily as evidence regarding the contemporary operation and maturation of the Greek Target Model during the 2023–2025 period. Extending the analysis to earlier periods, including the initial im-

plementation phase of the Target Model and the energy crisis years, represents an important direction for future research and would allow a more comprehensive assessment of the long-term evolution of price discovery across market stages.

6.2. European Comparison and Generalizability of the Greek Results

Although the present study focuses on the Greek wholesale electricity market, the results can be interpreted within the broader evolution of European electricity markets under the Target Model. Directly comparable VECMX studies jointly modeling day-ahead, intraday, and balancing prices across several European countries remain limited. Nevertheless, related empirical evidence from Italy, Spain, Germany, and the Nordic markets provides useful qualitative benchmarks.

First, the finding that the day-ahead market is the dominant source of long-run price discovery is consistent with the institutional role of the day-ahead auction in European electricity markets. Under the European market design, the day-ahead market remains the central reference point for scheduling, price formation, and cross-border allocation, while intraday and balancing markets operate closer to real time as adjustment mechanisms. This sequential logic is explicitly embedded in the European internal electricity market design, which is organized around forward, day-ahead, intraday, and real-time balancing stages.

Evidence from the Italian market supports this interpretation. Caporin, M., et al., (2022) [26] examine the long-run relationship between Italian day-ahead and balancing electricity prices and show that these two markets are linked through convergence dynamics. Their results indicate that balancing prices do not evolve independently from day-ahead prices, but are connected to the preceding market stage through long-run adjustment mechanisms. This is consistent with the Greek evidence reported here, where imbalance prices remain anchored to day-ahead and intraday market outcomes.

The Spanish experience also provides a relevant comparison. Studies of the Spanish intraday market show that intraday trading has played an important role in balancing renewable generation and reducing forecast errors. (Chaves-Ávila, J.P., et al., 2015) [27] show that the Spanish intraday market contributed to renewable generation balancing, although market distortions could also create incentives for arbitrage between day-ahead and intraday markets. This evidence is consistent with our finding that the intraday market in Greece functions mainly as a short-run adjustment mechanism that helps correct forward schedules before real-time balancing.

Evidence from Germany similarly emphasizes the adjustment role of intraday trading under high renewable penetration. Studies of German day-ahead and intraday markets show that intraday prices are strongly influenced by forecast deviations in wind, solar generation, load, plant availability, and cross-border conditions. This supports the interpretation that intraday markets become increasingly important as systems absorb larger shares of variable renewable energy. However, these markets usually complement rather than replace the day-ahead market as the main platform for price discovery.

The Nordic market provides an additional benchmark. Research on Nordic day-ahead, intraday, and regulating power markets has explicitly examined whether markets closer to real time increasingly dominate trading activity and price discovery. More recent Nordic reforms, including the adoption of flow-based market coupling, have aimed to improve grid efficiency, increase renewable integration, and enhance price convergence across bidding zones. This experience is consistent with the broader European tendency toward stronger integration of market stages, higher granularity, and more efficient use of cross-border capacity.

Overall, the Greek results appear to be broadly consistent with the European experience. Across European markets, the day-ahead market generally remains the principal

venue for information aggregation and price discovery, while intraday and balancing markets serve increasingly important adjustment and flexibility functions under rising renewable penetration. What appears more specific to Greece is the intensity of balancing-market interactions during the recent Target Model maturation phase, reflecting the relatively recent restructuring of the market, the rapid increase in renewable penetration, and the importance of balancing activation costs.

Therefore, the findings of this paper should not be interpreted as purely idiosyncratic to Greece. Rather, they reflect a broader European pattern in which forward market coordination remains central, while intraday and balancing markets become progressively more important for flexibility, renewable integration, and system resilience. At the same time, the quantitative strength of these relationships is likely to remain country-specific and dependent on market liquidity, generation mix, interconnection capacity, balancing-market design, and regulatory maturity. A fully harmonized cross-country VECMX analysis of DAM-IDM-BM interactions therefore represents an important avenue for future research.

Directly comparable studies jointly modeling day-ahead, intraday, and balancing prices within a unified VECMX framework remain limited in European literature. Consequently, the comparison presented here is necessarily qualitative and based on related studies examining interactions among different market stages

6.3. Policy and Sustainability Implications

The results of this study have important implications for electricity market design, system operation, renewable energy integration, and the broader transition toward sustainable energy systems under the European Target Model.

6.3.1. Implications for Regulators and Market Designers

The strong dominance of the day-ahead market in the price discovery process suggests that efficient forward market design remains essential for overall market performance. Since the majority of long-run information is incorporated into day-ahead prices, regulators should prioritize policies that enhance day-ahead market liquidity, transparency, and forecasting accuracy. At the same time, the increasing contribution of intraday and balancing markets observed during the later stages of the sample indicates that market designs should continue evolving toward higher temporal granularity, improved cross-border integration, and greater flexibility to accommodate increasing renewable energy penetration.

The results also suggest that balancing costs should not be viewed solely as a balancing-market problem. Since imbalance prices remain strongly linked to forward market outcomes, improvements in forecasting, scheduling, and intraday trading may be more effective in reducing balancing costs than interventions targeting balancing markets alone.

6.3.2. Implications for Transmission System Operators

For Transmission System Operators (TSOs), the findings highlight the importance of maintaining efficient coordination among market stages. The persistence of strong long-run integration between DAM, IDM, and balancing markets indicates that system operation benefits from coherent market signals across different trading horizons. The observed strengthening of market integration following developments such as the implementation of European balancing platforms further supports ongoing efforts to enhance cross-border balancing cooperation and reserve sharing.

The increasing role of balancing activation during periods of system stress also emphasizes the importance of investment in system flexibility resources, advanced forecast-

ing tools, and real-time operational capabilities that can support reliable system balancing under high renewable penetration.

6.3.3. Implications for Market Participants and Aggregators

For generators, suppliers, traders, and aggregators, the results demonstrate that day-ahead market outcomes remain the primary determinant of subsequent market developments. Consequently, accurate forecasting, effective portfolio management, and optimized participation in day-ahead auctions continue to be critical sources of competitive advantage.

At the same time, the increasing importance of intraday adjustments observed in recent years suggests that market participants should develop enhanced intraday trading capabilities. For aggregators managing distributed renewable resources, storage systems, and flexible demand portfolios, intraday markets are likely to become increasingly important as a mechanism for minimizing imbalance exposure and improving portfolio performance.

6.3.4. Implications for Balancing Market Efficiency

The analysis indicates that balancing markets primarily perform a corrective function rather than acting as independent sources of price discovery. Imbalance price shocks are largely transitory, while day-ahead shocks explain most long-run variation in balancing prices. This finding suggests that balancing-market efficiency should be evaluated not only by balancing price levels but also by the extent to which balancing actions successfully resolve deviations arising from earlier market stages.

The results further imply that improvements in balancing-market efficiency may be achieved through better coordination with day-ahead and intraday markets, enhanced reserve procurement mechanisms, and greater participation of flexible resources.

6.3.5. Implications for Renewable Energy Integration

The increasing role of intraday and balancing markets observed during the sample period is closely linked to the growth of renewable energy generation. As renewable penetration rises, forecast uncertainty and variability naturally increases, creating a greater need for short-term market adjustments and balancing actions.

The results therefore highlight the complementary roles of the three market stages in facilitating renewable integration. The day-ahead market provides the primary platform for efficient scheduling, the intraday market allows corrections to forecast errors, and the balancing market resolves residual deviations in real time. Together, these mechanisms support the reliable integration of variable renewable energy sources while maintaining market efficiency.

6.3.6. Implications for System Flexibility and Resilience

The findings suggest that the Greek electricity market is gradually evolving toward a more flexible and resilient market structure. Although the day-ahead market remains dominant, the growing contribution of intraday and balancing markets indicates increasing responsiveness to real-time system conditions. Such flexibility is essential in power systems characterized by higher shares of wind and solar generation.

Moreover, the persistence of stable cointegration relationships during periods of system stress demonstrates that market integration remains robust even under challenging operating conditions. This resilience is particularly important as electricity systems become more dependent on variable renewable generation and face increasing uncertainty associated with weather-dependent production.

6.3.7. Implications for European Decarbonization Objectives

From a broader sustainability perspective, the results support the view that the European Target Model can facilitate the transition toward a low-carbon electricity system. Efficient interaction among day-ahead, intraday, and balancing markets improves resource allocation, reduces operational inefficiencies, enhances system flexibility, and supports the integration of increasing shares of renewable energy.

The gradual evolution toward a more interactive and information-rich price formation process observed in Greece is consistent with the objectives of the European Green Deal and the EU decarbonization strategy. By improving the coordination of market stages and strengthening incentives for flexibility, electricity markets can play a central role in enabling large-scale renewable deployment while maintaining security of supply and economic efficiency.

Overall, the results indicate that well-functioning market integration, supported by efficient balancing mechanisms and flexible trading arrangements, constitutes a critical component of a sustainable, resilient, and decarbonized European electricity system.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Appendix A.1. Day-Ahead Market (DAM) Parameters

The Day-Ahead Market (DAM) in Greece, overseen by ADMIE (IPTO) and operated by HENEX, is a wholesale electricity market where *15-minute or hourly quantities* for the next day are traded, using Marginal Pricing to set the Market Clearing Price (MCP). Key parameters include daily, 12:00 CET gate closure, hourly/block orders, and integration into the European Single Day-Ahead Coupling (SDAC). The key parameters of the ADMIE/HENEX DAM are:

Timeframe: 24-hour, 15-minute intervals (or hourly).

Gate Closure (GCT): 12:00 CET on the day prior to delivery.

Pricing Mechanism: Marginal Pricing/Market Clearing Price (MCP) in €/MWh.

Order Types: Hourly hybrid orders (step/linear), block orders (minimum acceptance ratio), and linked/exclusive group block orders.

Data Outputs: Pre-market data, market prices, aggregated volume/technologies, and anonymous curves.

Scheduling: The DAM schedule sets the baseline for the Integrated Scheduling Process (ISP) and Balancing Market.

The market operates daily, with results determining the physical dispatch for the following day. In the Greek Day-Ahead Market (DAM) operated under the EU Target Model, these parameters represent the core hourly clearing data published by ADMIE and HENEX. They define the electricity supply–demand balance and price setting:

DAM Sell MCP (€/MWh): The Market Clearing Price, representing the final price determined by matching supply and demand curves.

Sell production (MWh): Total electricity generation scheduled from domestic units.

Sell imports (MWh): Energy imported from neighboring systems.

Buy demand (MWh): Total hourly consumption requested by suppliers/consumers.

Buy exports (MWh): Energy scheduled for export to neighboring systems.

Appendix A.2. Intra-Day Market (IDM) Parameters

The Intra-Day Market (IDM) in Greece, operated via ADMIE (IPTO) and EnEx, consists of *continuous trading (XBID)* and *three Intraday Auctions (IDAs)* at 15:00 (D-1), 22:00 (D-1), and 10:00 (D). Parameters include cross-zonal capacity, clearing prices, aggregated volumes per market time unit and technology portfolio.

Key IDM parameters and data published by EnEx and ADMIE include:

Intraday Auctions (IDAs): Three (3) daily auctions implemented since 13 June 2024, to allocate cross-zonal capacity and define clearing prices.

Market Data Publications: Divided into Pre-Market Data (DAM/previous IDM results), Market Results (prices, volumes per unit/technology), and Post-Market Data (anonymous buy/sell curves).

Trading Volumes: Continuous trading via XBID, which allows for real-time position adjustments, generally shows higher daily volumes compared to IDAs.

Performance Metrics: Average Intraday Market Prices (MCP) and volumes are tracked, with continuous trading serving as the primary mechanism for flexibility.

Technical Constraints: IDM schedules must consider technical constraints, and, if violated, may be treated as Imbalance.

In ADMIE's Intra-day market, CRIDA1, the spot summary parameters represent the results of the first Complementary Regional Intraday Auction (CRIDA). These include the market clearing price (MCP), total volume cleared (production/demand), and scheduled imports/exports between bidding zones, typically visualized in EnExGroup's IDA market figures (<https://www.enexgroup.gr/el/day-ahead-market-figures>). CRIDA1 Spot Summary SELL/BUY MCP: the price (€/MWh) determined where the aggregate supply (sell) curves intersect with the aggregate demand (buy) curves for each delivery hour.

Production (Sell Volume): The total quantity of electricity (MWh) sold by participants in the CRIDA1 session.

Demand (Buy Volume): The total quantity of electricity (MWh) purchased by participants in the CRIDA1 session.

Imports/Exports (Net Position): The scheduled cross-zonal exchanges resulting from the auction, indicating the net import or export position for the Greek market in that session.

CRIDA1 (Complementary Regional Intraday Auction 1) is the first of three daily intraday auctions in the Hellenic Energy Exchange (HENEX) spot market, designed to allow participants to adjust their commercial positions following the Day-Ahead Market (DAM) results.

Key Aspects of CRIDA1:

Purpose: Provides a mechanism for balancing and adjustment after the DAM, utilizing implicit allocation of cross-border capacity (specifically with Italy, and transitioning towards broader European coupling via IDAs).

Timing: Opens at 12:55 CET and closes at 15:00 CET on the day before delivery (D-1).

Products & Pricing: Involves hourly hybrid orders (buy/sell) with marginal pricing, executed for all Intra-Day Market (IDM) time units.

Market Context: It is part of the HENEX Spot Market, which includes the Day-Ahead Market and three Intraday Auctions (CRIDAs).

As of 2024, CRIDAs are in the process of being converted into European Intra-Day Auctions (IDAs) to implement broader implicit capacity allocation. CRIDA2 (Intraday Market Auction 2) refers to a specific, second session within the continuous, cross-border intraday electricity market coupling process, often organized by operators like GME (Italy) or EnExGroup (Greece). On February 29, 2024, an issue with the Greek order book caused a temporary, partial inability to trade during this session.

Key Details regarding CRIDA 2:

Definition: It is a key step in the market-driven, pan-European intraday trading system designed to allow participants to trade electricity closer to real-time.

Market Coupling: It facilitates the exchange of electricity across borders (e.g., between Italy/Greece/neighboring areas).

Operational Issue (February 2024): A technical error in the Greek order book on 29 February 2024 impacted the “CRIDA 2” session.

Appendix A.3. Balancing Market Parameters

In ADMIE (IPTO), balancing market data comprises 15- minute, 30- minute, or 60- minute interval data for energy volumes and prices. Total activated energy (UP/DOWN) measures MWh for mFRR/aFRR. IDEV/UDEV reflects imbalances, while mFRR prices follow a pay-as-clear principle for imbalances. Data is available on the ADMIE website via www.admie.gr.

Total Activated Balancing Energy UP/Down (MWh): The volume of energy activated to increase (Up) or decrease (Down) generation/load to balance the system, calculated separately for mFRR and aFRR in 15- minute settlement periods.

Balancing Energy IDEV/UDEV (MWh): These represent deviation volumes, where IDEV often refers to the *Imbalance Deviation (total)* and UDEV likely refers to *Upward or Downward deviations* in the context of settlement calculations (e.g., in spreadsheets like the ones provided by ADMIE reports).

Imbalance Price (Euro/MWh). The price applied to the final imbalance of a Balance Responsible Party (BRP), often linked to the marginal price of the activated balancing energy, is determined in €/MWh for each 15-minute period.

mFRR Price UP/Down (Euro/MWh). The remuneration for upward (mFRR Price UP) or downward (mFRR Price Down) manual frequency restoration reserves, based on the pay-as-clear principle (maximum/minimum price of activated bids).

Technical Price Limits: Per ADMIE regulations, bidding limits for balancing energy were historically $\pm 99,999$ €/MWh, but are transitioning to stricter European standards.

These values are part of the daily imbalance settlement, published by ADMIE to show how much energy was activated in either direction. These metrics are critical for calculating the *financial compensation for balancing service providers (BSPs)* and the *charges for balance responsible parties (BRPs)* due to their imbalances.

Appendix A.4. IDM's CRIDA3 Price and All Its Parameters

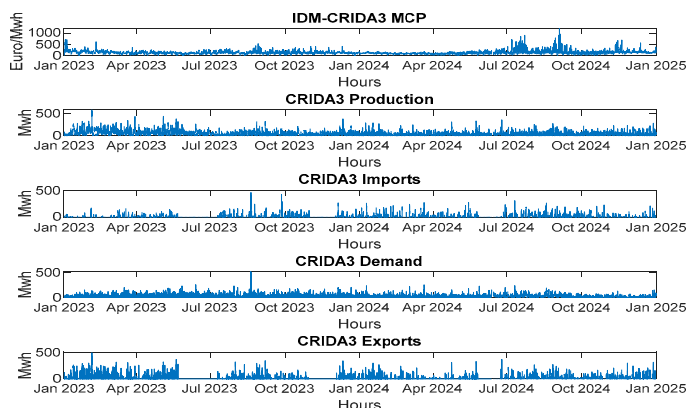


Figure A1. Time series of IDM (CRIDA3) parameters, 2023–2024.

Appendix A.5. European Context and Integration of Balancing Markets (BM)

The development of balancing markets in Europe is guided by the Electricity Balancing Guideline, EBGL (ENTSO-E, 2018; ENTSO-E, Balancing report 2020; ACER 2020; EU EBGL Regulation 2017/2195), which aims to harmonize balancing market design across EU member states and improve cross-border balancing efficiency. The regulation promotes the integration of national balancing markets through common European platforms for the exchange of balancing energy. Two key platforms have been established under this framework. The PICASSO platform (Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation) facilitates the cross-border activation of *automatic Frequency Restoration Reserves (aFRR)*, enabling transmission system operators to procure balancing energy from a wider pool of resources across Europe. Similarly, the MARI platform (Manually Activated Reserves Initiative) enables the coordinated activation of *manual Frequency Restoration Reserves (mFRR)* across interconnected European power systems.

The integration of national balancing markets through these platforms aims to improve *market efficiency, competition, and system reliability* by allowing balancing energy to be sourced from the most cost-effective providers across participating countries. In principle, this integration should reduce balancing costs by increasing liquidity and competition in balancing energy procurement.

Appendix A.5.1. Balancing Market Design in Greece

The Greek balancing market operates under a *central dispatch, unit-based model* in which the Independent Power Transmission Operator (IPTO) determines generation schedules and dispatch instructions through the *Integrated Scheduling Process (ISP)*. This framework ensures that sufficient balancing capacity is available to maintain system reliability and that balancing services are activated efficiently when deviations between supply and demand occur. The structure of the Greek balancing market follows the *European Target Model* and the regulatory framework established by the EBGL. The EBGL aims to harmonize balancing mechanisms across European electricity markets, improve competition, and enable cross-border balancing energy exchange through common platforms coordinated by ACER and ENTSO-E, including MARI for mFRR and PICASSO for aFRR. Within this framework, the Greek balancing market consists of three main components: (i) the *Balancing Capacity Market*, (ii) the *Balancing Energy Market*, and (iii) *Balancing Market Settlement* (Figure A2).

The sequence of the Greek Balancing Market Procedures



Figure A2. The sequence of procedures of the Greek balancing market.

Appendix A.5.2. Balancing Capacity Market

Balancing reserves are procured through the *Integrated Scheduling Process (ISP)*, which determines the optimal commitment of generating units and the allocation of balancing capacity. The ISP is formulated as a *Mixed Integer Linear Programming (MILP)* optimization problem that co-optimizes balancing energy and balancing capacity offers submitted by Balancing Service Providers, while respecting transmission system constraints and operational requirements. The ISP determines: the commitment status of generating units, the awarded upward and downward balancing capacity products, and the inter-zonal power flows in the transmission network. IPTO defines reserve requirements for each 15-minute dispatch period, including: *Frequency Containment Reserve (FCR)*, *automatic Frequency Restoration Reserve (aFRR)*, and *manual Frequency Restoration Reserve (mFRR)*. During the transitional phase prior to full intraday market coupling, the ISP is executed *three times per dispatch day*, allowing the operator to update schedules based on revised forecasts and system conditions. Figure A3 show how information flows for the balancing capacity payments, and the IA3 account (see section, in the Greek market).

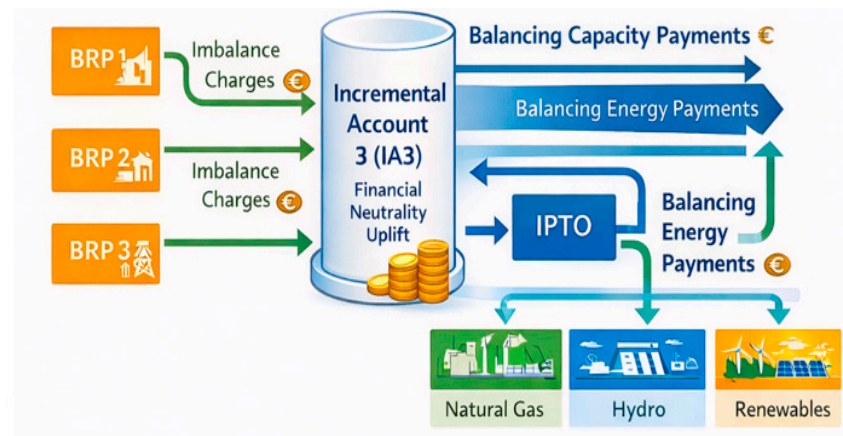


Figure A3. Information flow map for the balancing capacity payments and the IA3 account in the Greek market.

Appendix A.5.3. Balancing Energy Market

The Balancing Energy Market determines the real-time activation of balancing energy required to maintain the balance between electricity supply and demand. Balancing energy is activated through two mechanisms: *manual Frequency Restoration Reserve (mFRR)* and *automatic Frequency Restoration Reserve (aFRR)*.

For mFRR, IPTO evaluates system conditions close to real time and issues dispatch instructions for each 15-minute period, *activating the most cost-efficient bids*. In contrast,

aFRR is activated automatically through the *Automatic Generation Control (AGC)* system, which adjusts generation approximately every *four seconds* according to system frequency deviations (Figure A4).

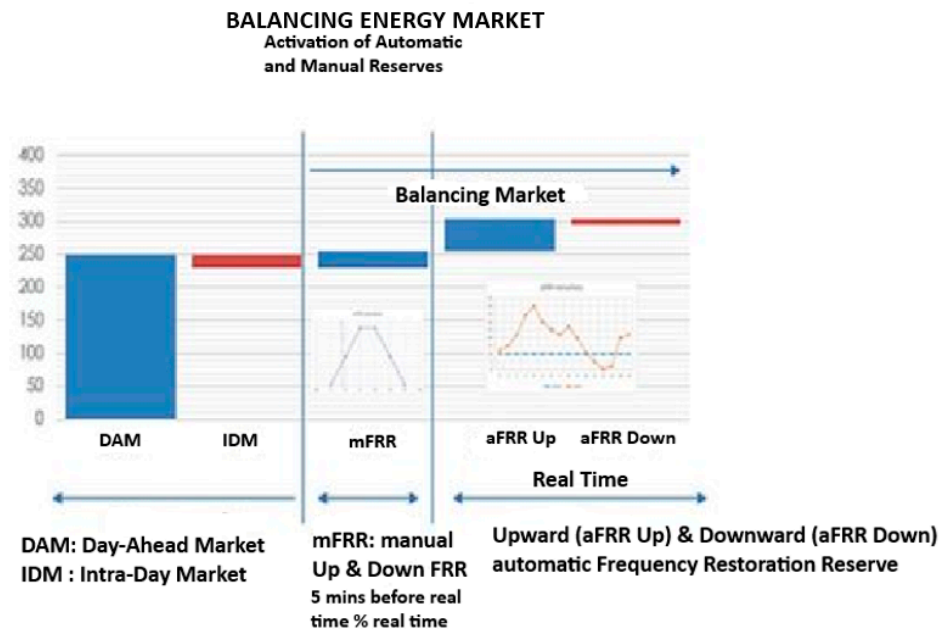


Figure A4. Sequence of sub-markets in the Greek spot electricity market with details for the balancing energy market: activation of automatic and manual reserves.

Appendix A.5.4. Balancing Market Settlement

Balancing market settlement determines the financial transactions associated with balancing capacity procurement, balancing energy activation, and system imbalances. Settlement is conducted *weekly*, after real-time operations have been completed, and includes *balancing capacity settlement*, *balancing energy settlement*, and *imbalance settlement*. Imbalances are calculated for each *15-minute Imbalance Settlement Period (ISP)*, using a *single Imbalance Price (IP)* derived from the weighted average price of the activated balancing energy in the predominant direction. This mechanism ensures that *balancing costs* are allocated to market participants responsible for deviations from their scheduled positions. A detailed description of this market, with all mathematics involved, is given in reference [1]; also, Appendix B provides a simple example of how IP is calculated and associated with activated balancing energy.

The overall settlement structure can be conceptually represented as a process in Figure A5.

Figure A5 illustrates the settlement process. After the scheduling of market participants in DAM and IDM, system imbalances occurring in real time are corrected through the *activation of balancing energy* (aFRR and mFRR). The resulting costs are settled through imbalance pricing and *reconciled via the IA3 financial neutrality account* managed by IPTO. This mechanism ensures that balancing costs are transparently allocated among market participants while maintaining the operational and financial neutrality of the transmission system operator.

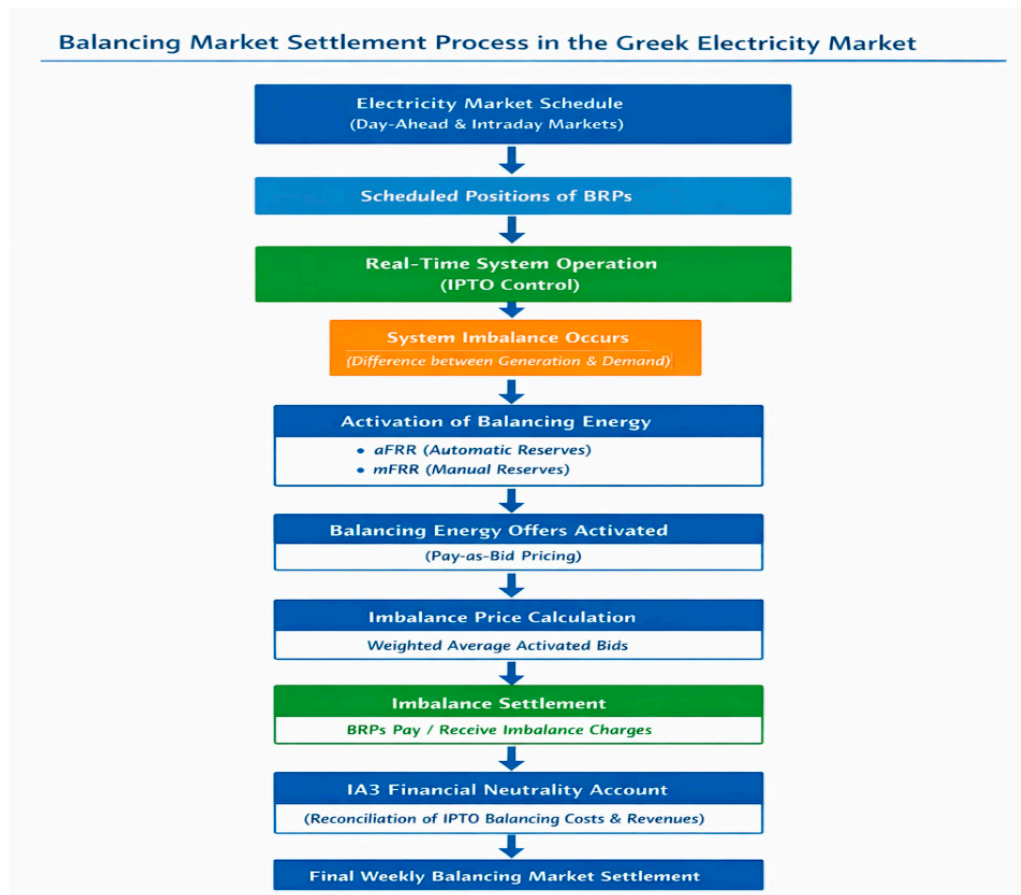


Figure A5. Balancing market settlement process in the Greek electricity market.

Appendix A.6. Balancing Energy Costs in Greece

Balancing energy costs in Greece were projected to exceed €1 billion in 2025 (HelleniQ Energy, 2025), driven by structural distortions, high demand, and market inefficiencies rather than purely technical needs. Key costs, particularly the *Incremental Account 3* (IA3), surged by up to 150% from July 2024, reflecting *high volatility in the balancing market* (the spread between minimum and maximum daily prices widened from €128/MWh in 2024 to €143.4/MWh in 2025). The *key trends and factors for 2024–2025* were: (a) *cost Explosion*: Balancing costs were heavily impacted by unpredictable behavior in the pay-as-bid mechanism, (b) *market drivers*: high reliance on natural gas for grid balancing, alongside renewable curtailments and persistent grid bottlenecks, were maintaining high, volatile costs, (c) *impact of renewables*: despite renewables accounting for over 57% of electricity output in 2024, their variability necessitated significant, expensive, and sometimes inefficient, balancing actions, and finally (d) *regulatory focus*: efforts were ongoing to address the “paradox” of high costs despite the increased penetration of lower-cost renewables. Thus, during 2024, the market was dealing with the consequences of high, unpredictable costs, with ongoing scrutiny of the procurement and allocation processes.

The significant increase in IA3 (Financial Neutrality Uplift Account) during 2024–2025 can be attributed to several interacting factors. First, the rapid growth of renewable energy penetration increased forecast uncertainty and system balancing requirements, leading to more frequent activation of balancing energy. Second, periods of elevated demand and system stress increased the utilization of balancing reserves, particularly mFRR activations. Third, transmission constraints and local system imbalances occasionally required costly balancing actions beyond normal market operation. Fourth, the growing

complexity of real-time system management under higher shares of variable renewable generation increased the need for corrective balancing interventions. Finally, the ongoing maturation of the Greek Target Model and the progressive integration with European balancing platforms altered balancing-market participation and cost allocation mechanisms, contributing to changes in IA3 outcomes. Collectively, these factors increased balancing-related expenditures and explain the observed rise in IA3 during the study period.

Appendix B

The *imbalance price* (IP) is derived from the *activated balancing energy* offers during each settlement period. In simplified form, the imbalance price can be expressed as:

$$IP = \frac{\sum_{i=1}^n (P_i \times E_i)}{\sum_{i=1}^n E_i}$$

where IP = Imbalance Price (€/MWh), P_i = price of activated balancing bid i (€/MWh), E_i = activated energy from bid i (MWh) and n = number of activated bids in the predominant direction.

This formulation reflects the **weighted average price of the activated balancing energy**, ensuring that the imbalance price accurately reflects the marginal cost of system balancing during the specific settlement interval. The formula above means that each activated balancing bid has a **price** and **energy quantity**, prices are **weighted by the amount of energy activated** and the final imbalance price reflects the **average cost of balancing the system** in that settlement period. We give a simple example (fictitious values):

Activated Bid	Price (€/MWh)	Energy (MWh)
Bid 1	100	20
Bid 2	120	30
Bid 3	150	10

Thus, the IP is:

$$IP = \frac{(100 \times 20) + (120 \times 30) + (150 \times 10)}{20 + 30 + 10}$$

$$IP = \frac{2000 + 3600 + 1500}{60} = 118.3 \text{ €/MWh}$$

This price is then used to **settle imbalances for all BRPs during that ISP**. A central component of the Greek balancing market settlement framework is the **Financial Neutrality Uplift Account UA-3**, commonly referred to as **Incremental Account 3 (IA3)** or **UPLIFT3**. The purpose of IA3 is to ensure the **financial neutrality of the Hellenic Transmission System Operator (IPTO)** in the execution of balancing operations. In practice, IA3 reconciles the difference between the costs incurred by IPTO when activating balancing energy and the revenues collected from BRPs through imbalance charges. Any resulting surplus or deficit is redistributed among market participants so that balancing actions do not affect the financial position of the system operator.

The IA3 mechanism includes several cost components. These include the net financial outcome of activated balancing energy, particularly **automatic and manual Frequency Restoration Reserves (aFRR and mFRR)**. The account also incorporates costs associated with **energy activated for non-balancing purposes**, such as the resolution of network constraints, as well as costs related to **cross-border exchanges of balancing energy**, both intentional and unintentional.

Appendix C

Robustness Analysis of Recursive Ordering and Generalized Impulse Responses

Table A1. FEVD Alternative Cholesky: DAM–IP–IDM.

FEVD Alternative Cholesky: DAM–IP–IDM			
Horizon	Response Variable: DAM		
Hours	DAM_Shock	IDM_Shock	IP_Shock
<i>h1</i>	0.987	8.281e-06	0.0120
<i>h6</i>	0.933	0.0002	0.066
<i>h24</i>	0.898	0.0003	0.101
<i>h72</i>	0.889	0.0003	0.110
<i>h168</i>	0.886	0.0003	0.112
Horizon	Response variable: IDM		
hours	DAM_shock	IDM_shock	IP_Shock
<i>h1</i>	0.390	0.603	0.0060
<i>h6</i>	0.644	0.306	0.049
<i>h24</i>	0.797	0.112	0.090
<i>h72</i>	0.852	0.041	0.105
<i>h168</i>	0.870	0.018	0.110
Horizon	Response variable: IP		
hours	DAM_shock	IDM_shock	IP_Shock
<i>h1</i>	0.070	6.154e-08	0.929
<i>h6</i>	0.391	4.833e-05	0.608
<i>h24</i>	0.709	0.0002	0.290
<i>h72</i>	0.820	0.0003	0.179
<i>h168</i>	0.856	0.0003	0.143

Table A2. FEVD Reverse Cholesky: IP–DAM–IDM.

FEVD Reverse Cholesky: IP–DAM–IDM			
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Response Variable: DAM			
<i>Horizon</i>			
<i>Hours</i>	<i>DAM_Shock</i>	<i>IDM_Shock</i>	<i>IP_Shock</i>
<i>h1</i>	0.708	0.216	0.075
<i>h6</i>	0.639	0.181	0.179
<i>h24</i>	0.600	0.164	0.235
<i>h72</i>	0.589	0.159	0.250
<i>h168</i>	0.586	0.158	0.254
Response variable: IDM			
<i>Horizon</i>			
<i>hours</i>	<i>DAM_shock</i>	<i>IDM_shock</i>	<i>IP_Shock</i>
<i>h1</i>	0.071	0.894	0.034
<i>h6</i>	0.293	0.577	0.129
<i>h24</i>	0.477	0.311	0.211
<i>h72</i>	0.544	0.214	0.240
<i>h168</i>	0.566	0.128	0.250
Response variable: IP			
<i>Horizon</i>			
<i>hours</i>	<i>DAM_shock</i>	<i>IDM_shock</i>	<i>IP_Shock</i>
<i>h1</i>	0.011	0.003	0.985
<i>h6</i>	0.217	0.061	0.720
<i>h24</i>	0.453	0.123	0.422
<i>h72</i>	0.536	0.145	0.318
<i>h168</i>	0.563	0.152	0.284

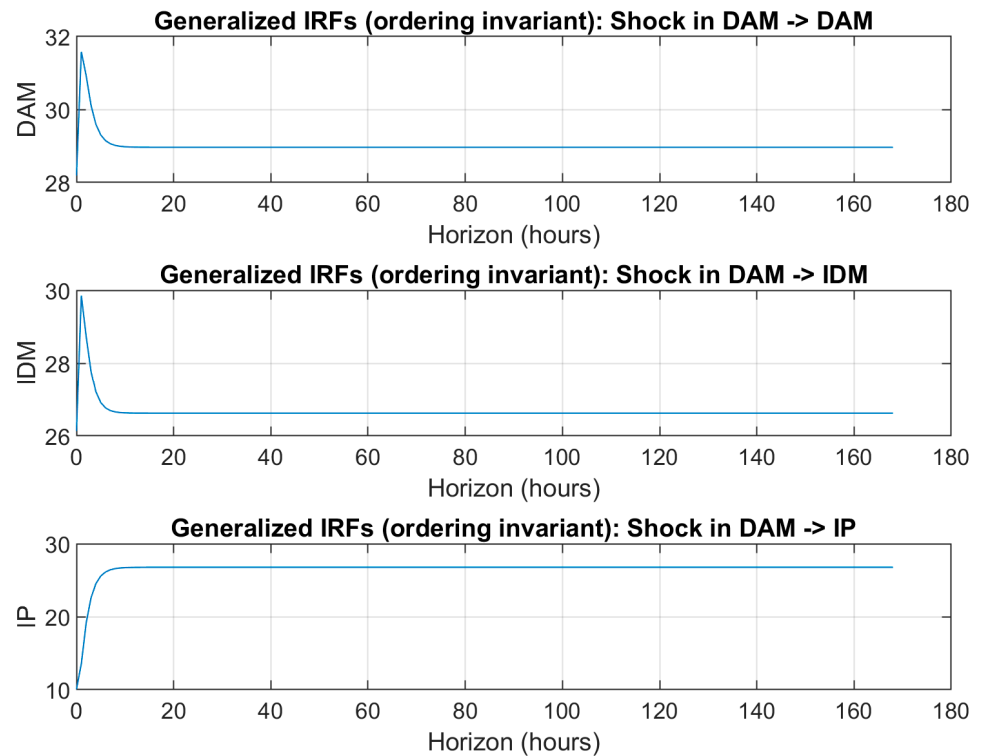


Figure A6. Generalized IRFs of ordering invariant: Shock in DAM.

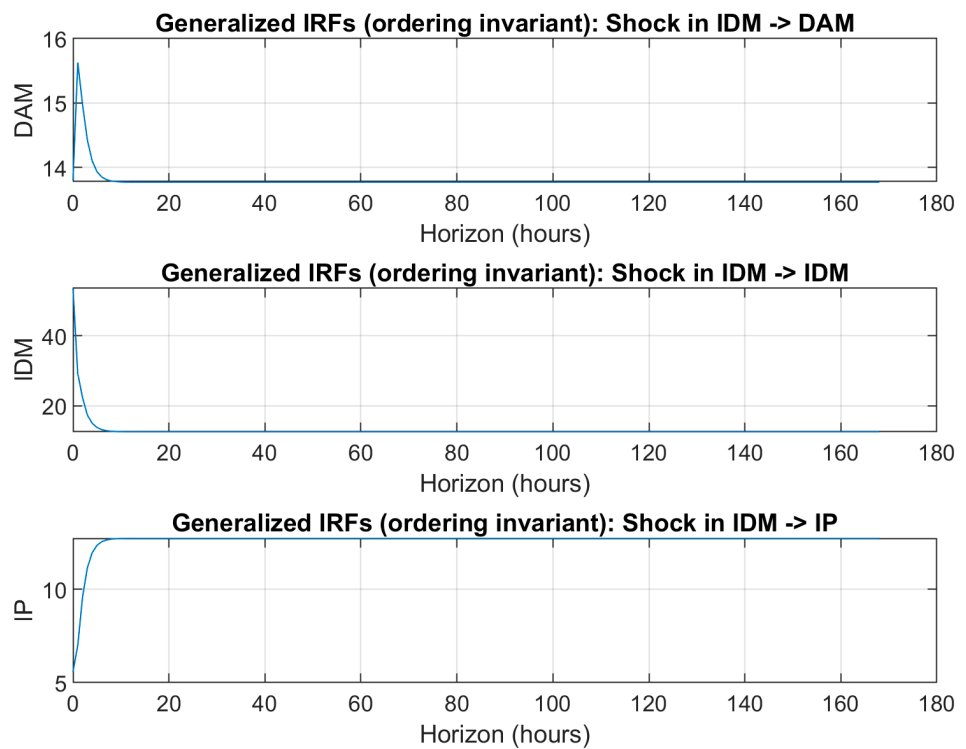


Figure A7. Generalized IRFs of ordering invariant: Shock in IDM.

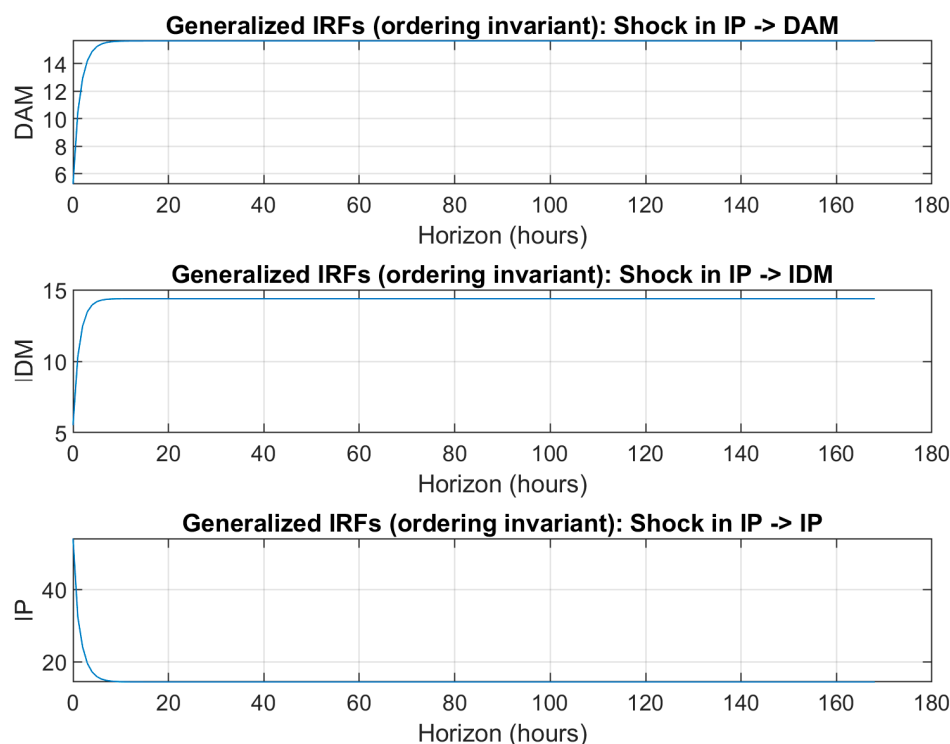


Figure A8. Generalized IRFs of ordering invariant: Shock in IP.

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